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Research Article

A Simple Technique to Estimate the Flammability Index of Moroccan Forest Fuels

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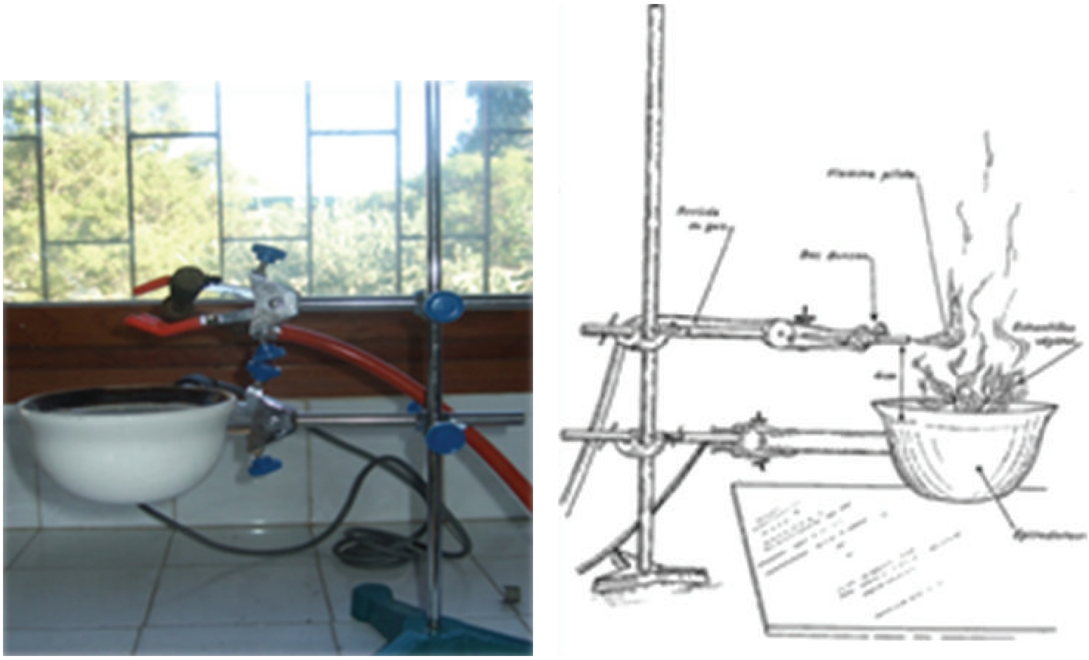
A formula to estimate forest fuel flammability index (FI) is proposed, integrating three species flammability parameters: time to ignition, time of combustion, and flame height. Thirty-one (31) Moroccan tree and shrub species were tested within a wide range of fuel moisture contents. Six species flammability classes were identified. An ANOVA of the FI-values was performed and analyzed using four different sample sizes of 12, 24, 36, and 50 flammability tests. Fuel humidity content is inversely correlated to the FI-value, and the linear model appears to be the most adequate equation that may predict the hypothetical threshold-point of humidity of extinction. Most of the Moroccan forest fuels studied are classified as moderately flammable to flammable species based on their average humidity content, calculated for the summer period from July to September.

1. Introduction

Wildland fire intensity is highly related to forest vegetation type and structure, importance of fine and coarse fuel types, biomass of live and dead surface fuels, fuel moisture content, land topography, weather factors, and to forest stand growth conditions. Therefore there has been need to study these parameters to develop helpful tools for forest-management decision makers [1–9] based on fuel hazard and fire risk assessment. Most of previous investigations have focused on determining the forest fuel species fire behavior based on their flammability values estimated through thermal and chemical calorimetric studies [10–17], thermo-gravimetric or limiting oxygen index analysis [18–21], or through simple laboratory flammability tests performed using an electric radiator equipped with an external pilot flame [22–24] as shown in Figure 1.

No standard norm exists for testing forest species flammability, because the flammability parameter can be seen as a plant property that has no unit, involving three components [25]: ignitability (time to ignition), the most important factor to consider, combustibility (rate of burn after ignition), and sustainability (total burning time). Liodakis et al. [26] have also related the sustainability term to the rate of fire spread. Anderson's study [25] was extended by Martin et al. [27] to include a 4th component named "consumability", corresponding to the amount of vegetation that is consumed [28].

Regarding the simple laboratory flammability test method, we have to run a group of 50 flammability tests [22]. Positive tests are noted in order to estimate the ignition frequency (IF) parameter as a percentage. Negative tests are those for which there was no ignition at all. Also, time to ignition (TI), total burning time or time of complete combustion (TC), and flame height (FH) are the parameters recorded for each species flammability test [22]. The most important parameter in ranking forest species is TI [12, 22, 23]. However, Valette [22] has combined the mean time to ignition (MTI) classes with those of the IF parameter under a cross-link table that helps to determine flammability index values (Table 1). This classification method gives only qualitative values of the species-flammability index (FI) leading to a 6-grade ranking scale system as shown in Table 1. This concept, based on a discrete notation system, has been conceived



(a) (b)

Figure 1: Electric radiator apparatus used for fuel species flammability testing: (a) the real apparatus used in this study and (b) its illustrating schematic components.

because the flammability aspect determination is not easy and can be appreciated only in a general sense, and not in a very precise scientific way [22]. Nevertheless, dimensions of flames are other measures of flammability considered for species characterization purpose [29, 30]. Beside pyrolysis gas, the FH parameter could be an indicator of the volatilized essential oils contained mainly in vegetal leaves. The role of extractives in the propagation of forest fire was investigated by Shafizadeh et al. [31] who found that ether extractives contribute greatly to the heat release from the foliage fuels. Also, it is of great interest to study this FH parameter in relation to fire propagation in a vegetation vertical continuity direction. Another neglected parameter is the sustainability component (TC), which characterizes the ability of fuel to sustain combustion for a long time. This total burning time is related to the fuel bulk density and, subsequently, to the energy intensity that ensures, to a certain extent, carrying fire to next fuel [32]. The TC and FH parameters were not included in the classification method proposed by Valette [22].

