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The South African Lowveld Fire Danger Index (LFDI) and Its Applicability in Greece

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Abstract: The necessity for Greece to adopt a National Fire Danger Rating System that combines convenience and objectivity was the reason to analyze once again the suitability of the Lowveld Fire Danger Index (LFDI) applied in Greece. The analysis proved that LFDI is based on the Swedish Angstrom Index and it is structured on the shape of the Canadian Forest Fire Index. LFDI is related to the Rate of Spread (ROS) of the Greek forest fires and it is the same effective in predicting ROS like other well-known and long used, simple fire weather indices. LFDI's maximum daily values serve as an indicator of the maximum possible burnt areas, while its 5 fire danger classes as an indicator of the average burnt area per fire. Due to its mathematical structure, modifications are possible for an even better adaptation to Greek physical conditions. Apparently, LFDI is also applicable in other extra tropical countries.
Key words: fire weather index, Lowveld, ROS
JEL codes: Q5

1. Introduction

There is no doubt that Fire Weather Indices are some of the most useful tools in the hands of fire managers to reduce firefighting cost, since they are used to determine readiness levels for fire suppression crews, to schedule prescribed burns and to allocate resources (Sharples et al., 2009). In other words, fire managers must make decisions each day on how many resources they will need and where those resources should be positioned. Fire crews and air-tankers are assigned an alert status indicating how quickly they must be able to respond or may be sent to forward attack bases to be pre-positioned for quicker response in a particular area (Wotton, 2009). These decisions and many more throughout the day and throughout the fire season depend on the fire risk level of each day provided by Fire Weather Indices as major subsystems (Varela et al., 2018) of the Nationals Forest Fire Danger Rating Systems.

The Lowveld Fire Danger Index (LFDI or simply FDI) is the one applied in South Africa and with its daily forecast by the South African Weather Service (SAWS, 2021) estimates the risk of wild fires ignition and spreading based only on meteorological conditions, classifying it into 5 categories. It was originally developed in Zimbabwe (Rhodesia) in 1968 by the scientist Michael Laing and slowly adopted the local weather stations in Mpumalanga and other Lowveld areas (South Africa's lowland north-eastern provinces) before becoming the

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national standard much later on. The LFDI is now the official National Fire Danger Rating System of South Africa (Madula, 2013; Oxford, 2017) after being evaluated and selected among seven different operating systems used in other countries, including more sophisticated models such as Canadian Fire Weather Index and the Australian McArthur Forest Fire Danger Index (Willis et al., 2001; Steenkamp et al., 2012). Based on the values of the same index, decisions are also made on the suitability of conditions for the application of prescribed burning in the savanna (Trollope et al., 2007). It is very easy to use. With a single A4 size brochure from South Africa's Department of Water Affairs and Forestry (2021) it can be even directly calculated by firefighters at the field, using a nomogram and two tables on one side of the leaflet, as long as they have available measurements of local air temperature and relative humidity, wind speed, last rainfall amount and date of its occurrence. The LFDI calculation automatically refers to one of its 5 hazard classes and then, using tables on the other side of the leaflet, to information about expected fire behavior (average spread rate, flame length, etc.) and to appropriate suppressive measures (Madula, 2013). The above mentioned were the reason before 9 years ago, for a first exploration of the feasibility of applying LFDI in Greece for every fire season (May 1st-October 31st). The LFDI (if it was applicable in Greece) and the forest fire risk index issued by the General Secretariat for Civil Protection during the days of large forest fires in the wider area of 10 representative meteorological stations of the Hellenic National Meteorological Service (HNMS), were compared and their correlation with the daily number of wildfires across the country for the 2007 and 2008 fire seasons were studied, making LFDI applicable and effective for Greek conditions (Iliopoulos et al., 2010). The present analysis goes a step further by investigating:

1) The correlation between LFDI and the average rates of fire spread, as well as the size of burned areas in Greece.
2) Its ability to be modified in order to be used outside the fire period.
3) Useful information underlying this easy to use index.

Obviously, LFDI is examined in order to find out a more convenience and objective National Fire Danger Rating System (NFDRS) for Greece. Another important reason is to find out a simple (taking into account only meteorological parameters) and easy interpreting Fire Weather Index in order to estimate if weather conditions are getting worse or better for the rest of the day in terms of firefighting after the ignition of any forest fire, since Daily Fire Risk Forecast Maps in Greece are produced once a day. Fosberg Fire Weather Index (FFWI) came to solve the same problem in USA (Goodrick, 2002). FFWI was designed as a supplement to the once-daily fire danger calculations provided by the US-NFDRS (US-NFDRS is designed to reflect the near upper limit of potential fire behavior that may occur in a rating area on a given day based on average worst-case conditions: mid-afternoon weather conditions, mid-slope on south or south-west aspects). The FFWI is basically a non-linear filter of meteorological information (temperature, relative humidity and wind speed) that provides land managers with a useful tool for interpreting the impacts of small-scale/short term weather variations on fire potential. So, land managers can calculate the FFWI using hourly observations from all available weather stations to evaluate the spatial and temporal evolution of the weather component of the fire environment (Goodrick, 2002).

