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Using calorimetry for determining the risk indices to prevent and fight forest fires☆

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Abstract

A method is proposed for calculation of risk indices of different forest formations existing in Galicia. These values are helpful to predict the behaviour of forest species in case of forest fires and thus to prevent and/or fight these wildfires.

Main parameters for calculation of risk indices are calorific values measured by bomb calorimetry and flammability measured by a standard epiradiator. These parameters were studied together with chemical analysis of different forest samples and an intensive research of physical and environmental parameters. All the data presented were determined in the last 10 years in Galicia (NW of Spain).

Keywords: Risk indices; Calorific values; Flammability; Calorimetry

1. Introduction

From the 1960s, forest fires devastated in Spain around 6,400,000 ha (2,600,000 ha covered by trees and 3,800,000 ha of bush covered surface). Apart from this ecological damage, forest fires caused economical losses of around € 7.5×10^9 (€ 2.3×10^9 in raw materials and € 5.2×10^9 in environmental damage).

Because of these damages, campaigns must be developed to prevent and fight forest fires trying to slow down one of the main causes of desertification. Even if people often refer to forces of nature, it must be pointed out that 98% of forest fires are originated by man (either intentionally or coincidentally). Table 1 shows main causes of forest fires in Spain.

In spite of the great technological steps forward and the appearance of new means to fight them, forest fires keep being one of the worries of the international scientific community. For this reason, preventing and/or fighting forest fires should be a main task for every government policy encouraging the search for new strategies. Within these new alternatives, calculation of risk indices of the different forest species, which occupy the woodland of a given zone plays an important role.

These risk indices, are numerical values based on different physical, chemical, environmental and climatic parameters. These values can be obtained for every forest species and from the knowledge of risk indices the behaviour of a given zone with respect to forest fires can be predicted.

From the 1990s, our research group TERBIPROMAT has developed a method to determine risk indices from field and laboratory data. This method has the advantage over the traditional methods that it is based on real data and not on simulations.

2. Experimental procedure

The first stage of the experimental work begins with sampling. This is a very important stage since the usefulness of the experimental measurements greatly depends on the representativeness of samples. The sampling method here proposed was developed in the last 10 years, in which more than 1000 trees and 150 t of forest samples were analyzed. Most part of samples belonged to *E. globulus* Labill and *P. pinaster* Aiton,

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Table 1
Main causes of wildfires are listed and quantified in this table

Intentional (%)	75.5
Unknown origin (%)	16.8
Burning (%)	3.1
Negligence (%)	2.8
Dumps (%)	0.6
Rays (%)	1.7
Others (%)	0.5

It can be seen that more than 98% of forest fires are originated by anthropoid activities either accidental (unknown, dumps, negligence, burning and others) or intentional. Only 1.7% of fires are originated by natural causes such as storms (thunderbolts). This table can be extended to every country.

Table 2
Simple were collected in seven different periods

Spring	Summer	Autumn	Winter
May	July August September	November	January March

These periods were chosen over the four seasons to analyze the annual evolution of all the parameters studied. The fact of collecting samples three times during summer is because in this season forest fires are abundant and devastating. Two sampling were collected in winter because climatic conditions are very changeable, and forest species, because of their null vegetative activity, are very vulnerable to forest fires. All sampling were performed halfway through the months, always in the same zones, but with similar different similar trees, as samplings are destructive (the trees are cut). Collection of samples takes around 1 week and the time between collection and laboratory treatment is less than 12 h.

two forest species that cover more than 850,000 ha [1], more than one-half of Galician forest surface, and represent around 6% of Galician GDP (gross domestic product) [2].

The different zones studied were chosen because of their ecological and economical significance according to the Third Spanish Forest Inventory [1].

For selection of a sample zone, the species under study should occupy homogeneously, at least, 1 ha. Once chosen, in each zone a certain number of trees, which depends on the extension of the zones, were selected.

To be selected, the trees must be representative of the whole, and because of this, we must avoid the selection of young, old, ill or any irregular trees. Also trees situated in the border of the zone should be considered as not representative. Using a hypsometer, the average height of the trees was estimated, and the representative trees were chosen as those having the average height, as from our experience we know that trees with similar height show similar behaviour.