The objectives of this study are (i) to improve Valette's classification method by including more parameters and conceiving a continuous quantitative notation scale system and (ii) to assess the fire hazard properties of Moroccan forest species by ranking them according to their flammability index values determined based on their average moisture contents observed during the critical summer period, from July to September.

2. Materials and Methods

2.1. Forest Study Sites and Vegetation Material. Laboratory flammability tests were performed on fuels of a large variety of forest species collected from three different Moroccan forest regions named, in increasing order of fire occurrence [33]: Mamora lowland forest located on the Atlantic coast near Rabat city, Middle Atlas forests in the central part of Morocco, and Rif mountain forests located in the North part of the country along the western Mediterranean coast. A total of 31 tree and shrub species were tested within a wide range of fuel moisture content (fresh, air-dried, and oven-dried samples). Among these species, a group of only 17 tree and shrub species was used for a preliminary study of different flammability parameters determined using the Valette's method [22]. These species are *Acacia mollissima*, *Arbutus unedo*, *Cistus crispus*, *Cistus ladaniferus*, *Cistus monspeliensis*, *Cistus salviifolius*, *Cupressus sempervirens*, *Erica arborea*, *Eucalyptus camaldulensis*, *Lavandula stoechas*, *Myrtus communis*, *Olea europea*, *Pinus pinaster* var. *maritima*, *Pistacia lentiscus*, *Quercus suber*, *Teline linifolia*, and *Thymelaea lythroides*. The results obtained from this preliminary study were extended and applied to the second remaining species group composed of *Buxus balearica*, *Cedrus atlantica*, *Cistus albidus*, *Halimium halimifolium*, *Juniperus thurifera*, *Phyllerea angustifolia*, *Pinus brutia*, *Pinus canariensis*, *Pinus coulteri*, *Pinus halepensis*, *Quercus faginea*, *Stipa tenacissima*, *Tetraclinis articulata*, and *Viburnum tinus*.

For each species, a sample of terminal twigs with their leaves or needles, cut in a sufficient quantity from 3-4 different individual mature plants, was collected and immediately put in large sealed plastic bags. Once in laboratory, and in order to estimate the ignitability of the live fresh fuel, a quantity of about 160 g is immediately taken and separated into two sets. The first set composed of 150 samples, of 1 g each, was used to realize three flammability test replicates

Table 1: Flammability index (FI*) as a function of the ignition frequency (IF) and mean time to ignition (MTI) variables [22].

	IF (%)					
MTI (s)	<50	50–79	80–84	85–89	90–94	>95
> 32.5	0	0	0	1	1	2
27.5< – ≤32.5	0	0	1	1	2	2
22.5< – ≤27.5	0	0	1	2	2	3
17.5< – ≤22.5	0	1	2	2	3	3
12.5< – ≤17.5	1	1	2	3	3	4
≤12.5	1	2	2	3	4	5

* Valette's classification [22]: very little flammable (FI = 0), little flammable (FI = 1), moderately flammable (FI = 2), flammable (FI = 3), highly flammable (FI = 4), and extremely flammable (FI = 5).

(50 tests/replicate [22]). The second set of three samples, of 2 g each, was used for moisture content determination purpose. The remained samples were then left inside the laboratory for air-drying operation, constituting further a raw material for testing the species flammability at different moisture content levels. To get moisture content levels between 0% and 30% (case of dead fuels such as leaves or needles litter), a quantity of vegetation is taken from the air-dried samples and put in the oven at 102,5°C for different drying times according to the target values of the expected moisture content levels. For each moisture content level, the same quantity of about 160 g is used as described above. So, if it is intended to test species fuel flammability at 10 different moisture content levels, one must collect from the field at least 1600 g of vegetation material. The moisture content was expressed as the percentage of the oven-dry weight (%O.D.W.) and its average is calculated on the basis of three replicates.

The data obtained from flammability tests were statistically analyzed. Linear and nonlinear regression models were tested in a first step on the overall obtained data related to all species together, to examine the relationships between explicative variables (moisture content H, and desiccation index Id), separately considered on one hand, and dependant variables (FI- and TI-values) on the other hand. In a second step, the same regression models were tested for each one of the studied species in order to select the best regression equation that could help to classify it, given its observed average moisture content during the critical summer period, and also to estimate its hypothetical moisture of extinction (ME). Excel package of Microsoft Office was used to carry out all the data analysis.

2.2. Flammability Testing Method. The laboratory flammability test was performed using an electric radiator, an ignition apparatus with an electric heating resistance (500 watt of heat capacity) beneath a ceramic plate, of 10 cm diameter, situated at 4 cm below a pilot flame (Figure 1). A graduate rule, calibrated to the ceramic plate level, is vertically maintained beyond the apparatus in order to measure the maximum flame height. Flammability test method described by Moro [24] was used as follows: once the electric radiator is well heated, we put one gram species sample on the heated ceramic surface (Figure 1(b)) and we simultaneously start a chronometer to measure the following parameters: time to ignition (TI) in second, time of complete combustion (TC) in second. The maximum flame height (FH) in cm is read through the vertical graduated rule. For each replicate, 50 flammability tests were performed and served to calculate the means of time to ignition (MTI), time of complete combustion (MTC), and flame height (MFH). The total number of positive ignition tests was used to calculate the ignition frequency (IF) in percentage [22, 24].