2. Material and Methods

LFDI as well as Canadian Forest Fire Weather Index (Canadian FWI) values were calculated from daily meteorological data (maximum temperature and minimum relative humidity of the air, mean wind speed and rainfall amount) of 31 HNMS's meteorological stations for a 3-year period: 1/1/2014-31/12/2016. For the same period and from the .xls files of the "Open Data" for forest fires of the Hellenic Fire Corps (2021) official website, all wildfires were selected based on the burned area of forest and grassland fires of at least 10 Ha, except those in Attica (greater area of the capital city of Athens, to minimize possible effects of the rapid mobilization and the large number of ground and aerial means in Attica on the results of this work). Based on this criterion, the selection yielded 390 fires from all over Greece, for each of them the closest of the HNMS's 31 meteorological stations was considered representative. For 311 of these fires, which occurred during the 2014-2016 fire seasons and through the website of Daily Fire Risk Maps issued by the General Secretariat for Civil Protection (GSCP, 2021), the forest fire risk index of their wider area was obtained. The Canadian Forest Fire Weather Index (Canadian, FWI) was chosen to be examined due to the interest in it by many Greek researchers (Xanthopoulos et al. 2014; Varela et al., 2018) and despite its great complexity, it can be easily calculated through an online calculator (Miller 2021). Its 6 fire danger classes, used in this study, are according to European Forest Fire Information System (EFFIS) classification scheme (Varela et al., 2018):

Very Low	<5.2
Low	5.2-11.2
Moderate	11.2-21.3
High	21.3-38.0
Very High	38.0-50.0
Extreme	>= 50.0

The rather few known measurements of Rate of Spread (ROS) of Greek forest fires used in the present analysis are derived mainly from the works of Athanasiou (2008) and Xanthopoulos (2002), from the Forest Fire Book of Kailidis (1990), as well as from a few, relatively recent cases of fires (after 2014), which velocities were calculated using the "hot spots" detected by NASA's MODIS and VIIRS satellite sensors. The correlation between the Rate of Spread (ROS in km/h) of forest fires with the LFDI, FFDI (McArthur), F index and Fosberg index was examined and these relationships were compared. This comparative analysis was limited to these fire weather indices because of their relatively easy calculation from meteorological data only, as one notes in the work of Sharples et al. (2009). In addition, knowing the value of those indices in a given fire at any time of the day, could help the on-site coordinator to estimate fire behavior for the next hours, based on his own experience, as opposed to the US and Canadian Indices, which can only be calculated once a day (Goodrick, 2002; Oxford, 2017). Canadian FWI was excluded from these comparisons due to the long time series of weather data of all these fire cases needed for its calculations.

Analysis between the different cases examined was carried out mainly through comparison of R^2 (Coefficient of Determination) values and, where necessary, through Standard Error of Estimate (S) values of the equations obtained by Least Squares-Method.

The numerous calculations of LFDI required in the present study could not be made solely with the available nomogram and its accompanying tables (Madula, 2013), which were also cited in the study of Iliopoulos et al. (2010). In such cases it is necessary to know its equations. LFDI is therefore calculated in detail as follows:

$$LFDI = (BI + WF) * RCF \tag{1}$$

Where:

BI=Burning Index

$$BI = (T-35)-((35-T)/30)+((100-RH)*0.37)+30 \tag{2}$$

T = Air temperature (°C) and RH = air relative humidity (%),

WF = Wind Factor

$$WF=-0.0000227*WS^4+0.0026348*WS^3-0.09087*WS^2+1.65*WS+0.2 \tag{3}$$

or, less accurately,

$$WF=0.8*WS \tag{4}$$

WS = Wind Speed (km/h)

RCF = Rain Correction Factor

$$RCF=0.62-0.0342*P+0.000609*P^2-0.000004*P^3+0.176*D-0.01141*D^2+0.000279*D^3 \tag{5}$$

P = Amount of last rainfall event (mm)

D = Number of days since last rainfall

Equation (2) is the exact way of calculating the Burning Index (Madula, 2013). Equations (3) and (4) have been derived from the LFDI calculation tables of Madula (2013) using the Least Squares-Method, achieving very accurate estimates of WF (R^2 = 0.99 and S = 1.2) and RCF values (R^2 = 0.97 and S = 0.05) listed in the same tables.

LFDI values change during the day due to diurnal variation of meteorological parameters, as can be seen at figures 9 and 10 of Trollope et al. (2007). Therefore, its maximum daily value, usually observed during early afternoon hours in Greece, determines the Fire Hazard Index of each day (Madula, 2013). For this reason, but also to allow comparability with the forest fire risk index issued by the Greek GSCP, the maximum air temperature and minimum relative humidity values of each day of the 390 fires, as stated above, instead of their values at the ignition time of the fires, were used.

3. Results and Discussion

The process by which LFDI was developed and the assumptions that were made were never documented by its creator, Michael Laing (Willis et al., 2001). There was therefore no basis on which to judge the validity of the system, given that other suitable and well documented systems are available, so Willis et al. (2001) did not recommend that LFDI be selected to underpin a South African NFDRS. However, careful examination of equation (2) reveals similarities between LFDI's Burning Index and the Swedish Angstrom Index, an old index which remains one of the most sensitive measure of the fire occurrence risk forecasting (Skvarenina et al., 2003; Lukić et al., 2017). With help of the Least Squares-Method, it is easy to show (Figure 1) that the relationship between the two indices (BI and Angstrom) is:

$$BI=-9*(Angstrom\ Index) + 62 \quad (R^2 = 0.99, S = 2) \tag{5a}$$

Based on the above equation, values of Angstrom Index higher than 4 (meaning fire occurrence unlikely) correspond to values lower than 26 of the Burning Index, while values of Angstrom Index lower than 2 (fire occurrence very likely, according to Skvarenina et al. (2003) correspond to values higher than 44 of Burning Index. It is recalled that with no wind and values of Burning Index < 20 (hence LFDI < 20) fires are not likely to ignite, but if they do, they are likely to go out without suppression action, while for Burning Index > 45 fires ignite readily and spread rapidly (Madula, 2013).

