Development of a Keetch and Byram – based drought index sensitive to forest management in Mediterranean conditions

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HIGHLIGHTS

- Two releases of the well-known KBDI were applied and evaluated.
- Those versions were not sensitive to forest operations like thinning.
- A new version of KBDI sensitive to forest management was proposed.
- Correlating KBDI&BAI can be applied to other stands with the same type of forest.
- The effect of thinning is evaluated in term of forest fire risk reduction.

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.

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

Forest fires are strongly affected by weather conditions (Liu *et al.*, 2009), 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; Planisek *et al.*, 2011). The relationship between meteorological conditions and fire occurrence is well known (Piñol, 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.*, 2009). 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.* (2010) 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 *et al.*, 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.

MATERIALS AND METHODS

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 (39º05′30′′N, 1º12′30′′W) at 950 m a.s.l. The average annual rainfall is 465.7 mm, the mean annual temperature is 13.7 ºC, the mean annual potential evapotranspiration is 749 mm (Thornthwaite, 1948), and the reference evapotranspiration is 1200 mm (Hargreaves and Samani, 1985). Table 2 summarizes the mean weather conditions during the experimental period, which were representative of the climate reigning in this area. The soils have a basic pH of 7.6, are relatively shallow (0.5–0.6 m) and have a sandy silty loam texture. The *P. halepensis* plantations were established in the area during the late 1940s with high densities (approximately 1500 trees ha^{-1}), and no forest management has been carried out since then due to the role of the forest in soil protection.

The experimental data on volumetric soil water content (SWC, $m^3 \cdot m^{-3}$), tree water use (sap flow) and tree growth were taken from the above-cited study and are only outlined here. SWC was continuously measured by FDR sensors (EC-TM, Decagon Devices Inc., Pullman, WA) every 20 min for all treatments during the entire reference period (April 01, 2009 to April 01, 2011). For each treatment, 6 to 9 sensors were placed at a 0.3 m depth considering whether existed tree influence or not. A justification of the measuring depth can be found below, since it is first necessary to understand KBDI and its performance. Field calibrations were carried out by determining the gravimetric water content on four sampling dates (saturation, field capacity, between field capacity and wilting point, and wilting point) to obtain the full range of SWC at the study site. The field capacity in each treatment was calculated from the average SWC readings on three dates when the rainfall depth was higher than 30 mm in the previous 2 days.

To complete the description of the soil profile, under the mineral soil we can find several meters of karstified limestone. Thus, drainage was not limited and water table was not detected.

Sap flow velocity was measured in four trees per treatment in the same reference period by the HRM method (Burgess *et al.*, 2001; Hernandez-Santana *et al.*, 2011; Williams *et al.*, 2004) programmed to average the data every hour. Sap flow sensors (HRM, ICT International, Australia) were installed on each selected tree on the north side of the trunk at 1.3 m height. The method is based on a heat pulse emission by a heater, and temperature increases are subsequently measured in two needles equidistantly placed 5 mm downstream and upstream from the heating element at two depths. Each needle contained two thermocouples located 27.5 (inner) and 12.5 (outer) mm from their bases. Each pair of measurements (inner and outer) was then used to estimate heat pulse velocity at both depths, and the data were converted to sap flow velocity (Burgess *et al.*, 2001).

Tree growth was studied using dendrochronological procedures by coring each selected tree (same ones as for sap flow measurements) with a 5 mm increment core at the end of the study. To avoid underestimation (Merian *et al.*, 2013), between four and eight additional trees per plot were cored in the same way. All cores were visually cross-dated and measured to the nearest 0.01 mm (LINTAB 6.0, coupled with the TSAP-Win software package). Cross-dating of the tree-ring series was evaluated using the COFECHA software (Holmes, 1983). The basal area increment (BAI) was selected as an indicator of growth because it is closely related to the sapwood area.

Rainfall was continuously measured by a tipping bucket rain gauge with 0.2 mm resolution (7852, Davis, USA) located in an open area 400 m apart from the experimental plots. Measurements of air temperature were collected using a single sensor (RH/T, Decagon Devices, Pullman, USA) placed at 1 m height close to the rainfall gauge.

Keetch and Byram Drought Index (KBDI)

The KBDI, developed by Keetch and Byram (1968), is based on a daily simple water balance, and accounts for cumulative soil water depletion due to the effects of evapotranspiration and precipitation on deep duff and upper soil layers. It ranges from 0 to 203.2 when rainfall is expressed in mm, (from 0 to 800 when is expressed in inches) from low to high fire risk or from no soil water depletion to very dry conditions.

In the original work, the amount of water lost in a forested or wildland area is calculated using the following mathematical expression:

$$dQ = \frac{[800 - Q] \cdot \left[0.968 \cdot e^{(0.0486 \cdot T)} - 8.30\right] \cdot dt}{1 + 10.88 \cdot e^{(-0.0441 \cdot R)}} \cdot 10^{-3} \qquad (1)$$

The original expression does not use SI units. Temperature is expressed in ºF and rainfall in inches. The equation can be transformed easily and can be written as follows:

$$dQ = \frac{[203.2 - Q] \cdot \left[0.968 \cdot e^{(0.0875 \cdot T + 1.5552)} - 8.30\right] \cdot dt}{1 + 10.88 \cdot e^{(-0.001736 \cdot R)}} \cdot 10^{-3} \quad (2)$$

where dQ is a drought factor or soil water depletion (in mm) during a period of time dt, with the 1-day time step recommended by the authors; Q is the accumulated soil water depletion (in mm); T is daily maximum temperature (in ºC); R is mean annual rainfall (in mm); 203.2 is the field capacity of soil expressed in mm (203.2 mm = 800 hundredths inches). Due to the exponential nature of the index, mathematically reaching the 203.2 point would require an infinite time (Keetch and Byram, 1968).

In equation (2), potential evapotranspiration (ETP) is estimated on a daily basis as the ratio of an exponential function of the daily maximum temperature (T), divided by an exponential function of the mean annual rainfall (R):

$$ETP = \frac{\left[0.968 \cdot e^{(0.0875 \cdot T + 1.5552)} - 8.30\right] \cdot 10^{-3}}{1 + 10.88 \cdot e^{(-0.001736 \cdot R)}} \quad (3)$$

The numerator describes a general curve that calculates ETP as a function of daily maximum temperature, which is then adjusted to a specific region using the exponential function of the mean annual rainfall located in the denominator. The authors have indicated that vegetation tends to adjust to rainfall in a given area and for this reason is a good indicator of the evapotranspiration capacity.