3. Results and Discussion

3.1. Investigation Basic Concept. Based on the flammability index classification proposed by Valette [22], who used only MTI and IF parameters (Table 1), it was found that almost all the tested species are extremely flammable (FI = 5) at humidity contents below 100%, except for *Quercus suber* L. Also, some species, such as *Acacia mollissima* L. and *Teline linifolia* L., belonged to the class FI = 5, even at moisture content greater than 140%. The only species that are more affected by moisture content are *Cistus salviifolius* L., *Thymelaea lythroides* L., and *Pinus pinaster* var. *maritima*. This showed that Valette's classification method [22] presents some disadvantages such as (i) the method is based on two parameters only, MTI and IF for which the interval classes are not well equilibrated; (ii) the range time scale interval (12.5 s–32.5 s) considered for the MTI parameter is narrow and would work only for live forest fuels. If we want to extend the classification to include dry fuels such as dead fine twigs and leaves or needles litter, this interval should be enlarged because the most of the observed MTI-values were less than 12.5 s. This is probably due to the presence of high content of extractives and volatilized aromatic essential oils in the north-African foliage fuels. Also, (iii) the FI-value is not a continuous variable that permits to discriminate between species having the same FI-values as it was observed for *Acacia mollissima* L. and *Teline linifolia* L. This lack in species discrimination consistency led us to try and investigate another approach to express the flammability index formula that would improve Valette's classification method. However, before starting to build this formula, let us assess the relationship existing between all the flammability parameters. A Pearson linear correlation coefficient analysis was performed on the data provided by the preliminary study trial done on the first set of 17 Moroccan species fuels. The results of this statistical analysis are shown in Table 2.

Obviously, the moisture content has a strong effect on MTI and MFH. Also, the MTI is the parameter mostly correlated to the IF parameter with $r = -0.89$. This means that there is no need to use both of them in building Table 1. MTI parameter would by itself constitute a classification scale basis. However, a decrease in its correlation is noted in case of MTC and MFH with $r = -0.58$ and $r = -0.71$, respectively. This is probably due to the existence of other vegetation parameters such as ash content, organic composition, and essential oils.

It appears, according to all the precedent developed points, that the species flammability index (FI) should be estimated through its three characteristic components: ignitability, expressed as time to ignition (TI, in s); sustainability, expressed as time of complete combustion (TC, in s); and combustion intensity that can be partially expressed through the maximum flame height (FH, in cm). The way to integrate these three components into a unique and simple formula is the use of the following empirical mathematical expression:

$$\mathrm{FI} = \left[\frac{\mathrm{TC}}{\mathrm{TI}}\right] * \mathrm{EXP}\left[\frac{\mathrm{FH}}{\mathrm{Hmax}}\right], \quad (1)$$

where Hmax (in cm) is the maximum value observed for FH parameter.

The basic conception pursued in choosing (1) is that the TC/TI ratio would really well-characterize species flammability tendency: the FI-value increases as the numerator (total burning time) increases and the denominator (time to ignition) decreases. The FH parameter was weighed to the maximum observed Hmax-value. The exponential term for the FH parameter was chosen to reduce its effect on the global FI-value since the FH parameter represents a postignition stage that corresponds to the maximum released gases that could vary among species in types and chemical compositions. This would help to discriminate between species that have same values for the major parameters TC and TI. According to the flammability testing method undertaken in this study, Hmax was found to be equal to 40 cm. To keep the same flammability index variation interval as the one developed by Valette [22], the TC/TI ratio was calibrated using the class averages of the two extreme MTI-variation interval classes of Table 1 (10 s and 35 s) as shown in (2). Also, to ovoid aberrant values in case of probable high values of FH greater than 40 cm, the FH/40 ratio has been transformed into FH/(FH + 40), term for which its value would vary between zero and not more than 2/3. This latter expression was raised to exponent 2 in order to diminish more again the effect of FH parameter which is considered of a secondary variable order. The obtained empirical equation (2) is as follows:

$$\mathrm{FI} = \left[\frac{\mathrm{TC} + 35}{\mathrm{TI} + 10}\right]\mathrm{EXP}\left[\frac{\mathrm{FH}}{\mathrm{FH} + 40}\right]^2. \quad (2)$$

Equation (2) would give FI-values that vary on a continuous variation interval between 0 and 6. Fuel samples that do not ignite are identified as negative tests and characterized by TC = 0 s, TI = 60 s [24], and FH = 0 cm; therefore, their corresponding value is FI = 0.5. However, to let the FI take the null value for these negative tests, a transformation of (2) was operated by integrating the value of 0.5 to obtain the final empirical flammability index (FI) formula which is

$$\mathrm{FI} = \left[\frac{\mathrm{TC} + 30 - \mathrm{TI}/2}{\mathrm{TI} + 10}\right]\mathrm{EXP}\left[\frac{\mathrm{FH}}{\mathrm{FH} + 40}\right]^2. \quad (3)$$

All the values presented here for the species flammability are computed using (3).

3.2. Sampling Size Determination of the Flammability Test. The proposed equation (3) permits to calculate the FI-value for each performed flammability test, since it does not integrate the ignition frequency IF. Given that, one can wonder if the commonly used 50 flammability tests [22] are still necessary to be conducted. To answer this question, four different sampling sizes, conceived from the 50 already performed ones, were tested as follows: 12, 24, and 36 first flammability tests only; and the fourth size of the 50 flammability tests together. The FI-values were calculated for each of these four sampling sizes and an analysis of variance was done to compare these different FI-calculating methods (Table 3). The results of this analysis, applied to all the 31 Moroccan forest species, showed that the overall F-test is not significant at $\alpha = 0.05$. This means that the four FI-calculating methods are all suitable since they give almost the same mean FI-values varying between a minimum of FI = 3.25 for a sampling size of 12 samples and a maximum of FI = 3.32 for the 50 flammability test sample. As a practical conclusion, we suggest for each replicate to perform only 12 laboratory flammability tests instead of 50 tests. This would encourage researchers to multiply the number of sampled forest sites and cover more species origins, or to simply enlarge the study scope, investigating other potentially explicative factors of interest.