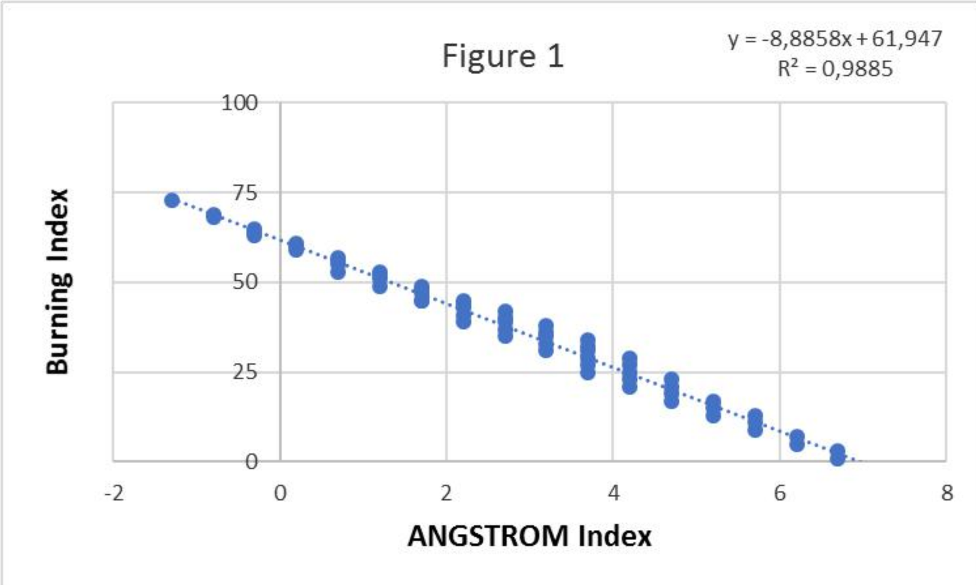

Figure 1 Plot indicating the Relationship Between Angstrom Index and LFDI's Burning Index

Therefore, the Burning Index of LFDI is nothing but Angstrom Index on another scale and for those who are familiar with Angstrom Index, an approximate form of LFDI is:

$$LFDI = 62 - 9*(Angstrom\ Index) + 0.8*WS \quad (5b)$$

Where WS = Wind Speed in Km/h.

Thus, for the meteorological data of 6 cases of experimental burns of pine needle fuel bed listed in Table of of Kailidis's forest fire book (1990, p. 137), the following equation is derived, giving the rate of fire propagation (ROS in km/h) as a function of Burning Index (BI):

$$ROS = 0.0003*BI + 0.0026 \quad (R^2 = 0.45) \quad (6)$$

For the rest, however, 9 cases of needle fuel experimental burns under windy conditions on the same table of Kailidis (1990), we have:

$$ROS = 0.0020*BI + 0.0152 \quad (R^2 = 0.51) \quad (7)$$

$$ROS = 0.0022*LFDI + 0.0388 \quad (R^2 = 0.66) \quad (8)$$

Consequently, addition of a function of wind speed (Wind Factor, WF) to BI in order to form LFDI must be considered successful, since it increases at about 15% the ROS variance explained by Equation (7) due to wind blow.

Burning Index acts as a measure of equivalent moisture content percentage of dead fuels (EMC), calculated according to Simard's (1968) equations for small temperature ranges, e.g.:

$EMC=-24.36*ln(BI)+103.45$, with R^2=0.94 for temperatures 30-35°C (Figure 2),

provided that any water gained by precipitation has been evaporated. Thus, multiplying BI by Rain Correction Factor (RCF) attempts to correct (decrease) the LFDI, increasing rainfall amount and decreasing number of days since last rainfall. When RCF = 1, then all excess water gained by rainfall is eliminated and fine dead fuels absorb or lose moisture depending mainly on relative humidity fluctuations of the air (Johnson and Miyanishi, 2001). It must be mentioned that Angstrom index (Burning Index, consequently) presented high correlation with litter moisture content (r = 0.70) in Greece (Ganatsas et al., 2011).

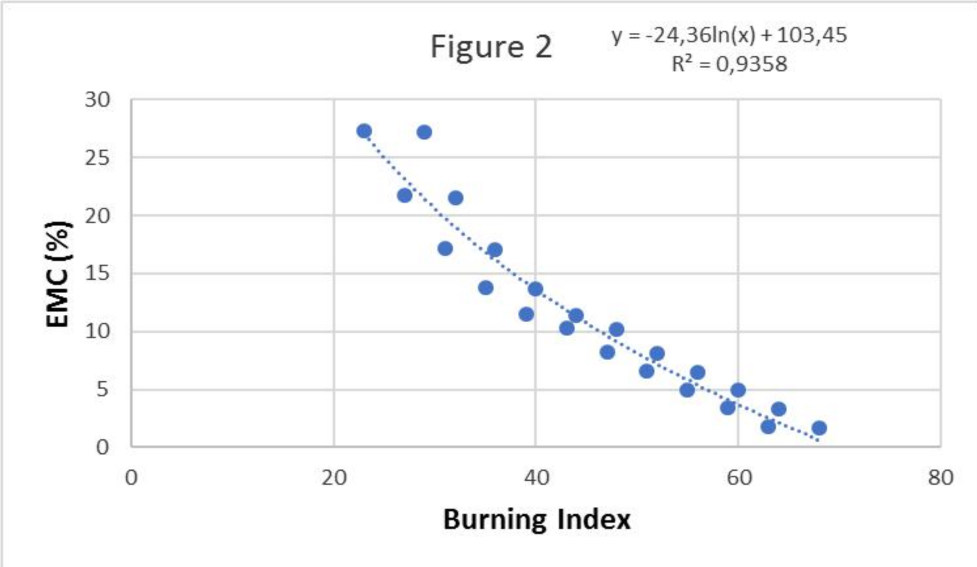

Figure 2 Relationship of the Dead Fuels Equivalent Moisture Content (EMC in %) With Burning Index Values for air Temperature Range 30-35°C.