Finally, potential evapotranspiration is converted to actual evapotranspiration as a linear function of soil water depletion, i.e., ETP is reduced as soil dries as described by equation (4):

$$dQ = ([203.2 - Q]) \cdot ETP \quad (4)$$

Once dQ is calculated, KBDI for today ($KBDI_t$) is obtained by adding dQ to the yesterday's KBDI value ($KBDI_{t-1}$) minus the net rainfall on a current day (P_n). If the result is negative, then KBDI is equated to zero. Note that $KBDI_{t-1}$ is equal to Q.

$$KBDI_t = KBDI_{t-1} + dQ - P_n \quad (5)$$

The net rainfall is computed by subtracting 5.08 mm (0.2 inch) from the value of daily rainfall. If there are consecutive wet days (no drying between showers), 5.08 mm is subtracted only once, on the day when cumulative rainfall exceeds 5.08. A wet period ends when two rainy days are separated by one day without measurable rainfall, thus 5.08 has to be subtracted again in the next rain period.

Is usual the end results to be expressed ranging from 0 to 800, in order to compare them with other studies, due to is the more extended form. To do that, we simply had to multiply $KBDI_t$ by the factor (100/25.4).

Soil water content measuring depth

KBDI is a Drought Index that uses a *virtual soil* composed of a superficial duff layer associated to an upper layer of mineral soil, thus forming an equivalent soil-duff layer with 203.2 mm (8 inches) of field capacity (FC). The Keetch and Byran's original paper says: "For a heavy soil at field capacity, 8.0 inches of free water would require a soil layer about 30 to 35 inches deep. In a lighter sandy soil the depth would be somewhat greater. The soil-duff layer gains moisture from rainfall and loses moisture by evapotranspiration". It is well known that the depth of many forest soils is less than 889 mm (35 inches) and, therefore, their water storage capacity is less than 203.2 mm (8 inches), but this concern is not essential (Keetch and Byran, 1968). The point is that the *virtual soil* or *equivalent soil* composed of a duff layer and an upper mineral layer have to produce null KBDI values when SWC is close to FC and values near 203.2 mm (800 hundredth inches) when SWC is near the wilting point, thus maintaining an exponential variation of soil water depletion as the soil dries.

With these considerations in mind, we can consider KBDI as the accumulated soil water depletion in the aforementioned *virtual soil*, and therefore, calculating a simple balance between water inputs (net rain) and outputs (evapotranspiration) is a SWC as well. The question is where do we put a SWC probe to measure a real value that would be similar to KBDI expressed as volumetric soil water content? If the probe is located in the duff layer, the measured values will be similar to a Fuel Dryness Index, with high-frequency fluctuations produced by drying and wetting processes, according to weather conditions, because only evaporation takes place (in the dead fuel layer there are no roots), but not evapotranspiration. If the probe is located too deeply, it will not be sensitive to SWC variations due to net rainfall. We had to find a location capable of representing SWC fluctuations with the water balance as proposed by Keetch and Byran.

In our case, the mineral soil had 0.5 to 0.6 m (19.6-23.6 in.) of homogeneous material under the duff layer, and it is classified as sandy loam. This is why we found a good agreement between SWC and KBDY by measuring SWC at a 0.3 m depth. If measured in upper layers, SWC fluctuates similarly to a Fuel Dryness Index, while upon measuring in deeper layers SWC does not change when rain takes place. Probably, SWC should be measured closer to the duff layer in heavy soils and at a deeper point in coarser soils.

Keetch and Byram Drought Index modified by Ganatsas *et al.* (G-KBDI)

Keetch and Byram derived the original equation by establishing several functional relationships between evapotranspiration, maximum temperature, and mean annual rainfall. In order to obtain the coefficients of equation (2), they set T to 26.7ºC (80 ºF) and R to 1,270 mm (50 in.) as the reference values. Following the same procedure as in the original paper, Ganatsas *et al.* (2011) changed the reference value of R from 1,270 to 762 mm (50 to 30 in.)

to adapt the index to Mediterranean conditions. Thus, the Ganatsas-modified KBDI can be written as follows:

$$dQ = \frac{[200 - Q] \cdot \left[1.71 \cdot e^{(0.0875 \cdot T + 1.5552)} - 14.59\right] \cdot dt}{1 + 10.88 \cdot e^{(-0.001736 \cdot R)}} \cdot 10^{-3} \qquad (6)$$

Finally they set the net rainfall threshold from 5.08 mm (0.2 inches) to 3 mm (0.12 inches) and calculated G-KDBI using the aforementioned KBDI methodology.

Starting a Drought Index Record

Both KBDI and G-KBDI account for accumulated soil water depletion. This cumulative feature means that it is not possible to automatically start a drought index record at zero. The index has to be initialized when a soil reaches the field capacity (FC). Keetch and Byram (1968) suggested going back to a period of abundant rainfall such as 152.4 to 203.2 mm (6 to 8 in.) per week.

In locations with such low rainfall that KBDI does not periodically get reset to zero, initialization could be a major problem. Burgan (1993) proposed a method to initialize the drought index based on the volumetric soil water content (SWC) relative to FC and defined the percentage of field capacity (PFC) and the starting value of KBDI as follows:

$$PFC = 100 \cdot \frac{SWC}{FC} \qquad (7)$$

$$KBDI_{start} = 8 \cdot (100 - PFC) \qquad (8)$$

This methodology not only allows us to know the initial value of KBDI, but it also allows conversion of actual SWC values to KBDI and *vice versa*.

Hydrology-Oriented Silviculture KBDI (HYDROSIL-KDBI)

Taking into account that ETP defined by Keetch and Byram is an empirical equation, several authors have tried to improve the index and supersede the ETP expression by another, more accurate one. For instance, Snyder *et al.* (2006) used the Hargreaves and Samani reference evapotranspiration equation (Hargreaves and Samani, 1982) and obtained KBDI values more consistent with actual seasonal changes in fuel availability and fire danger. Following this approach, the empirical equation used for ETP (the numerator in the Keetch and Byram equation):

$$\left[0.968 \cdot e^{(0.0875 \cdot T + 1.5552)} - 8.30\right] \quad (9)$$

can be re-written in the following exponential form:

$$\left[a \cdot e^{(b \cdot T)} - c\right] \quad (10)$$

where a, b, and c are empirical coefficients which have to be determined using an optimization procedure (decision variables). The root mean squared error (RMSE) was considered as the objective function in this work:

$$F = min\ RMSE = min \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \quad (11)$$

and subjected to the following constraints:

$$a, b\ and\ c \geq 0$$

where observed (O_i) and predicted (P_i) values are actual measured SWC values (converted to KBDI by using the Burgan method) and calculated KBDI values, respectively, and n is the number of observations.

The optimization procedure was performed using the Evolutionary Solver algorithm in Excel.

Statistical metrics

A complete assessment of model performance should include at least one absolute error measure and one goodness-of-fit measure (Legates and McCabe, 1999). For these reasons, the model's behavior was assessed using RMSE and the Nash-Sutcliffe modeling efficiency (E).