3.3. Values of the Flammability Parameters. The mean values of the parameters MTI, MTC, and MFH, measured via the laboratory flammability tests are shown in Table 4. To understand the moisture effect on the remaining variables, and be able to estimate the natural experimental variability, the minimum and maximum values are also included in this table. The studied species are sorted in a decreasing order of the flame height values (Table 4). As it may be noted, *Phyllerea angustifolia*, *Eucalyptus camaldulensis*, and *Quercus suber* are the only species that have a MFH-value greater or equal to 22 cm and a MTI less or equal to 4 s. This means that these species are potentially very flammable. Therefore, the observation related to *Eucalyptus camaldulensis* species seems to be in agreement with the result found by Dimitrakopoulos and Papaioannou [23] who classified it as an extremely flammable species. Whereas, the lowest MFH-value of 7 cm was observed for *Cistus monspeliensis*, that shows also a high MTI of 16.7 s (Table 4). It appears that the two flammability parameters (MTI and MFH) are inversely proportional. The shortest mean time to ignition (MTI = 2.4 s) was observed for *Quercus suber*. In comparison with the results of Liodakis et al. [26], the shortest value among the six studied Mediterranean species was observed for *Pistacia lentiscus*.

TABLE 2: Pearson correlation-coefficient matrix of the means of time-to-ignition (MTI), time of combustion (MTC), and flame height (MFH), the ignition frequency (IF) and the moisture content (H) measured on 17 Moroccan tree and shrub species. This correlation analysis was done on 145 observations, and each observation is the mean of 50 flammability tests [22, 24].

Variable parameters	MTI [s]	MTC [s]	MFH [cm]	IF [%]	Moisture content H [%]
MTI [s]	1				
MTC [s]	−0,58***	1			
MFH [cm]	−0,71***	0,13 n.s.	1		
IF [%]	−0,89***	0,65***	0,51***	1	
Moisture content H [%]	0,85***	−0,34*	−0,81***	−0,61***	1

* Significant effect ($\alpha = 0,05$); ***very highly significant effect ($\alpha = 0,001$); n.s., no significant effect ($\alpha = 0,05$).

TABLE 3: Analysis of variance of the four sampling sizes applied to determine the flammability index (FI) through laboratory experimental tests performed on 31 tree and shrub species.

Source of variation	Sum of squares	Degree of freedom	Mean square	*F*-test	Probability	*F*-value
FI-calculating methods	0.6672	3	0.2224	0.1251 n.s.	0.9453	2.622
Residual error	938.8316	528	1.7781			
Totals	939.4988	531				

n.s.: no significant effect at $\alpha = 0.05$.

Also, *Pinus brutia* has a short mean time to ignition, with 6,8 s (Table 4), but it is classified by Liodakis et al. [26] as a species that presents the longest ignition delay time. The MTC-value varies between 7.8 s and 23 s for *Cistus salviifolius* and *Erica arborea*, respectively (Table 4). *Pinus halepensis*, which was classified by Liodakis et al. [26] as the most sustainable fuel, presents a moderate MTC-value of 14.3 s (Table 4).

The results in Table 4 should be analyzed with care regarding their corresponding moisture content variation interval which shows differences among species. In fact, the minimum and the maximum moisture content intervals are 4–36% and 5–244% observed for *Cedrus atlantica* and *Lavandula stoechas*, respectively. It appears from these preliminary observations and comparisons that species classification based on one flammability component only is not a viable method, because there is undoubtedly an effect interaction of these four parameters, including moisture content effect, on the species flammability magnitude. This conclusion confirms, to a certain extent, the idea behind the willing to establish a new method for classifying the fuel flammability of different forest species.

3.4. Moisture Effect on Time to Ignition. The moisture content has a high significant effect on all flammability-related parameters except for MTC. Its highest linear correlation coefficient ($r = 0.85$) is observed with the MTI variable. Figure 2 shows the tendency curves from the four tested models (MTI as a function of desiccation index Id) as fitted to the observed data. It is to remind that $\text{Id} = 2/(1 + \text{H}^2)$, with H as humidity content, given in absolute value [34]. The advantage to consider the Id parameter is its variation on a more restricted interval of $]0, 2]$. Among the tested regression equations displayed in Figure 2, the exponential model equation seems to be the best with a determination coefficient $R^2 = 0.73$. The data points shown in Figure 2 appear to be divided into two groups, separated by a threshold point at Id = 1: one group so called "dry" forest fuels, located at the right side (Id > 1 or H < 100%), that have their MTI-values almost less than 17.5 seconds (highly and extremely flammable classes). The other group so called "moist" forest fuels, positioned at the left side (Id ≤ 1 or H ≥ 100%) with MTI-values that are more scattered and covering the whole variation interval that is, between 5 s and 60 s, which covers all the flammability classes (Figure 2). This means that for the same Id-value of 0.62 (H = 150%), different species may have different MTI-values between 10 s (extremely flammable) and more than 32.5 (very little flammable). This result confirms the existence of other intraspecific factors, volatilized essential oils for instance that would interact with moisture content. This interaction is more obvious at high moisture content level.