Based on the above, it can be said that LFDI is structured on De Groot's (1987) scheme of Canadian Forest Fire Weather Index (FFWI), with LFDI corresponding to the Canadian Initial Spread Index (ISI), and BI*RCF to Canadian Fine Fuel Moisture Code (FFMC).

Regarding the correlation between LFDI and spread rate (ROS, in km/ h) of 48 cases of Greek forest fires, this was found to be (Figure 3a):

$$ROS = 0.049*LFDI - 1.60 \qquad (R^2=0.42 \text{ and } S = 0.77) \qquad (9)$$

For the same 48 cases of forest fires, but with independent variable the McArthur's Forest Fire Danger Index (FFDI), F index and Fosberg FWI (FFWI) respectively (Fig. 3b-3d), the relationship becomes:

$$ROS = 0.90*ln(FFDI) – 0.91 \qquad (R^2 = 0.33 \text{ and } S = 0.82) \qquad (10)$$

$$ROS=0.52*ln(F\ index)+1.57 \qquad (R^2 = 0.45 \text{ and } S = 0.75) \qquad (11)$$

$$ROS = 0.64*ln(FFWI) – 0.07 \qquad (R^2 = 0.47 \text{ and } S = 0.74) \qquad (12)$$

It should be noted that the duration of observation of all cases of fire velocity measurements above exceeded 1 hour, thus their velocities have to be considered as average Rates of Spread, in contrary to cases of fires with duration of observation less than 15 min, that may reach velocities of 12 km/h (Athanasiou, 2008). Working in the same way with the 26 cases of short duration (up to 15 min) observations of Athanasiou (2008), Equations (9)-(12) become:

$$ROS = 0.23 * LFDI - 11.8 \qquad (R^2 = 0.29 \text{ and } S =3.00) \qquad (13)$$

$$ROS = 4,03*ln(FFDI) - 9.05 \qquad (R^2 = 0.29 \text{ and } S =3.00) \qquad (14)$$

$$ROS=2,48*ln(F\ index) + 1,96 \qquad (R^2 = 0.30 \text{ and } S =2.97) \qquad (15)$$

$$ROS = 2,76*ln(FFWI) - 5,97 \qquad (R^2 = 0.25 \text{ and } S =3.08) \qquad (16)$$