Nash-Sutcliffe modeling efficiency

The Nash-Sutcliffe modeling efficiency (Nash and Sutcliffe, 1970) is defined as one minus the sum of the absolute squared differences between the predicted (P_i) and observed (O_i) values normalized by the variance of the observed values $(O_i-\bar{O}_i)^2$ during the investigation period (Krause *et al.*, 2005). It is calculated as follows:

$$E = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \quad (12)$$

A value of E equal to 1 indicates a perfect fit between O_i and P_i, while a value of $E<0$ implies that the simulated value is on average, a poorer predictor than the long-term mean of the observations (Duan *et al.*, 2006)

Root Mean Square Error (RMSE)

RMSE is a measure of the average error, weighted according to the square of the error. It ranges from 0 to infinity, with 0 being a perfect score, and is calculated as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \quad (13)$$

where O_i is an observed value, P_i is a modeled value, and n is the number of observations.

Both E and RMSE values can be used to distinguish between model performance in a calibration period and that in a validation period and also to compare the performance of an individual model with that of other predictive models.

RESULTS AND DISCUSSION

Soil water content in the plots and performance of the KBDI (Original and Ganatsas-modified)

Plot soil water content and performance of KBDI (original and Ganatsas-modified)

SWC at field capacity varied among the treatments in spite of being in close proximity (0.31 ±0.03, 0.26 ±0.02, 0.32 ±0.02, and 0.20 ±0.02 $m^3 \cdot m^{-3}$ for T100, T60, T10 and T10-98, respectively). Thus the water holding capacities were somewhat different. Based on the absolute values of the measured volumetric soil water content, the highest values were found in T10, followed by T60 and T100, while the lowest SWC values were found in T10-98 (Fig. 1).

In order to take into account the FC differences between the treatments, PFC (SWC to FC ratio) was calculated and plotted, as shown in Fig. 1 (bottom panel). In this case, T10 and T10-98 followed similar patterns with higher PFC values, while T100 and T60 also displayed similar patterns but with smaller SWC/FC ratios. In any case, the differences in SWC among the treatments justify a search for different responses in KBDI.

The original KBDI and Ganatsas-modified G-KBDI were calculated for the 2-year reference period. The indices were initialized following the Burgan methodology (Burgan, 1993) using the actual soil moisture levels measured on the first day of every thinning treatment. Fig. 2 shows the evolution of the indices from April 01, 2009 to April 01, 2011.

The daily measured values of volumetric soil water content were converted to KBDI using the same method that was used to initialize the index. Then, their performance was compared relative to the calculated values of KBDI and G-KBDI, with E and RMSE derived as can be seen in Table 3. It should be noted that PFC values greater than 1 imply that SWC is greater than FC. In this case, water is lost by deep percolation and not follow the evapotranspiration mechanism. For this reason, FC is the maximum value considered when calculating observed KBDI which corresponds to zero when SWC is greater or equal to FC. If we focus exclusively on the average value of Nash-Sutcliffe E (around 0.5), regardless of the thinning treatment (Table 3), it should be recognized that both KBDI and G-KBDI are in a relatively good agreement with the actual measured value of water content (it should be noted that some thinning treatments gave E far below 0.5) and thus could be applicable to assess the forest fire risk.

In spite of the fact that they were initialized according to the actual value of soil water content, as the indices rise nearly to the maximum value in summer and definitely when they drop to zero in the wet period, "auto-initialization" takes place (Fig. 2). From this point on, the indices become non-sensitive to the differences in water content between thinning treatments. This is why we are not able to claim that either is adequate to improve assessment of the fire risk associated with stand management strategies.

Hydrosil-KDBI

In order to state that KBDI is able to respond to the different observed patterns in soil water content according to each stand management strategy, the 2-year reference period was broken up into two one-year periods, the first one to calibrate a new KBDI-based model (April 01, 2009 to April 01, 2010) and the other one to validate the proposed model (April 02, 2010 to April 01, 2011).

Following the above described optimization procedure, new coefficients for ETP equation (10) were obtained based on the actual measured soil water content in each treatment. The coefficients derived minimized RMSE in the calibration period, dealing with each treatment separately. The coefficients and the associated statistical metrics can be seen in Tables 3 and 4. Both Nash-Sutcliffe E and RSME improved relative to those obtained in the KBDI and G-KBDI cases, either in terms of the average value or providing better separation by treatments. The average value of Nash-Sutcliffe E improved from 0.54 and 0.49 obtained for KBDI and G-KBDI, respectively, to 0.81 for Hydrosil-KBDI. The average RMSE value improved from 0.04 and 0.04 to 0.03, respectively.

The new equations were applied to the validation period and then evaluated using the same statistical metrics as in the former assessment. The average value of Nash-Sutcliffe E was 0.75 while the average RMSE value was 0.02, i.e. both were better than those obtained for KBDI and G-KBDI.

Evolution of Hydrosil-KBDI during the 2-year reference period was plotted and is shown in Fig. 3. Using different coefficients in the ETP formula guaranteed that the index was sensitive to different management strategies (different SWC measured), despite the fact that the indices went through auto-initialization due to the wet period that took place on February 2010. It is noteworthy that the T-100 and T-60 Hydrosil-KBDI followed similar patterns, and perhaps in practice they should be combined in a single equation.

Fig. 4 compares Observed-KBDI (derived from measured SWC), KBDI, G-KBDI and Hydrosil-KBDI, separately for each treatment. As has already been shown above using statistical metrics, the graphical evolution demonstrated that better goodness-of-fit was achieved with the proposed index.

Hydrosil-KDBI forest fire reduction assessment

In order to quantify the improvement, either in terms of KBDI reduction or risk reduction produced by the thinning treatments, Fig. 5 (top, secondary Y-axis) shows, as percents, the difference between the T100 and T10 Hydrosil-KBDIs. Depending on the season, the KBDI reduction ranged from 14.5% to 87.2%. Taking into consideration that a typical year is divided into periods of different fire risk, a good indicator of the accomplished improvement would be an average index reduction during the maximum fire danger risk period. In the Mediterranean area, a typical year is divided into three fire danger periods, low, moderate and high risk, respectively. If weather conditions remain normal, there exists a high risk of fire for 4 months, from the 1st of June to the 1st of October. In our case, the average reduction of KBDI due to the thinning treatments was 22.5% in the 2009 high risk period, while that in 2010 was 26.4%.

It is worth noting that the observed SWC increase caused by a thinning treatment decreases as the stand grows and occupies the space left by the removed trees. To analyze this effect, the T10-98 treatment was included. This plot was thinned 10 years before and now SWC was measured. Fig. 5 (bottom panel, secondary Y-axis) shows, as percents, the difference between the T100 and T10-98 Hydrosil-KBDIs. The average KBDI reduction 10 years after the thinning treatment was 12.5% in the 2009 high risk period while it was 6.7% in 2010. This means that the effect of thinning does not disappear but lasts for a long time.