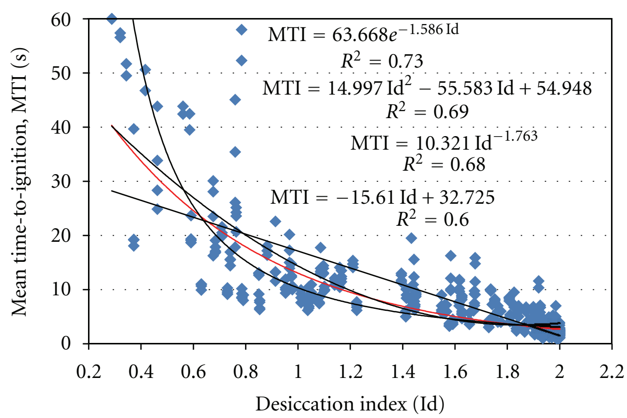


FIGURE 2: Mean time-to-ignition (MTI) values of Moroccan species as a function of their desiccation index Id.

The threshold point of Id = 1 (H = 100%) represents the middle center of the stabilized moisture interval between

Table 4: Mean values of the moisture content and the flammability test parameters observed for the forest fuel samples collected from different Moroccan forest species (species are sorted in a mean flame height decreasing order).

Species	Moisture content H [%]			Mean time to ignition [s]			Mean time of combustion [s]			Mean flame height [cm]		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
Phyllerea angustifolia	3	**39**	92	2	**4,0**	8	7	**9,7**	14	12	**23**	30
Eucalyptus camaldulensis	8	**39**	99	1	**3,8**	9	12	**12,9**	14	15	**22**	40
Quercus suber	12	**23**	51	1	**2,4**	4	11	**13,6**	18	16	**22**	27
Stipa tenacissima	4	**14**	29	2	**4,5**	7	13	**14,3**	15	14	**17**	19
Quercus faginea	21	**56**	116	2	**4,0**	7	10	**11,4**	14	16	**17**	22
Pinus brutia	4	**39**	85	3	**6,8**	12	11	**12,7**	15	10	**17**	24
Cistus albidus	6	**50**	124	2	**4,7**	9	12	**13,8**	17	4	**15**	21
Acacia mollissima	13	**54**	147	3	**5,7**	11	12	**14,5**	18	3	**15**	21
Pinus canariensis	5	**51**	87	3	**8,0**	12	12	**13,1**	14	9	**15**	26
Juniperus thurifera	1	**30**	62	2	**4,9**	7	14	**14,3**	15	11	**15**	19
Viburnum tinus	2	**70**	124	2	**6,7**	9	9	**11,1**	14	9	**14**	24
Myrtus communis	3	**38**	95	2	**5,6**	9	7	**8,2**	10	8	**14**	28
Pinus coulteri	2	**44**	91	2	**7,2**	14	12	**14,1**	18	9	**14**	24
Arbutus unedo	1	**66**	132	2	**6,3**	10	7	**12,3**	15	7	**14**	26
Olea europea	7	**68**	130	3	**9,3**	16	10	**10,8**	11	6	**13**	25
Thymelaea lythroides	4	**43**	155	1	**8,8**	60	0	**16,1**	26	0	**13**	17
Cedrus atlantica	4	**20**	36	2	**3,0**	5	20	**20,4**	21	7	**13**	18
Pistacia lentiscus	2	**37**	109	2	**6,1**	15	12	**13,0**	15	2	**13**	20
Buxus balearica	3	**35**	65	2	**4,7**	7	11	**15,9**	19	7	**13**	19
Pinus halepensis	3	**49**	95	3	**8,2**	14	12	**14,3**	16	7	**12**	18
Cupressus sempervirens	3	**58**	102	2	**6,9**	10	12	**15,6**	23	7	**12**	15
Pinus pinaster	11	**92**	154	3	**13,4**	20	13	**17,2**	19	4	**11**	23
Cistus ladaniferus	3	**68**	135	4	**12,2**	21	11	**15,0**	17	4	**11**	18
Teline linifolia	22	**96**	220	2	**12,8**	60	0	**16,5**	22	0	**10**	18
Cistus salviifolius	2	**55**	229	2	**15,9**	60	0	**7,8**	12	0	**10**	15
Tetraclinis articulata	1	**41**	128	1	**10,1**	32	6	**13,4**	23	1	**10**	17
Lavandula stoechas	5	**81**	244	2	**19,1**	60	0	**9,3**	15	0	**9**	17
Erica arborea	23	**37**	62	1	**9,6**	29	6	**23,0**	26	1	**9**	19
Halimium halimifolium	4	**48**	125	2	**12,7**	60	0	**12,3**	16	0	**9**	16
Cistus crispus	1	**60**	140	2	**12,2**	25	6	**12,5**	23	1	**8**	17
Cistus monspeliensis	16	**90**	195	3	**16,7**	60	0	**11,1**	16	0	**7**	14

120% and 80% H (0.82 < Id < 1.22) defined by Valette [22] for natural vegetation after August month period. It may be concluded that a forest vegetation with H < 100% will undoubtedly constitute a very high fire risk. The so-called "dry" forest fuels can be encountered, during summer period, in natural arid degraded-forest sites of the Rif Mountains. This situation becomes more risky in hot days with hot wind (Chergui) blowing from the east, (equivalent of the Sirocco wind). Under such conditions, wildland fires are frequently triggered, and the local forest staff should be kept on alert during this period of drought.