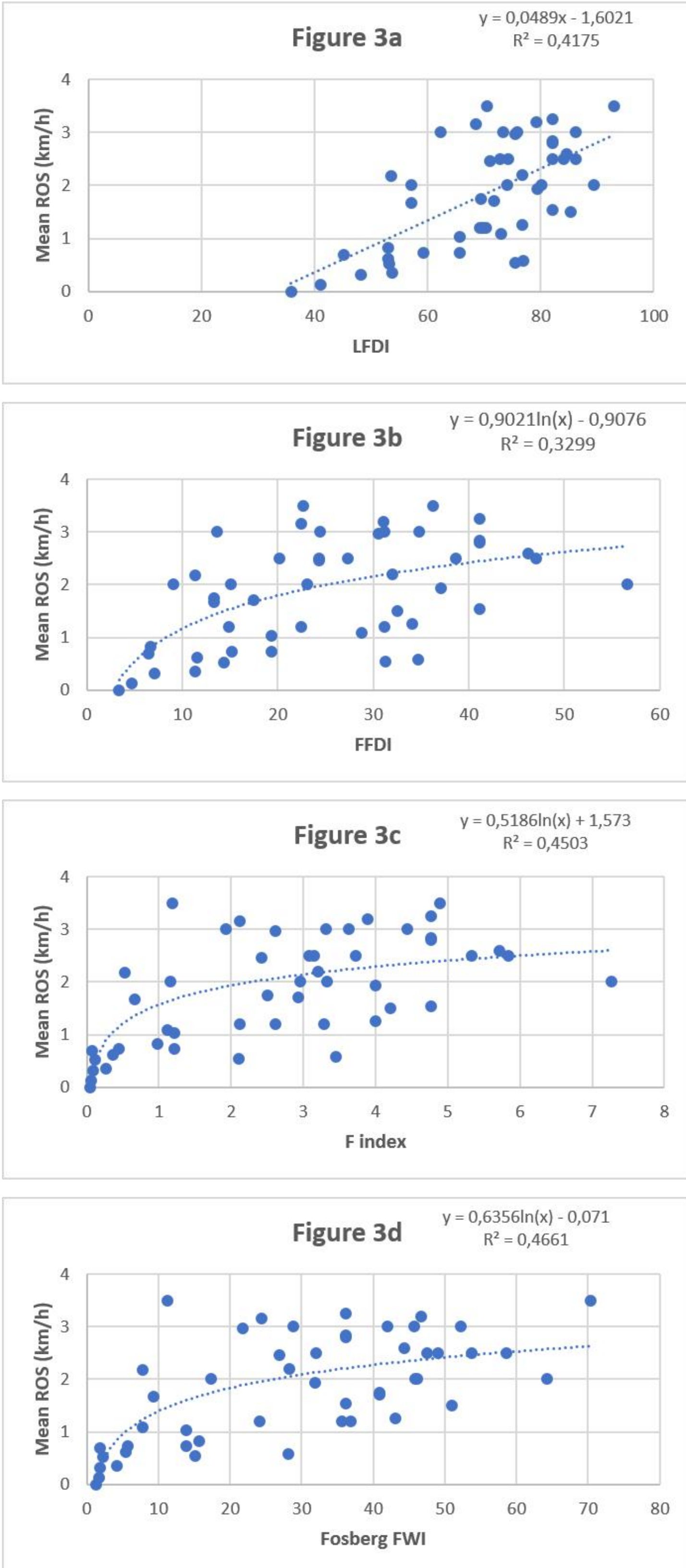

Figure 3 Relationship of the Mean Forest Fire Rate of Spread (ROS) with (a) LFDI, (b) McArthur's FFDI, (c) F index and (d) Forsberg's FWI.

A reduction of R^2 to levels of 0.25-0.30, as well as increase of the regression coefficients of the independent variables of all equations can be observed. It means that LFDI could be considered the same effective in combining meteorological information to interpret fire behavior, like the other three Fire Weather Indices examined, that have been successfully used for decades and been created on the basis of much more fire ROS data of other countries (Goodrick, 2002; Sharples et al., 2009). Despite that, the linear relationship between LFDI and ROS, in contrast to the logarithmic one between ROS and the other indices, makes LFDI more user-friendly. The explained variance of ROS (29%-42%) by equations (9) and (13) should not be considered negligible, given that composition and structure of vegetation (fuel models), as well as topography variables, factors that significantly influence ROS (Liu et al., 2015), are not taken into account.

It is also important to note that the leaflet for LFDI calculations (Department of Water Affairs and Forestry 2021), as well as related articles (Willis et al., 2001; Madula, 2013) give indicative values of fire ROS for each of its 5 fire danger classes in South Africa as following:

< 0.3 km/h for low fire danger (20 < LFDI < 45)

0.3-1.5 km/h for moderate fire danger (45 < LFDI < 60)

1.5-2.0 km/h for high fire danger (60 < LFDI < 75)

> 2.0 km/h for extreme fire danger (LFDI > 75)

Thus, if ROS values of 0 km/h, 0.3 km/h, 1.5 km/h and 2 km/h correspond to LFDI values of 20, 45, 60 and 75, the following equation is formed:

$$ROS = 0.0385*LFDI - 0.97 \quad (17)$$

These estimated ROS values are only slightly different from those derived from Greek fire data Equation (9) presented above.

Since the LFDI is related to the fire rate of spread, it is sure to be related to the area burned. Fig. 4 indicates the scatter plot of the 390 fires from all over Greece, which were burned at least 10 ha of natural vegetation (forests, shrublands and grasslands), in relation to the highest daily values of LFDI during the 3 years period 2014-2016. The vertical axis is necessarily logarithmic.

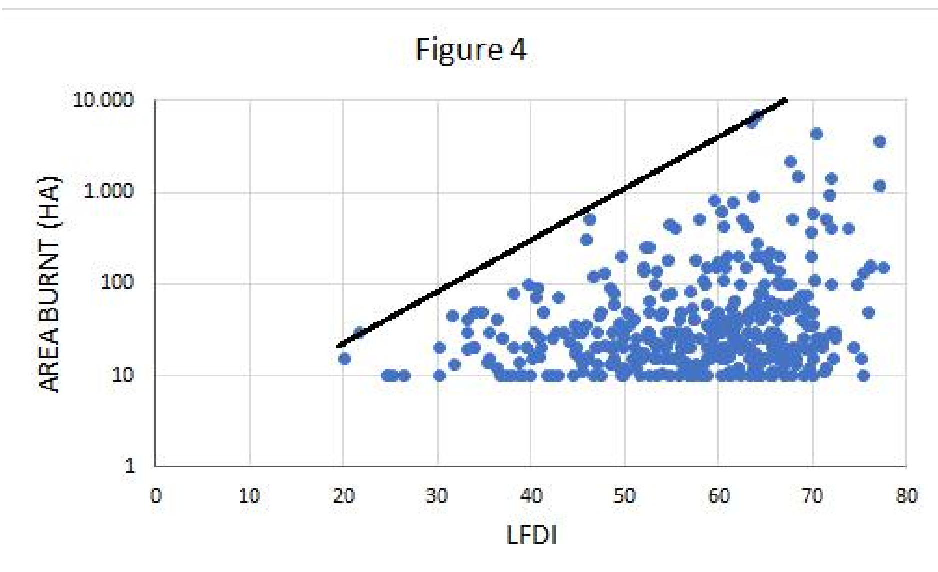

Figure 4 Relationship Between the Highest Daily LFDI Values And The Size of 390 Forest Fires (> 10 Ha) in Greece During 3 Years (2014-2016).

311 out of the 390 fires occurred during the fire seasons of the years 2014, 2015 and 2016 and their mean burned area per fire is given by squares for each of the 5 classes of LFDI, Greek GSCP fire risk index and Canadian FWI at Figures 5, 6 and 7 respectively. The bars on each side of these squares show the maximum and minimum burned areas of each class. Figure 5 shows that on days of low danger rating according to LFDI (class 2, with maximum daily LFDI values between 20 and 45) wildfires burn an average area of 22 Ha (reaching a maximum of 50 Ha), while on days of extreme danger rating (class 5 with maximum daily LFDI values > 75) the average burning area per fire is 441 Ha (reaching sometimes 2500 Ha). In contrast, there were no fires with burned area exceeding 10 Ha on days of insignificant danger rating (class 1, with LFDI < 20) during 2014-2016 (Figure 4 and Figure 5).