Relationship between Hydrosil-KBDI and tree-related and physiological variables: Generalization of the proposed index

In this work, two releases of KBDI were tested so far, and another one was proposed and evaluated, each working under different management conditions. It should be recognized, however, that those treatments are quite difficult to exactly replicate in other places. This is why in each treatment several tree-related and physiological variables were measured in order to relate them to a, b, and c coefficients of the proposed index. Thus, by measuring those variables in other stands, it would be possible to obtain suitable values of a, b, and c for the proper application of Hydrosil-KBDI. The following tree-related and physiological variables were selected: Basal Area Increment (BAI, cm^2) as an indicator of growth and Sap Flow (SF, $l \cdot d^{-1}$) and inner (Vsi) and outer (Vso) Sap Flow Velocity ($cm \cdot h^{-1}$) as indicators of stand-level transpiration.

A linear and 20 non-linear regression models were used to relate the variables. To assess the fit of the regression models, the following statistics were observed: P-value, R-squared statistic (R^2), correlation coefficient (r), and mean absolute error (MAE).

Models with P-values greater than 0.05 (statistically non-significant relationship between variables at the 95.0% confidence level) were rejected. Then, models with the minimum MAE were selected, taking into consideration that R should be >0.85 and R^2>75.0. Table 5 summarizes the regression models finally selected to obtain a, b and c coefficients of Hydrosil-KBDI based on the tree-related and physiological variables.

BAI is an easy to get variable by means of dendrochronology techniques. Sampling cores of wood on representative trees of the stand, it is possible to obtain the mean BAI value for the stand at the beginning of the growing season and then easily generate the Hydrosil-KBDI coefficients, with only one measure. The other tree-related and physiological variables need to be measured continuously using complex devices. This is why we recommend using BAI to extrapolate the proposed index to other stands.

To validate the proposed equations and to extrapolate the index to other Aleppo pine stands, a different site was analyzed, which had SWC previously measured. This new site is located 115.8 km apart from the experimental site used for the index definition, in the Middle West region of the Valencia province in Spain (40º07′58′′N, 1º16′51′′W) at 993 m a.s.l. The average annual rainfall is 432 mm. The soils have a basic pH of 7.8, are relatively shallow (0.4-0.5 m), and have a sandy clay loam texture. The stand shows medium density with approximately 715 trees ha^{-1}. Existing SWC measurements dating back to 2007 (December 13, 2006 to November 16, 2007) were used. The data were collected at a 0.3 m depth using similar equipment. Field calibrations were carried out by determining the gravimetric water content, and field capacity was established to be 0.23 $m^3 \cdot m^{-3}$. Finally, to apply the equations proposed in Table 5, a single BAI measurement from 2006 was performed using dendrochronological procedures, which gave 31.9 cm^2 and resulted in the following Hydrosil-KBDI expression:

$$dQ = \frac{[203.2 - Q] \cdot \left[8.057 \cdot e^{(0.0556 \cdot T + 0.9884)} - 3.0116\right] \cdot dt}{1 + 10.88 \cdot e^{(-0.001736 \cdot R)}} \cdot 10^{-3} \qquad (14)$$

As can be seen in Fig. 6, a good agreement was achieved between the modeled and measured SWC data. The same statistical metrics that was used to assess the performance of KBDI indices was used, and the following numbers were obtained for the new plot: Nash and Sutcliffe E was 0.90 and RMSE was 0.0131, which reveals a strong relationship between KBDI and BAI.

CONCLUSIONS

The main conclusions are:

- Silviculture management operations that modify the hydrological cycle and water balance also affect the fire risk; however, the more diffusive versions are not sensitive to take into account for this benefit.
- The proposed Hydrosil-KBDI index improved the behavior of the original and Ganatsas-modified KBDIs in Mediterranean conditions, both with and without stand management.
- The reduction in fire risk introduced by the silviculture management treatments was quantified in terms of KBDI reduction. In our case, the average KBDI reduction was 22.5% in the 2009 high risk period while it was 26.4% in 2010.
- This aforementioned effect lasts for a long time. Even 10 years after high intensity thinning, we still observed KBDI reductions of 12.5% and 6.7% in the 2009 and 2010 high risk periods, respectively.
- In practice, the best way to adapt the proposed index to other stands is by measuring their BAI. A single measurement at the end of the growing season allows index adaptation for the next season.

Finally, as stated in the introduction, forest fire indices are classified into two types, structural and dynamic. The former take into account variables that do not change easily over time, such as a fuel model or topography. The latter consider variables that change easily during the year, such as weather conditions. Drought and dryness indices such as KBDI are included in the second group. It has been demonstrated in this work that silviculture management can modify a dynamic index; however, structural variables, e.g. amount of fuel, are modified too due to this intervention. This leads to another improvement in fire risk prevention, which was not studied in this work but deserves to be included in future studies.

Now, new research needs to be done in other stands with other species to generalize the proposed index so that it can be applied to the entire Mediterranean landscape.

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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

Table 2. Mean weather conditions during the experimental period

Year	Mean Temperature (ºC)	Rainfall (mm)
2009	14.6	464
2010	13.5	396
2011	14.3	342

Table 3. Behavior of Original and G-KBDI according to each thinning treatment using statistical metrics.

THINNING	KBDI		G-KBDI		HYDROSIL-KBDI-CALIBRATION		HYDROSIL-KBDI-VALIDATION	
	E	RMSE	E	RMSE	E	RMSE	E	RMSE
T10-98	0.63	0.03	0.64	0.03	0.82	0.02	0.88	0.01
T10	0.77	0.03	0.20	0.05	0.84	0.03	0.76	0.02
T60	0.41	0.05	0.55	0.04	0.77	0.04	0.69	0.03
T100	0.38	0.05	0.58	0.04	0.82	0.03	0.70	0.03
Average	0.55	0.04	0.49	0.04	0.81	0.03	0.76	0.02

Table 4. Hydrosil-KBDI coefficients.

COEFFICIENT	THINNING			
	T100	T60	T10	T10-98
a	14.6582	13.0824	11.3218	9.5796
b	0.0183	0.0194	0.0182	0.0236
c	4.4051	3.2658	3.2866	7.9759

Table 5. Regression Models to obtain a, b and c coefficients of Hydrosil-KBDI as from tree-related and physiological variables.