3.5. Flammability Index Classes. The FI parameter was found to be inversely correlated ($r = -0.88$) to the species moisture content H. This tight relationship confirms the previous results which show that the fuel moisture content is an important fuel characteristic affecting fire behavior [5, 35]. To examine the tendency curves between the FI-values of all the species together as a function of the Id-values, different regression models were tested. This analysis showed that the best fitting regression model is the third degree polynomial equation, followed by the second degree polynomial, and the simple linear regression equations (Figure 3). Concerning the third degree polynomial equation, its null second derivative at its inflection point level was found to correspond to the FI-value of 2.0, which represents the middle class of the mostly flat curve central part from FI = 1.5 to FI = 2.5 (Figure 3). This class matches with the flammability index class defined by Valette as "Moderately flammable". Therefore, we suggest to keep the same species classification proposed by Valette [22], but in a continuous scale basis as follows: least flammable (FI < 0.5), less flammable (0.5 ≤ FI < 1.5), moderately flammable (1.5 ≤ FI < 2.5), flammable (2.5 ≤ FI < 3.5), highly flammable

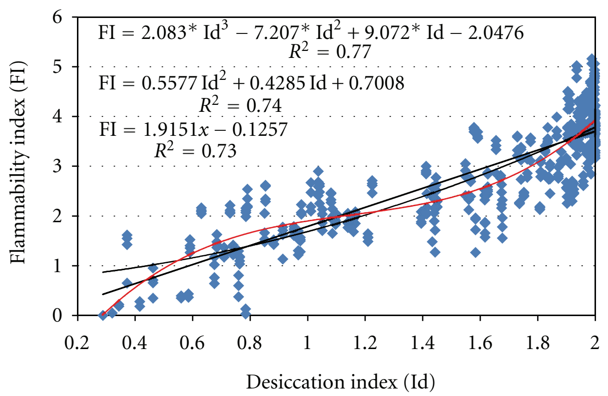


Figure 3: Flammability index (FI) values of Moroccan species as a function of their desiccation index Id.

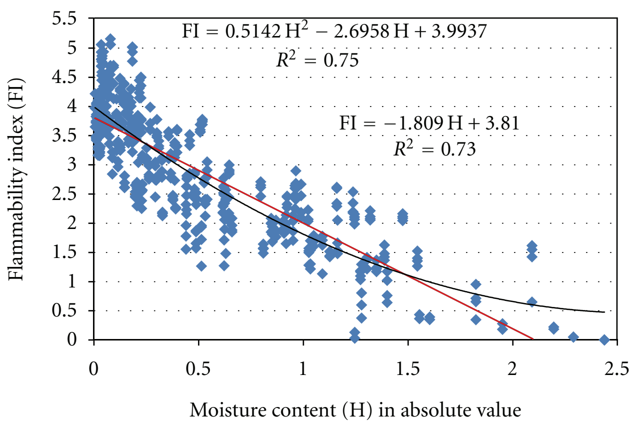


Figure 4: Flammability index (FI) values of Moroccan species as a function of their moisture content (H).

(3.5 ≤ FI < 4.5), and most flammable (4.5 ≤ FI). This latter flammability class would mainly correspond to the case of exceptionally very flammable species and dry fuel biomass of less than 15–20% H (Id > 1.90).

By proposing the above flammability index classes, the Valette's classification method was improved at two levels: (i) the magnitude of the FI-value belongs to a continuous numerical scale that is different from the previously used discrete notation system [22], and this would give best discriminating comparison between species flammability degrees; (ii) the FI-formula integrates, beside the time to ignition parameter, two other interesting factors, that is, the time of complete combustion, a good indicator of the potential biomass energy that sustains combustion and then the rate of fire spread [26, 28], and the flame height parameter that would indicate the importance contribution of the volatile essential oils or extractives to the heat released from the species foliage fuels [31]. In fact, the result obtained from the test on *Eucalyptus camaldulensis* confirms the contribution of its volatile essential oils to flammability since it exhibits a very high mean value of flame height of 22 cm and it was found to be an extremely flammable species [23].

3.6. Flammability Assessment of Moroccan Species. Since the FI-value is highly inversely correlated to species moisture content, two different tendency curves were tested with regard to the determination of the hypothetical moisture of extinction (ME). As shown in Figure 4, the best fitting model is the polynomial equation, followed by the simple linear regression one. However, the polynomial equation appears not to be adequate because its null derivative would give a hypothetical moisture of extinction ME = 262%, resulting in a minimum value of FI = 0,46 which is still much higher than the negative test FI-value of 0. This means that the polynomial equation will never get this null value. Consequently, the linear equation is the right one to use for predicting moisture of extinction, since for instance at FI ≤ 1, it would give ME = 155% and at FI = 0, ME would have a value of 211%, a value that makes sense because at this moisture content level, no fuels would probably ignite (Figure 4). For each studied species, a linear regression equation was then performed and used to calculate the corresponding hypothetical moisture of extinction (ME) on the basis of FI ≤ 1. The species ME-values and their corresponding regression constants "*a*" and "*b*" with R^2 are given in Table 5. The determination coefficient varies from $R^2 = 0.57$ observed for *Quercus suber* to $R^2 = 0.96$ for *Cistus ladaniferus*, *Cistus albidus*, and *Quercus faginea*. The values of the intercept "*a*" which correspond to the FI variation interval at H = 0%, vary between 3,071 observed for *Myrtus communis* and 4,795 for *Cedrus atlantica*. The values of the hypothetical extinction moisture content ME, calculated on the basis of FI ≤ 1, vary from a minimum of ME ≥ 72% observed for *Erica arborea* to a maximum of ME ≥ 243% noted for *Arbutus unedo* (Table 5). The estimation of the hypothetical moisture of extinction via the linear regression equation appears to give ME-values higher than those found by Dimitrakopoulos and Papaioannou [23] for the commonly studied species, except for *Pinus halepensis* and *Pinus brutia* for which the values are in agreement. However, for Erica arborea the value is low (≥72% versus >87%).