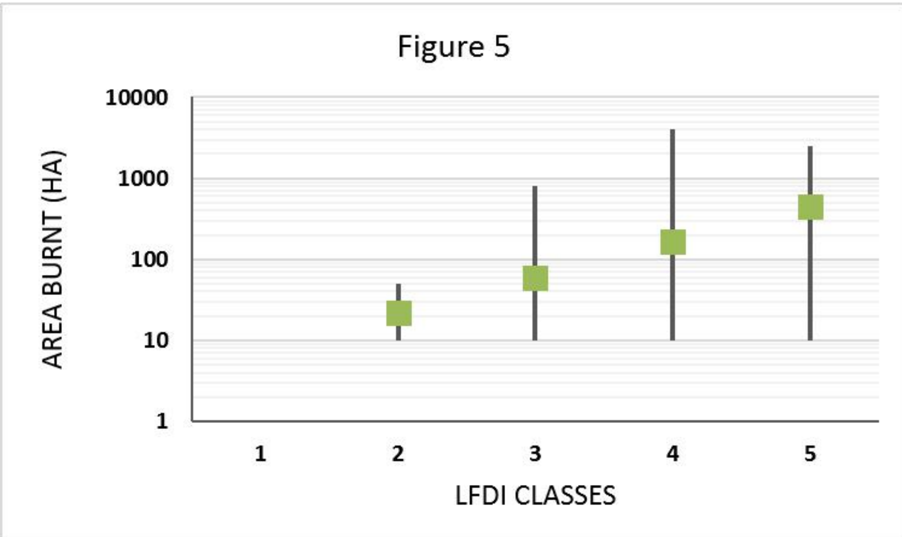

Figure 5 Relationship Between the LFDI's Fire Danger Classes and the Mean Size Of 311 Forest Fires (>10 Ha) in Greece During The Fire Seasons (May-October) of 3 Years (2014-2016).

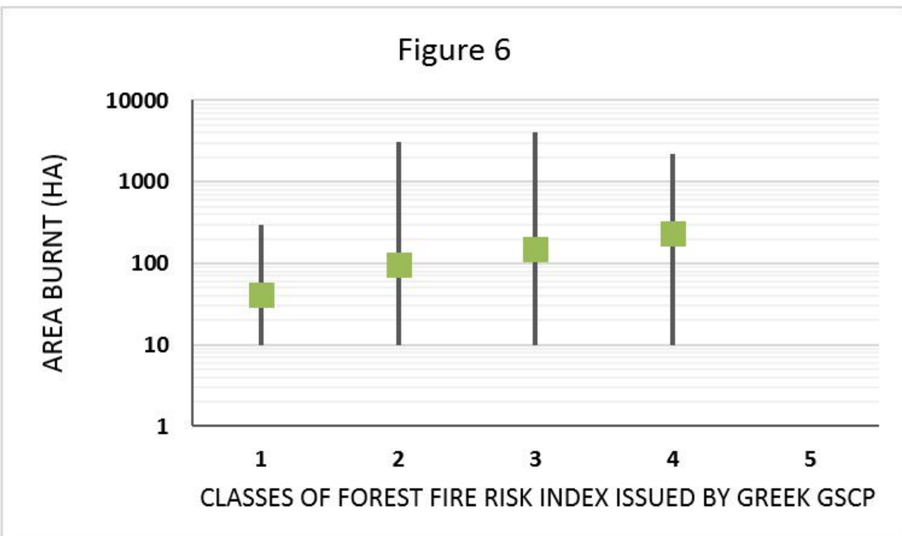

Figure 6 Relationship Between the General Secretariat for Civil Protection (GSCP) 's Fire Danger Classes and the Mean Size of 311 Forest Fires (>10 Ha) in Greece During the Fire Seasons (May-October) of 3 Years (2014-2016).

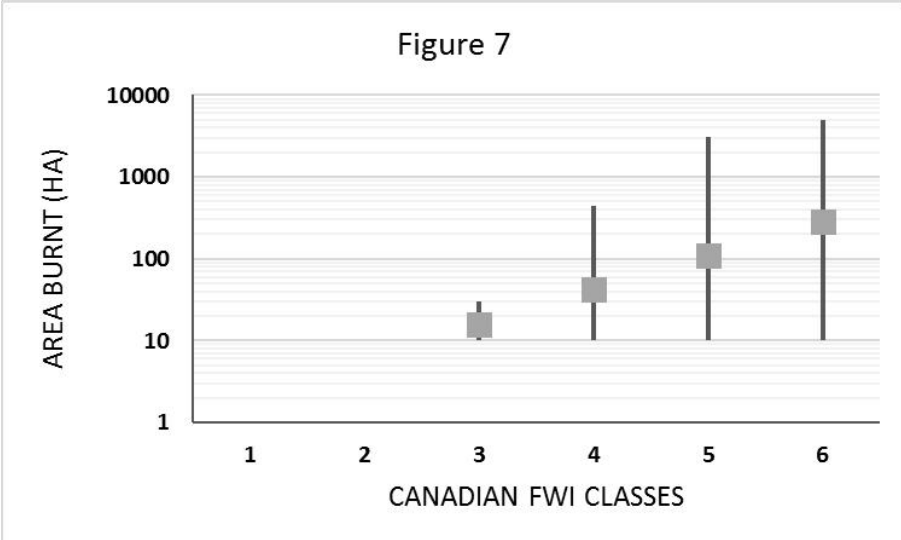

Figure 7 Relationship Between the Canadian FWI's Fire Danger Classes and the Mean Size of 311 Forest Fires (>10 Ha) in Greece During the Fire Seasons (May-October) of 3 Years (2014-2016).