Tree-related and Physiological variables	Model	KBDI parameter	Statistical Parameter				Regression Model Equation
			P-Value	R	R^2	MAE	
BAI*	Reciprocal-Y logarithmic-X	a	0.006	1.0	94.3	0.02	a = 1/(0.0358 *ln(BAI))
	Square root-X	b	0.018	0.9	88.0	0.01	b = 0.0055*sqrt(BAI)
	Reciprocal-Y logarithmic-X	c	0.013	0.9	77.7	0.07	c = 1/(0.0959 *ln(BAI))
SF	Reciprocal-Y logarithmic-X	a	0.004	1.0	95.5	0.02	a = 1/(0.03479*ln(SF))
	Square root-X	b	0.016	0.9	89.1	0.01	b = 0.0053*sqrt(SF)
	Reciprocal-Y logarithmic-X	c	0.045	0.9	78.7	0.10	c = 1/(0.0931*ln(SF))
Vsi	Reciprocal-Y square root-X	a	0.007	1.0	93.9	0.02	a = 1/(0.0655*sqrt(Vsi))
	Square root-X	b	0.015	0.9	89.3	0.01	b = 0.01499*sqrt(Vsi)
	Reciprocal-Y square root-X	c	0.030	0.9	83.6	0.09	c = 1/(0.1827*sqrt(Vsi))
Vso	Reciprocal-Y square root-X	a	0.008	1.0	93.3	0.02	a = 1/(0.0540*sqrt(Vso))
	Squared-Y reciprocal-X	b	0.049	0.9	77.3	0.00	b = sqrt(0.00056/Vso)
	Reciprocal-Y square root-X	c	0.020	87.4	95.4	0.08	c = 1/(0.1541*sqrt(Vso))

* Previous year

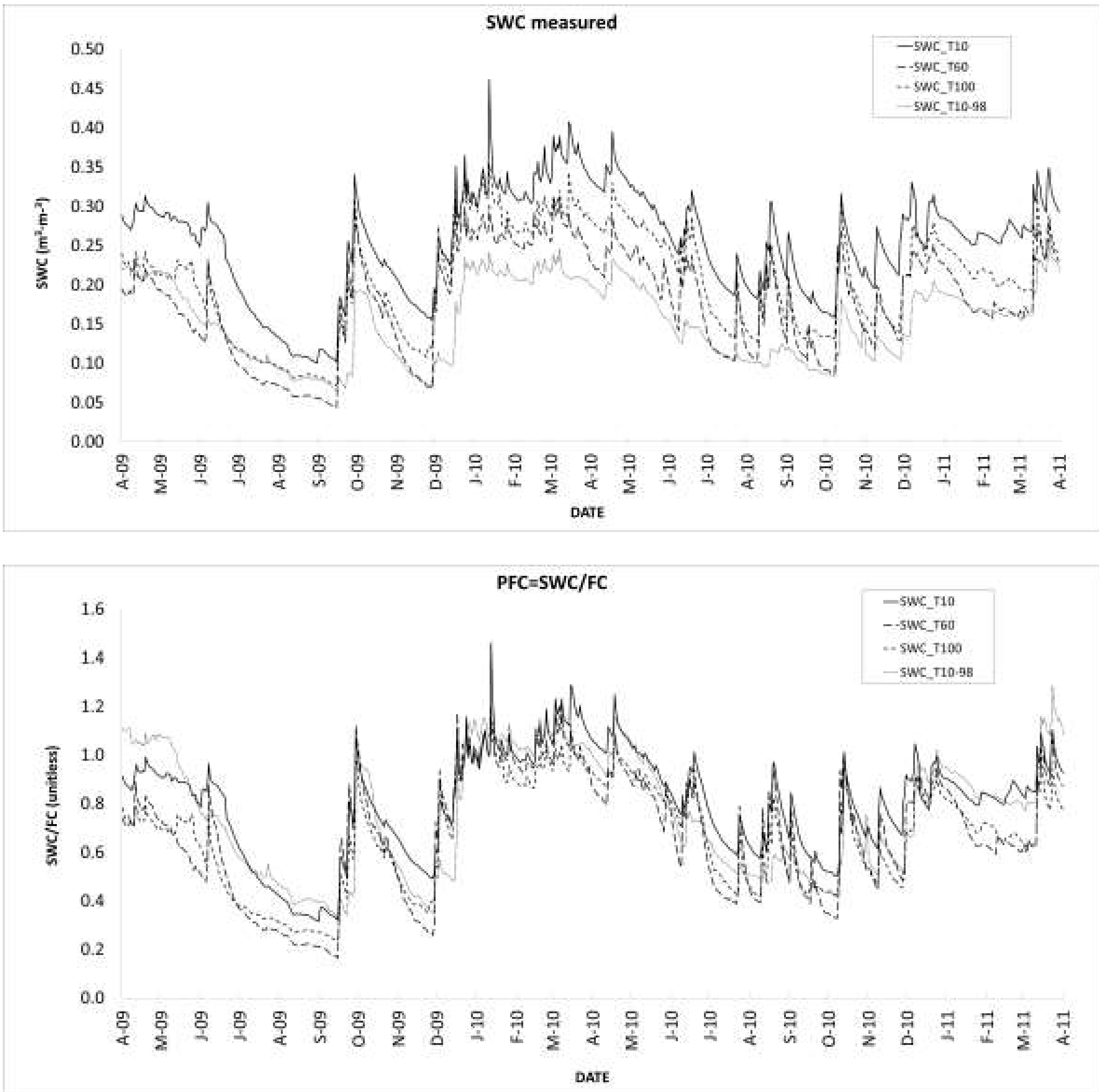


Figure 1. Soil water content (SWC, $cm^3 \cdot cm^{-3}$) (top panel) and percentage of field capacity (PFC) (bottom panel) measured for each thinning treatment.