After being cut down, the selected trees were taken for extraction of the residues usually abandoned on the forest surface after forestry works. These residues were sorted into three well differentiated classes: leaves, branches having a diameter less than 3 cm, and branches with a diameter between 3 and 6 cm. The reason for sorting into three classes is because each of them has different calorific values and flammability, thus showing different behaviour respect to forest fires.

After sorting the mentioned three groups, residues of each of them were carefully mixed and then reduced by a coning and quartering procedure to a representative bulk sample of 5–6 kg each. After being collected, the samples were stored in hermetically closed polyethylene bags, to avoid loss of moisture, and sent to the laboratory in less than 10 h.

This procedure was repeated seven times over the year as shown in Table 2. It can be seen that three samplings were made in summer, and two in winter while only one sampling was made in spring and in autumn. The reason for this choice is based on the fact that most part of forest fires happens in summer, and also that climatic conditions both in summer and winter are very changeable in Galicia having a strong influence on forest formations behaviour.

The zone where sampling was made was characterized by filling in a special technical form in which climatic data, and physical properties such as temperature, humidity, type of soil, slope, type of forest exploitation, etc., were recorded. All these parameters have an important influence on biomass vegetative production. These production capacities can be represented as free biological intensities (FBI) in the form of bioclimatic diagrams [2,3]. These diagrams are helpful to understand the influence of the environment on the origin and spreading of forest species, and on their behaviour in the case of fires. Fig. 1 shows the main parameters involved in the design of bioclimatic diagrams.

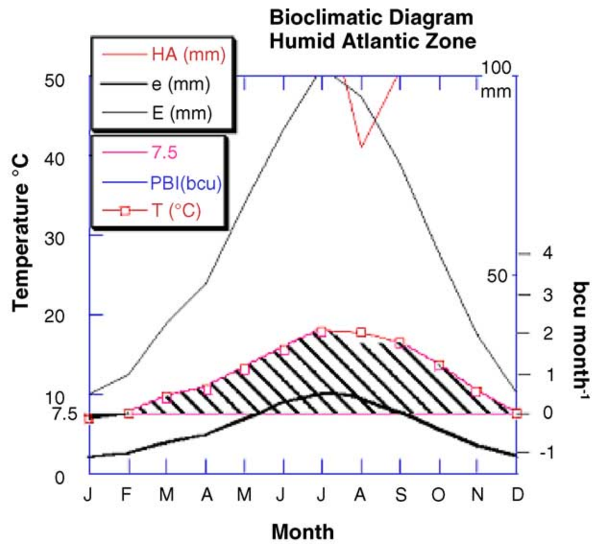
Once in the laboratory, samples were weighed to 0.1 or 1.0 g using a double scaled Salter EP-22KA balance. These samples were divided into two parts. A first part was used in the flammability experiments [4] that were performed, following the standard UNE-23-721, using a standard epiradiator of 500 W constant nominal power. To determine flammability class, experiments were performed on 75 samples of 1 g each of the 3 groups of residues of every forest species.

After determination of flammabilities the samples were sorted into the six classes recorded in Table 3. The flammability can be considered as the ease with which a material catches fire, both spontaneously or through exposure to certain ambiences, and also as the inverse to the resistance of forest species to starting and spreading wildfires.

A second part of the original samples was introduced in a Selecta 200210 natural desiccating oven and dried, at 105 °C, to constant weight to determine moisture contents as the weight loss of the sample after treatment in the oven.

Once the humidity was determined, the dry sample was ground using two mills of different power: a Retsch SM-1 blade mill and a Taunus MS-50 grinder, in order to homogenize the sample as much as possible, thus making the preparation of the sample pellets to be used in the calorimetric experiments easier. The ground sample was divided into three parts. One of these parts was sent to two different laboratories (SADER and Elementary Analysis Service of our University) to determine C, H, O, N, S and heavy metals. A second part was used for calorific measurements and the third part was stored in a refrigerator at −14 °C as a “witness” sample.