In the corresponding diagram of the same 311 fires in relation to the Greek GSCP fire risk classes (Figure 6), there is also an increasing, but less pronounced, trend of mean area burned per fire, increasing fire risk level. Comparison between Fig. 5 and Fig.6 reveals that it is safer to allow controlled burns on days of 1 and 2 fire danger classes of LFDI than on days of the 1st fire danger class of the Greek GSCP fire risk index.

The corresponding diagram of the Canadian FWI (Figure 7) seems more similar to that one of LFDI (Fig. 5) and more useful for practice purposes than that of Figure 6.

Returning to the scatter plot of Figure 4, we observe that there is no statistical relationship between burnt area of the 390 fires and LFDI, due to heavy concentration of points mainly in the area defined by the values 10 and 100 of the vertical axis. Whatever the mathematical function used by the Least Squares-Method, the coefficient of determination (R^2) does not exceed 7%. Due to multi-year experience gained from monitoring the evolution of the Greek forest fires at the Operational Center, the reduction of potentially burned area in most cases should be attributed mainly to:

1) Rapid dispatch of many ground and aerial forest fire-fighting means.
2) Usually more favorable conditions for fire-fighting at night (lower LFDI values).
3) Discontinuities of forest fuels due to the existence of rural areas, settlements, rocky areas, seashores etc. along the fire front.
4) Reduced flammability of live fuels early, late and out of fire season, which will be discussed below.

According to Xathopoulos et al. (2014) similar reasons also explain the poor results of the efforts spent looking for a mathematically expressed relation between Canadian FWI and burned area:

1) The varying capability of firefighting resources, temporally and spatially, which is a significant factor affecting the evolution of each fire.
2) The existence of fuel in the path of a fire which is also another important factor that acts randomly on every fire depending on where it starts and on the direction of its spread.

Thus, in such a diagram, only the fires with the largest burnt areas for any given LFDI value are of interest, namely, fires that could not be controlled in time and they expanded uncontrollably as long as weather, vegetation and topography conditions were favorable. These fires form the thick straight line in the semi-log diagram of Fig. 4, which is actually given by the exponential form equation:

$$\textit{Burnt area (Ha)} = 2.7573*\exp(0.1106*LFDI) \quad (18)$$

Therefore, using this Equation (18) we obtain that on days with maximum LFDI value of 20, 45, 60 and 75, uncontrolled forest fires of 25, 400, 2101 and 11040 Ha respectively could be expected, provided that:

1) Herbaceous plants are fully cured, according to Austin (2008), in order to behave as dead fuels, with their moisture content depending on atmospheric humidity and temperature only (Johnson & Miyanishi, 2001). When this doesn't happen, that is during early, late and outside fire season, when herbaceous plants are partially or completely green, their high moisture content slows down fire propagation (Allan et al., 2003) resulting in reduced ROS and area burnt for given LFDI values. In this case for South Africa, it is proposed by Trollope et al. (2007) to adjust LFDI multiplying its calculated values by the so-called "Grass Curing Factor", a fraction that takes values between 1 (when herbaceous plants are completely dry) and 0 (when they are completely green). For our country, Greece, the Grass Curing Factor can become zero for a few days (mainly every April and May, depending on the region) and only locally, because Greece has not the extended grassland areas of South Africa and Greek grasslands usually constitute of a mosaic of herbaceous and woody plants of various ground cover. Even on the driest mountains of Greece, woody plants (belonging to Phanerophytes and Chamaephytes) not only do predominate in coverage but also have an important role as species number (Gouvas & Theodoropoulos, 2007). Some of these species, mainly dwarf shrubs named "Phrygana" (*Genista acanthoclada*, *Sarcopoterium spinosum* and many others) become flammable even in winter during no-rain periods over 10-20 days (Gouvas et al. 2008). Thus, on days with LFDI > 45 in areas or seasons with green herbaceous plants, actual LFDI values should be considered lower than calculated but never zero, however, further research is needed. On the other hand, Grass Curing Factor cannot replace the Rain Correction Factor, as suggested by Trollope et al. (2007) for South Africa, for two reasons: a) Because, unlike African savannah, even light summer rainfall in Greece (< 5 mm) appears to alter water potential, hence the flammability of woody plants (Xanthopoulos et al., 2006), which usually constitutes the dominant form of live forest fuel in Greek ecosystems. b) Because heavy and prolonged rains are well moisturizing the flammable forest dead fuels (needle, leaf and woody debris in the dense forests and shrubs), making it resistant to the ignition and propagation of fires, as Kailidis (1990) proved and showed through diagrams illustrating the relationship between rain and moisture content of pine needles. This is also concluded by investigation of the relationship between the Rain Correction Factor (RCF) of LFDI and the Drought Factor (DF) of the Australian McArthur Forest Fire Danger Index (equations given by Willis et al. 2001), which reveals a high correlation between them during drought season. This relationship is given by the equation:

$$RCF=0.09*DF+0.1 \quad (19)$$

With $R^2 = 0.95$, for KBDI > 50 mm

2) Woody plants (trees and shrubs) are very flammable due to high deficiency of moisture content. Since Keetch-Byram Drought Index (KBDI) reflects to some extent water deficit in living plants and hence their flammability (Xanthopoulos et al., 2006), there is in progress an attempt to find a drought factor suitable for LFDI as a function of KBDI index (like Goodrick's (2002) Fuel Availability Factor), with encouraging results. KBDI usage has another advantage: our unpublished investigations about plant phenology in Athens district lowlands show that annuals, perennials and dwarf shrubs (phrygana) are usually fully cured when KBDI exceeds 100 mm during late spring or early summer. The ability of using Normalized Difference Vegetation Index (NDVI) from satellites instead of KBDI for this purpose is also being examined, due to its relationship with the moisture content

of live fuels (Chuvieco et al., 2004), as well as with Grass Curing Factor (Allan et al., 2003; Chaivaranont et al., 2018).