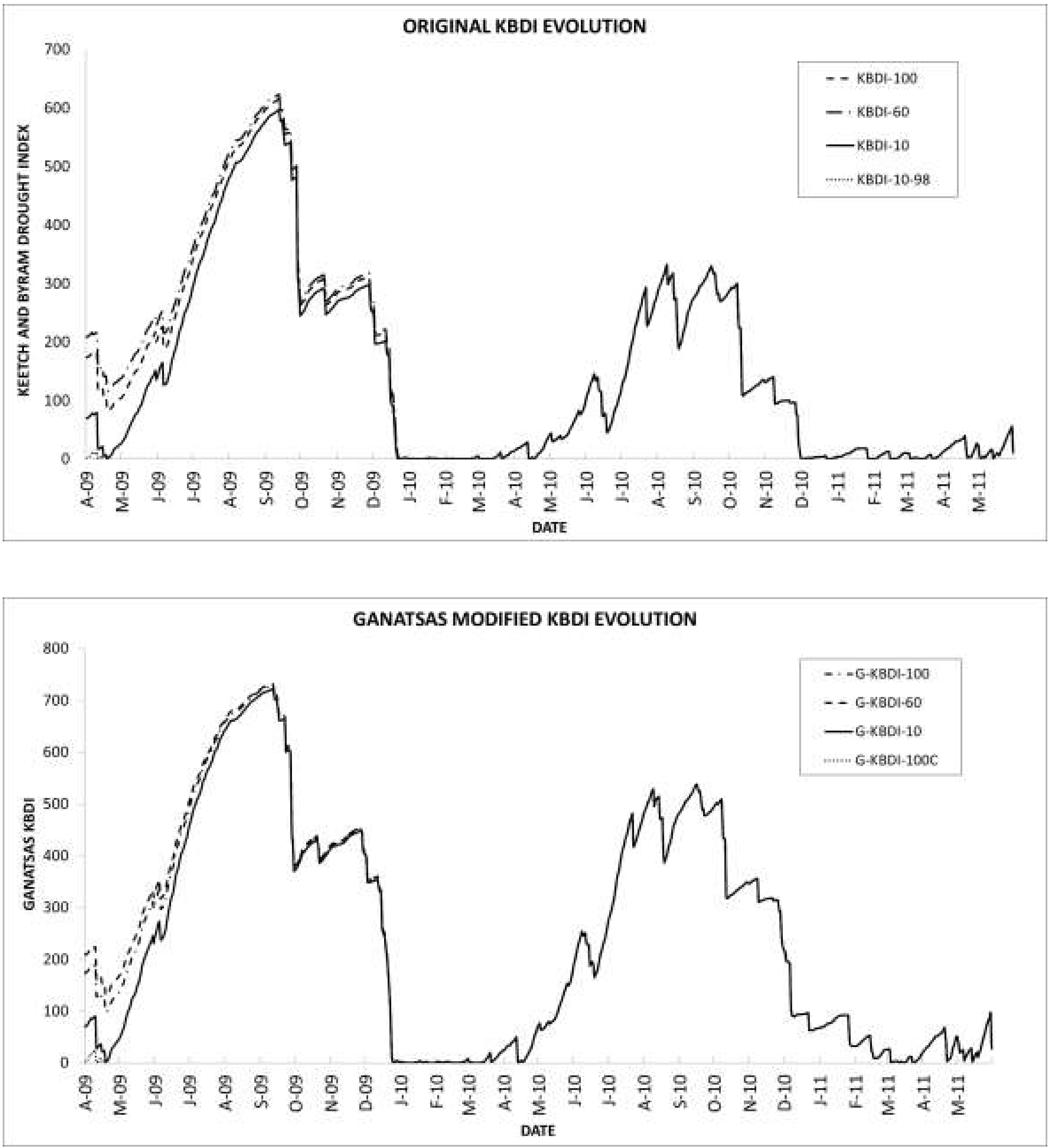


Figure 2. Original-KBDI (top panel) and G-KBDI (bottom panel) evolution along the studied period according the different thinning treatments.

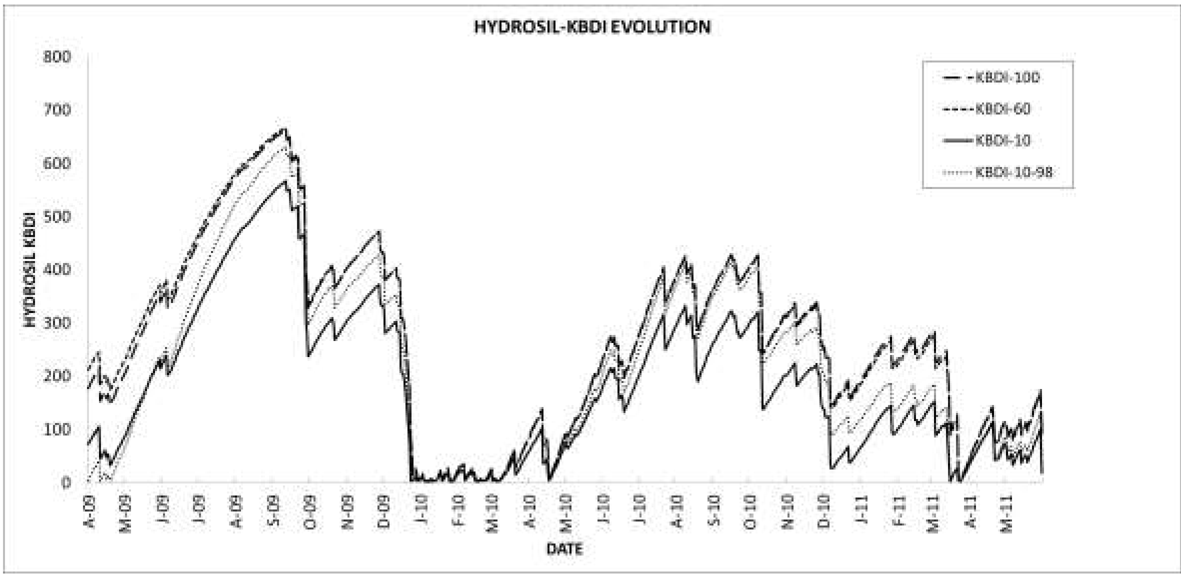
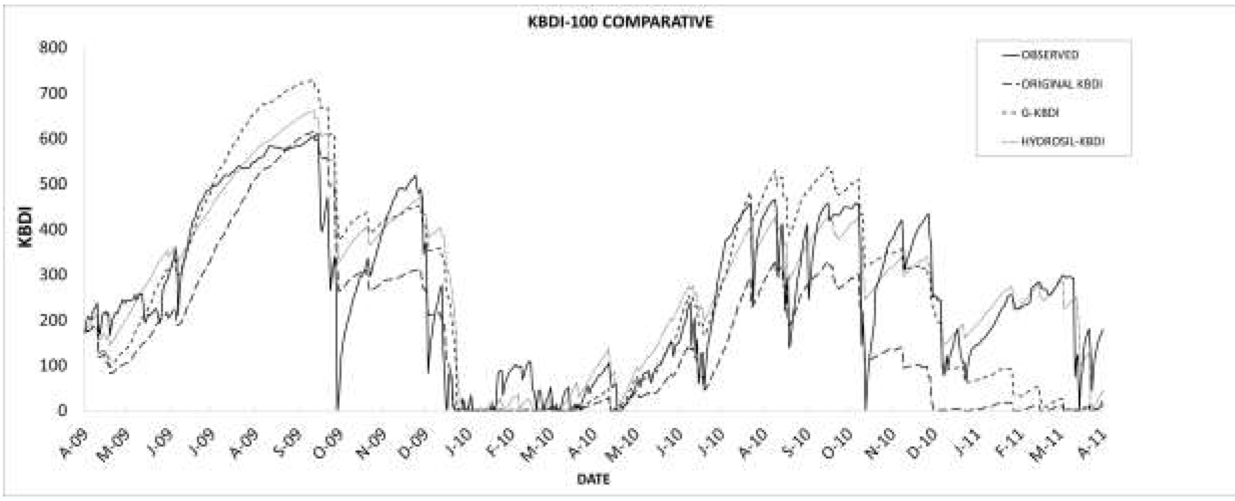


Figure 3. Evolution of Hydrosil-KBDI during the 2-year reference period, depending on the thinning treatment.