The calorimetric experiments were performed as follows: sample pellets of about 1 g size [5] were placed in a stain-



	J	F	M	A	M	J	J	A	S	O	N	D
T	6.2	6.6	8.8	9.5	12.6	15.8	18.3	17.7	16.2	12.8	8.6	6.0
E	11.0	17.5	40.0	58.5	88.0	104.0	117.0	97.0	59.0	32.0	12.0	9.0
e	2.2	3.5	8.0	11.7	17.6	20.8	23.4	19.4	11.8	6.4	2.4	1.8
HA	264.0	224.0	254.0		199.0	190.0	1	57.0		76.0		36.0
	65.6		130.0		235.0	262.0						
PBI			0.27	0.39	1.02	1.64	2.15	2.02	1.73	1.06	0.21	
FBI			0.27	0.39	1.02	1.64	1.18	0.40	1.73	1.06	0.21	
CBI	-0.27	-0.18										-0.29

T: temperature (ºC)
E: evapotranspiration (mm)
e: residual evapotranspiration (mm)
HA: hydric availability (mm)
PBI: potential bioclimatic intensity (bcu)
FBI: free bioclimatic intensity (bcu)
CBI: cold bioclimatic intensity (bcu)

Fig. 1. Parameters used to elaborate bioclimatic diagrams for the Galician Atlantic humid zone.

less steel crucible introduced into a Parr-1108 sealed static bomb calorimeter made of Carpenter-20-Cb-3 special stainless steel. The experiments were performed at 25 °C, following the method proposed by Hubbard et al. [6]. Lower heating values LHV reported in Table 5 are the average of four calorimetric experiments on each sample. The bomb was filled with C-45 oxygen 99.99995% pure from Carburos Metálicos (Spain). The calorimeter was placed in an isothermal-jacket with an air-gap separation of 10 mm between all surfaces. Water was added to the calorimeter from a weighed glass vessel and for each experiment a correction to the energy equivalent was made for the deviation of the mass of water added from 4631 g weighed to 0.1 g. The temperature of this water was measured to 10^{-4} K at intervals of 15 s by a stable and sensitive platinum thermometer (ASL S 391/100) and recorded by a resistance bridge (ASL F-26) connected to a computer (Amstrad PC-2086/30). The water in the jacket was circulated by stirring and its temperature was maintained at 298.15 K by a Tronac PTC-41 temperature controller with a precision of 0.003 °C over 1 week, and including a probe, a heater and cooling coil. The samples were ignited at 298.15 ± 0.01 K in oxygen at 3.04 MPa with 1 cm^3 of water added to the bomb. The electrical energy for ignition was determined from the change in potential across a 1256 or 2900 μF capacitor when discharged from about 40 V through a platinum wire. The pellet was connected to the ignition system by means of a cotton thread fuse, empirical formula $CH_{1.686}O_{0.843}$ with $-\Delta_c U_0$ = 16,250 kJ kg^{-1}.

The samples, crucible, platinum wire and cotton thread were weighed using a Sartorius R200D balance (sensitivity ±0.01 mg). The energy equivalent of the calorimeter was determined from the combustion of benzoic acid (BCS CRN-

Table 3
Flammability class values for Galician forest species studied

Specie	Spring	Summer	Autumn	Winter
Acer pseudoplatanus L.	3	5	4	3
Alnus glutinosa (L.) Gaertner.	1	2	1	1
Betula pendula Roth.	1	2	2	1
Bushes sp.*[1]	1	0	0	0
Castanea sativa Miller.	4	5	5	4
Eucalyptus globulus Labill.	1	0	1	0
Fagus sylvativa L.	5	5	4	5
Fraxinus excelsior L.	2	1	1	1
Laurus nobilis L.	4	5	5	4
Pinus pinaster Aiton.	0	3	1	0
Prunus avium (L.) L.	1	1	1	1
Pteridium aquilinum L.	1	5	5	3
Quercus pyrenaica Willd.	1	5	4	2
Quercus robur L.	5	5	4	4
Rubus fructicosus L.	4	5	4	2
Salix atrocinera L.	1	2	2	1
Sarothamnus scoparius Link.	4	5	4	4
Sorbus aucuparia L.	5	5	4	3
Taxus baccata L.	3	4	3	2
Ulex europaeus L.	4	4	3	4