It must be noted that, based to our multi-year experience, preconditions about live fuels mentioned above should be taken into account by application of any other Fire Weather Index (McArthur, Fosberg, Canadian etc.) early, late or outside fire season in Greece. So, every Fire Weather Index (FWI) should be corrected in the form:

$$Corrected\ FWI = a + b*(FWI-a) \tag{20}$$

Where:

a = threshold of FWI corresponding to ROS = 0 km/h (a = 20 for LFDI) and

b = live fuel correction factor as a function of KBDI and NDVI or as monthly empirical values after statistical analysis (ranging from 0 to 1.2).

All efforts now have been focused on determining this correction factor "b". Without such a correction, all Fire Weather Indices and especially the simplest ones show rather small fluctuations during each year like that one of LFDI in Krysna region (South Africa) before the destructive wildfire of June 2017 (Forsythe et al., 2019).

Finally, the relationship between LFDI and the Canadian Fire Weather Index (Canadian FWI) values for the 390 forest fires greater than 10 Ha in Greece during the 3 years 2014-2016 is shown by the scatter plot and the equation of Figure 8. Figure 8 seems enough to show that 73% of Canadian FWI's variance is explained by LFDI. This R^2 is very high given the ease of calculating LFDI and its corresponding complexity (many pages of FORTRAN program in the work of Wang et al. (2015) of Canadian FWI) and it also explains the similarity of the diagrams of Figure 5 and Figure 7.

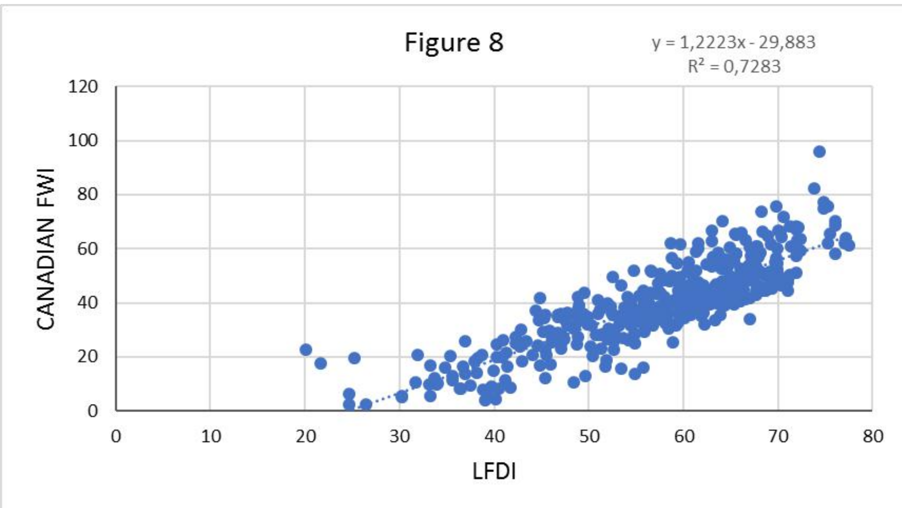

Figure 8 Relationship Between the Canadian Fire Weather Index (Canadian FWI) and the LFDI Values for 390 Forest Fires (> 10 Ha) in Greece During 3 Years (2014-2016).

4. Conclusion

The above analysis complements the arguments developed a decade ago about the suitability of the South African Lowveld Fire Danger Index (LFDI) for Greek conditions. It is shown that LFDI constitutes a simple, but neither arbitrary (in development) nor less effective index, compared to other well-known Fire Weather Indices used in other countries. So, it turns out that LFDI (Lowveld Fire Danger Index):

1) It is based on the Swedish Angstrom Index, so, for no wind condition, its values indicate the likelihood of a fire to ignite.

2) It is related to the Rate of Spread (ROS) of forest fires in Greek ecosystems about the same as other known Fire Weather Indices.

3) Its maximum daily values serve as a measure of the possible maximum burnt area, while its 5 fire danger classes as a measure of the average burnt area per fire.

The above mentioned, combined with the ease of calculating LFDI through charts and tables of a single leaflet even at the scene of the event, as well as its predictability for the next few hours or days, make it a useful tool for decision making. Estimating, for example, fire-fighting conditions at night, which can vary from very favorable (self-extinguished fire) to very difficult, through an easy to use fire weather index is of great importance for management of ground or aerial means and staff.

4) It is an almost ready tool for operational use in our country during the fire season and its mathematical structure allows modifications (by adding new factors) in order to adjust (decrease) its values for use outside fire season. This must be done, because small burnt areas are observed outside fire season corresponding to LFDI (or any other FWI) values lower than calculated. Certainly, original LFDI values should be multiplied by the Grass Curing Factor, a fraction which in our country could never be equal to zero, combined to another factor (an indicator of the flammability of woody plants) as a function of the KBDI or NDVI indices.

5) It can also be easily integrated into the various numerical weather models to give a detailed forecast of LFDI for 2 or more days in Greece.

6) A strong relationship between LFDI and Canadian FWI seems to exist.

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