KBDI-100 COMPARATIVE
KBDI
DATE
OBSERVED
ORIGINAL KBDI
G-KBDI
HYDROSIL-KBDI
0
100
200
300
400
500
600
700
800
A-09
M-09
J-09
J-09
A-09
S-09
O-09
N-09
D-09
J-10
F-10
M-10
A-10
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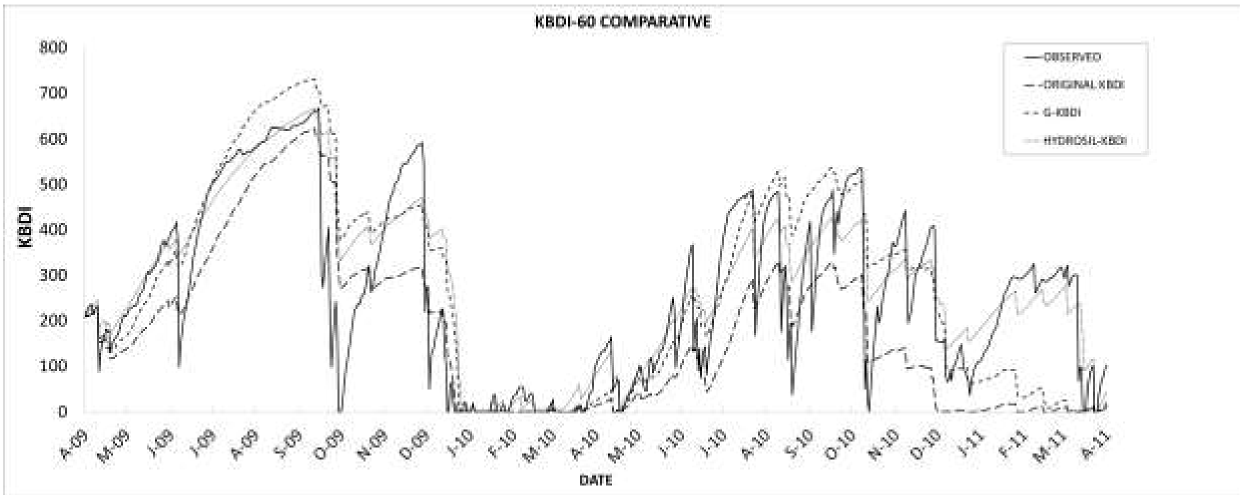
D-10
J-11
F-11
M-11
A-11


KBDI-60 COMPARATIVE
KBDI
DATE
OBSERVED
ORIGINAL KBDI
G-KBDI
HYDROSIL-KBDI
0
100
200
300
400
500
600
700
800
A-09
M-09
J-09
J-09
A-09
S-09
O-09
N-09
D-09
J-10
F-10
M-10
A-10
M-10
J-10
J-10
A-10
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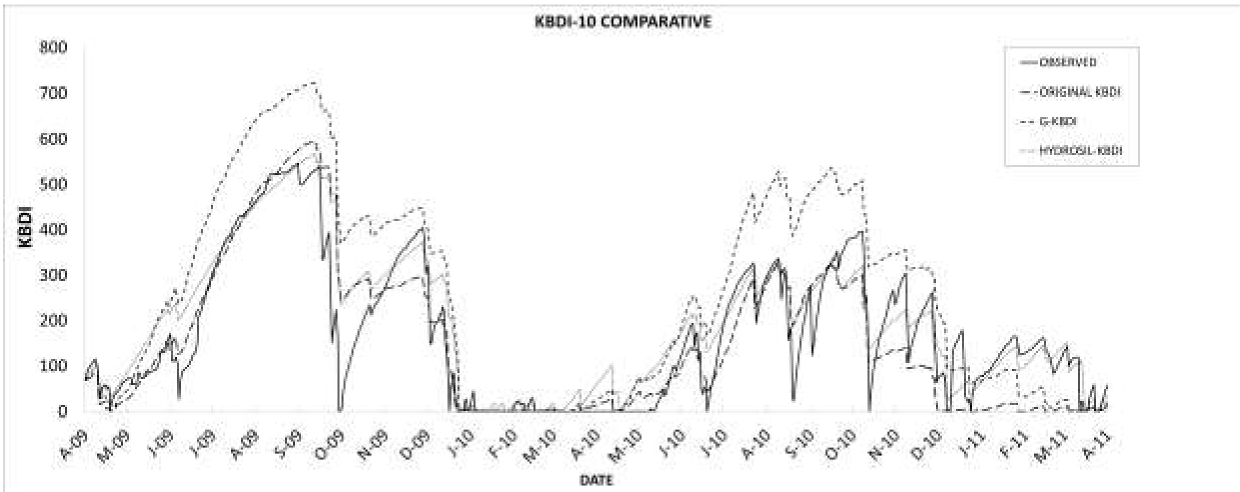
F-11
M-11
A-11