3.7. Flammability Classification of Moroccan Species. The average moisture content of 22 Moroccan species has been calculated on the basis of data collected during critical summer periods, from July to September of the years 2007 and 2008 [34]. Based on their average moisture content values, their corresponding FI-values were calculated, using the simple linear equations shown in Table 5. Table 6 shows the FI-values of these species and their corresponding flammability classes. According to the above classification method using the proposed flammability index formula, and based on the obtained FI-values, the studied Moroccan species are divided into four flammability classes (Table 6). The results of this species classification would partially explain, to a certain extent, the difference in fire occurrence existing between the three studied forest regions.

(i) The Mamora lowland forest is considered of low fire risk given that its shrub stratum is almost occupied by the ecological association of *Thymelaea lythroides* L. that has the lowest FI = 0.47. The *Teline linifolia* L. unit (FI = 1.96) stretches on small area, and the most

Table 5: Regression coefficient characteristics of the flammability index (FI) equations determined for Moroccan species as a function of the moisture content H (in absolute value), (FI = $a + b$H), and their hypothetical moisture of extinction ME (in %) at FI ≤ 1.

Tree/shrub species	FI-equation			Hypothetical moisture of extinction ME (%) at FI ≤ 1
	a	b	R^2	
Acacia mollissima	3,667	−1,119	0.85	≥238
Arbutus unedo	3,333	−0,961	0.90	≥ 243 (58–96%)*
Buscus balearica	3,815	−1,607	0.80	≥175
Cedrus atlantica Manetti.	4,795	−3,448	0.82	≥110
Cistus albidus L.	3,915	−1,289	0.96	≥226
Cistus crispus L.	3,387	−1,835	0.91	≥130
Cistus ladaniferus L.	3,120	−1,449	0.96	≥146
Cistus monspeliensis L.	3,772	−1,744	0.91	≥159
Cistus salviifolius L.	3,160	−1,476	0.95	≥146 (>112%)*
Cupressus sempervirens L.	4,389	−2,576	0.83	≥132 (>117%)*
Erica arborea L.	3,492	−3,445	0.73	≥72 (>87%)*
Eucalyptus camaldulensis D.	4,446	−2,112	0.91	≥163 (>140%)*
Halimium halimifolium	3,773	−2,579	0.94	≥108
Juniperus thurifera L.	3,672	−1,857	0.78	≥144
Lavandula stoechas L.	3,469	−1,475	0.83	≥167
Myrtus communis L.	3,071	−1,330	0.67	≥156
Olea europea L.	3,252	−1,419	0.84	≥159 (70–120%)*
Phyllerea angustifolia L.	3,921	−1,640	0.82	≥178
Pinus brutia Ten.	3,572	−1,977	0.78	≥130 (81–130%)*
Pinus canariensis L.	3,840	−2,399	0.95	≥118
Pinus coulteri	3,788	−2,331	0.91	≥120
Pinus halepensis Mill.	3,660	−1,979	0.86	≥134 (89–138%)*
Pinus pinaster var. *maritima*	3,511	−1,557	0.85	≥161
Pistacia lentiscus	3,930	−2,270	0.82	≥129 (80–85%)*
Quercus faginea	3,960	−1,284	0.96	≥230
Quercus suber L.	4,333	−1,597	0.57	≥209
Stipa tenacissima L.	3,844	−3,733	0.61	≥76
Teline linifolia L.	4,132	−1,593	0.78	≥197
Tetraclinis articulata	4,083	−2,815	0.83	≥110
Thymelaea lythroides L.	4,426	−2,903	0.80	≥120
Viburnum tinus L.	3,800	−1,901	0.86	≥147

* The data between parenthesis correspond to the moisture of extinction determined by Dimitrakopoulos and Papaioannou [23].

fire disaster observed in Mamora was in this unit but in a fenced parcel where the vegetation density of *Teline linifolia* L. was very high and animal grazing was forbidden. The Mamora area is known by a high population density and by grazing activities. Also, the litter under the pine stand was always gathered by local population for domestic energy uses.

(ii) Middle Atlas forests are of a moderate fire risk. In these forests, the vegetation is mainly composed of *Cedrus atlantica*, *Pinus pinaster*, *Quercus rotundifolia*, *Pistacia lentiscus*, *Olea europea*, *Arbutus unedo*, and so forth. In these mountains, although there is more vegetation, grazing activity is extensive, basically sheep. Most forest fires trigged in the pine stands mixed with *Quercus rotundifolia*.

(iii) Finally, the highest fire occurrence is observed in Rif mountains that are characterized by a *Quercus suber* forest on steep topography and with a very dense shrub stratum, mainly composed of *Phyllerea angustifolia* L, *Cistus monspeliensis* L, *Viburnum tinus* L., *Cistus crispus* L., *Cistus ladaniferus* L., *Erica arborea* L., and so forth. In this area, goats constitute most of the grazing activity.

Except for *Cistus salviifolius*, ranked in the same “Moderately flammable species” class as suggested by Dimitrakopoulos’ method [36], the other commonly studied species

Table 6: Moroccan species classification using their flammability index (FI) values calculated from their linear equations (FI = $a + b$H) and their average moisture content of their leaves or needles determined during the critical summer period from July to September.