KBDI-10 COMPARATIVE
KBDI
DATE
OBSERVED
ORIGINAL KBDI
G-KBDI
HYDROSIL-KBDI
0
100
200
300
400
500
600
700
800
A-09
M-09
J-09
J-09
A-09
S-09
O-09
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F-10
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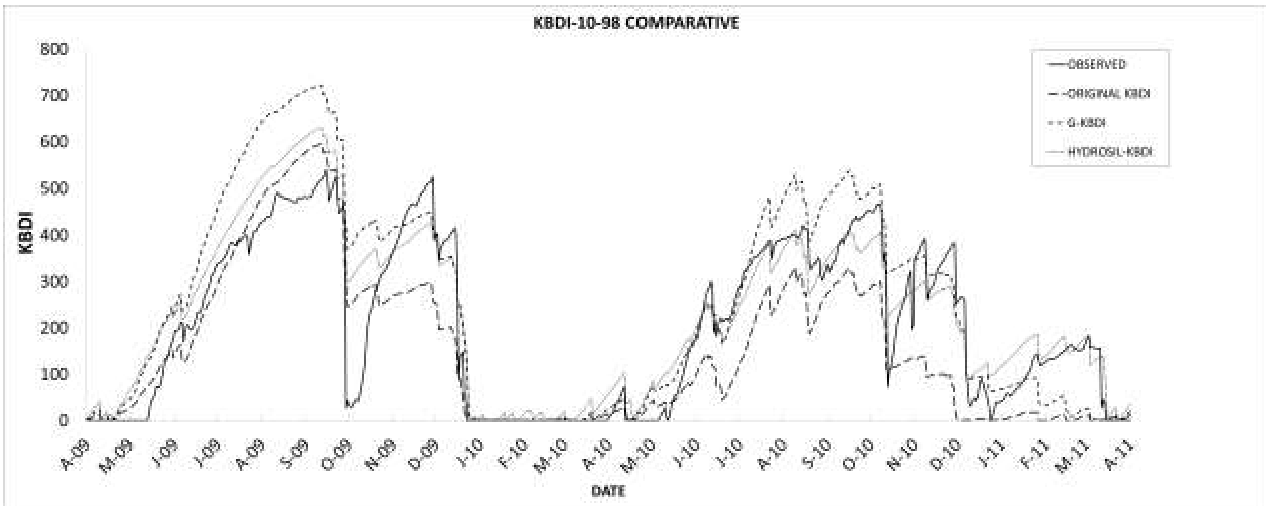
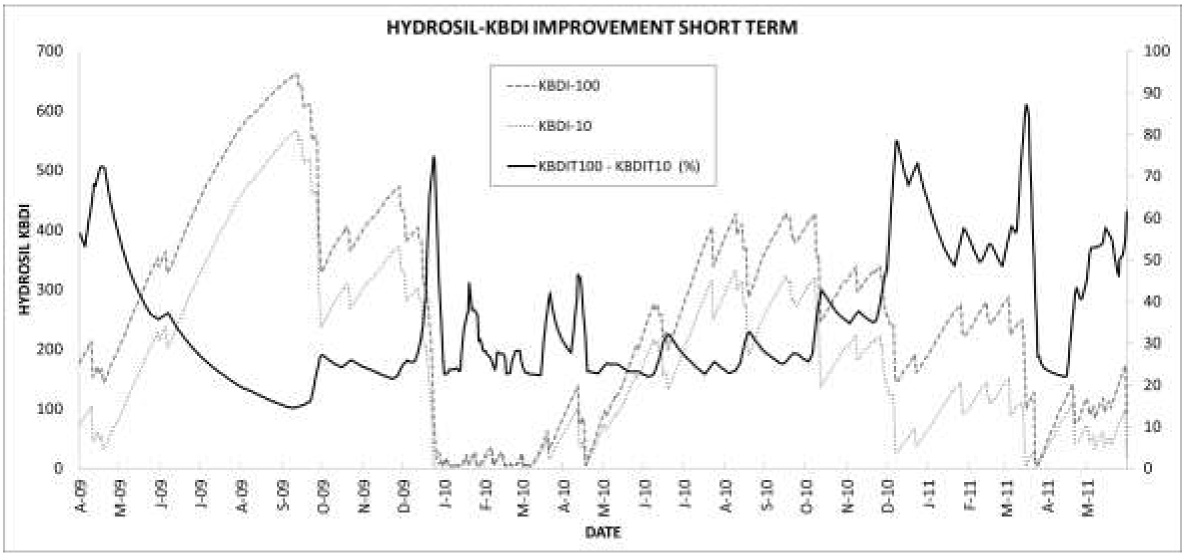


Figure 4. Comparison of KBDI releases for different thinning treatments.



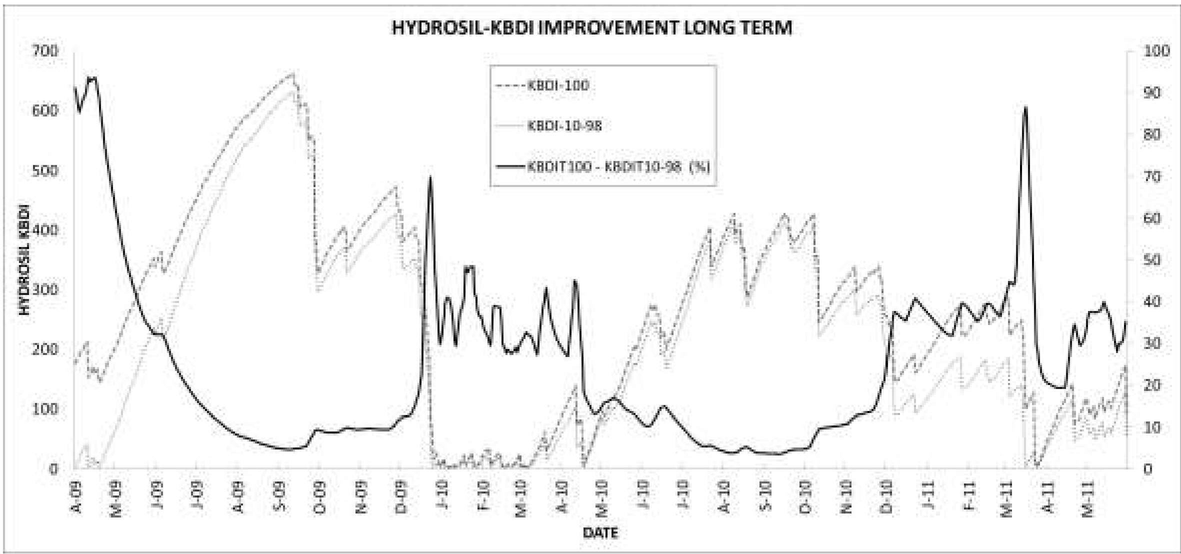


Figure 5. Estimation of short- and long-term KBDI improvement due to the thinning treatments.

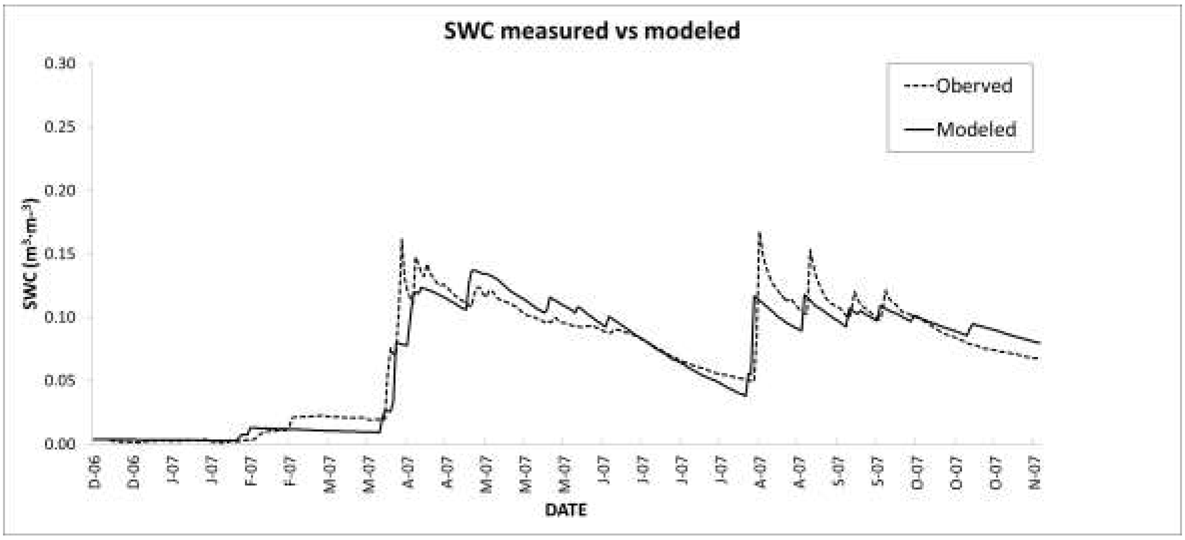


Figure 6. Observed *vs* modeled SWC values in a stand different from that used for the index definition.