Tree/shrub species	Flammability index (FI-value)	Species flammability classification
Quercus suber L.	2,97	Flammable species (2.5 ≤ FI < 3.5)
Phyllerea angustifolia L.	2,97	
Acacia mollissima	2.85	
Quercus faginea L.	2,83	
Cistus monspeliensis L.	2,69	
Viburnum tinus L.	2,41	Moderately flammable species (1.5 ≤ FI < 2.5)
Arbutus unedo L.	2,38	
Lavandula stoechas L.	2,33	
Cistus crispus L.	2,27	
Cistus albidus L.	2,16	
Cistus ladaniferus L.	2,14	
Erica arborea L.	2,11	
Eucalyptus camaldulensis D.	2,12	
Cistus salviifolius L.	1,96	
Teline linifolia L.	1,96	
Pistacia lentiscus L.	1,88	
Olea europea L.	1,69	
Pinus canariensis L.	1,65	
Pinus pinaster var. *maritima*	1,64	
Cedrus atlantica L.	1,35	Less flammable species (0.5 ≤ FI < 1.5)
Myrtus communis L.	1,21	
Thymelaea lythroides L.	0,47	Least flammable species (FI < 0.5)

FI-value classification scale: least flammable (FI < 0.5), less flammable (0.5 ≤ FI <1.5), moderately flammable (1.5 ≤ FI < 2.5), flammable (2.5 ≤ FI <3.5), highly flammable (3.5 ≤ FI < 4.5), and most flammable (4.5 ≤ FI).

Arbutus unedo and *Pistacia lentiscus* belong, according to the same method, to a superior class of "flammable species". This latter method corresponds to a statistical classification based on the canonical discriminate analysis of chemical (heat content, total and silica-free ash content) and physical (surface area-to-volume ratio and fuel particle density) properties of eight Mediterranean species [36]. Even though the concepts of the two classification methods are similar, in terms of aiming to establish a ranking scale for forest species with regard to their fire behavior, their comparison should be done with care because their using conditions are completely different: the classification method developed in this study is based on a flammability index value, calculated from characteristics of experimental flammability tests, as a function of the average moisture content recorded for each species during the summer period from July to September. Whereas, that of Dimitrakopoulos [36] is totally based on an indirect estimation of the flammability through thermal and physical properties of the forest species, and without taking into account the moisture content effect.

On the other hand, however, the results found by Papio and Trabaud [10] showed that *Pistacia lentiscus*, *Cistus salviifolius*, and *Phyllerea angustifolia* are species of least, greatest, and intermediate hazard, respectively, whereas the same species are classified according to the current developed method as moderately flammable for the two first species and flammable for the third one. Liodakis et al. [21] have defined only two ignitability classes: the most and the least ignitable species; and for them, *Pistacia lentiscus* is ranked as the least ignitable species. All these differences in species classification are due, on one hand, to the difference in the number of the defined flammability or ignitability classes and the intrinsic characteristics of species from different origins, and to the importance of the moisture content effect that should not be neglected. On the other hand, it is due to the flammability estimating-method concepts that are different from one author to another. This demonstrates that, for future studies, the fuel moisture content must be always associated to the species flammability estimated by whatever method used.

From a practical point of view, the flammability index concept developed in this study would be of great interest for Moroccan forest managers in terms of fuel hazard and fire risk assessment, mainly for the already managed forests with known ecological association units. Mapping the fire risk for this kind of forests would take less time if we study the vegetation through setting sufficient number of sampling plots in different ecological association units. Even though the species flammability index remains the major parameter in forest fire studies, other factors are needed to be considered such as vegetation structure and architecture, surface fuel biomass, moisture content, and weather. Finally, the conclusion to be drawn from this study is that the developed findings constitute a well-established knowledge basis for future forest fire prevention studies in Morocco.

4. Conclusions

The aim of the study was to improve the flammability index estimation method suggested by Valette [22]. In fact, an empirical formula that estimates species flammability index (FI) was developed, integrating three parameters: time to ignition (TI), time to combustion (TC), and flame height (FH). The FI-value varies within an interval of [0, 6]. The ignition frequency (IF) was not considered in this formula because it is highly correlated to the other parameters, mainly to TI with $r = -0.89$. Since the FI-value is calculated for each flammability test, an analysis of variance, between four different sample sizes of 12, 24, 36, and 50 flammability tests, was performed in order to determine the sampling size to consider for species flammability estimation. The results showed that 12 flammability tests only are sufficient to obtain same values as with the sizes of 24, 36, or 50 tests.

The proposed species classification method is somewhat similar to the one suggested by Valette [22], but on the basis of a continuous scale as follows: least flammable (FI < 0.5), less flammable (0.5 ≤ FI < 1.5), moderately flammable (1.5 ≤ FI < 2.5), flammable (2.5 ≤ FI < 3.5), highly flammable (3.5 ≤ FI < 4.5), and most flammable (4.5 ≤ FI). This latter flammability class would mainly correspond to the case of exceptionally very flammable species and dry fuel biomass of moisture content less than 15–20% (Id > 1.90).

The FI-value was found to be inversely correlated to the species moisture content with $r = -0.88$. The polynomial and linear regression equations appear to be consistent. However, the best model to consider, regarding the estimation of the moisture of extinction, is the simple linear model which can be considered as a conservative one in the sense it would give the lower limit value of the threshold point for the moisture of extinction. Most of the Moroccan studied species are classified as moderately flammable to flammable species. However, *Thymelaea lythroides* is the only least flammable species.

Based on data comparison between the commonly studied species, it can be concluded that the developed classification method is somewhat similar to the statistical classification proposed by Dimitrakopoulos [36] which is based on the canonical discriminate analysis of the intrinsic species chemical and physical characteristics. However, a notable difference has been observed with regard to either the fire hazard classification proposed by Papio and Trabaud [10] or the ignition delay time method considered by Liodakis et al. [26]. For a practical purpose, the moisture content should be taken into account for any eventually proposed flammability estimating method.

Regarding the practical aspect of the current research findings, the concept of species flammability index in relation to the field species moisture content would constitute a basis for future research in terms of estimation of a global flammability index at the forest site level. This would facilitate the fire risk mapping, mainly for the already managed forests with known ecological association units.

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