Flammability class—class 0: very low flammability (>32.5 s); class 1: low flammable (27.5–32.5 s); class 2: flammable (22.5–27.5 s); class 3: moderately flammable (17.5–22.5 s); class 4: very flammable (12.5–17.5 s); class 5: extremely flammable (<12.5 s). All the species were studied along 10 years and were classified according to flammability over the year. Flammability experiments were carried out following the method proposed by Valette [5]. The table corresponds to mix formations of high size Erica species, *U. europaeus* L., *S. scoparius* Link. and various herbaceous.

Table 4
LHV class values for the different species studied

Specie	Spring	Summer	Autumn	Winter
A. pseudoplatanus L.	2	3	5	5
A. glutinosa (L.) Gaertner.	3	2	2	5
B. pendula Roth.	3	2	3	3
Bushes sp.*[1]	4	5	5	5
C. sativa Miller.	1	3	5	5
E. globulus Labill.	5	4	4	4
F. sylvativa L.	1	5	4	2
F. excelsior L.	2	2	5	4
L. nobilis L.	3	1	2	4
P. pinaster Aiton.	4	4	5	5
P. avium (L.) L.	4	4	5	5
P. aquilinum L.	1	1	5	4
Q. pyrenaica Willd.	5	5	5	5
Q. robur L.	3	3	5	5
R. fructicosus L.	2	2	2	4
S. atrocinera L.	2	1	3	5
S. scoparius Link.	0	1	1	0
S. aucuparia L.	2	2	3	4
T. baccata L.	4	4	4	4
U. europaeus L.	5	5	5	5

LHV classes—class 1: LHV < 4500 kJ kg^{-1}; class 2: LHV ≥ 4500 and <5500 kJ kg^{-1}; class 3: LHV ≥ 5500 and <6500 kJ kg^{-1}; class 4: LHV ≥ 6500 and <7500 kJ kg^{-1}; class 5: LHV ≥ 7500 kJ kg^{-1}. All the species were studied through 10 years and were classified according to LHVs over the year. The table was constructed following the model proposed by Doat and Valette, that was modified to take in account the values measured for Galician forest species. The table corresponds to mix formations of high size Erica species, *U. europaeus* L., *S. scoparius* Link. and various herbaceous.

ISOP standard reference sample) from the Bureau of Analysed Samples Ltd., having a specific energy of combustion under standard bomb conditions of 26,431.8 ± 3.7 J g^{-1}. The temperature rise measured in every experiment was corrected for stirring and heat exchange.

From five calibrations done with the bomb, the energy equivalent of the calorimeter was determined to be E_0 = 22,402.5 ± 1.9 J K^{-1} (0.0085%) where the uncertainty quoted is the standard deviation of the mean.

The objective of the calorimetric experiments was the obtention of the calorific values, that is, the energy contained in a mass unit of the forest biomass. Two calorific values must be pointed out:

- The higher heating value (HHV) is defined as the quantity of heat generated by complete combustion in a bomb calorimeter of a unit mass of sample in an oxygen atmosphere, assuming that both the water contained in the sample (moisture) and that generated from the combined hydrogen remains in liquid form. For a given forest species, this value depends on the zone and season.
- The lower heating value (LHV) can be calculated, through HHV, assuming that the water in the products of combustion remains in the form of vapor. Both calorific values are related through the equation:

$$(\mathrm{LHV})_\mathrm{d} = (\mathrm{HHV})_\mathrm{d} - 24.42(9\mathrm{H}_\mathrm{d}). \qquad (1)$$

where $(\mathrm{LHV})_\mathrm{d}$ corresponds to the lower calorific value of the dry sample, $(\mathrm{HHV})_\mathrm{d}$ the higher calorific value of the dry sample, and H_d the hydrogen percentage of the dry sample. The heat of vaporization of water is taken as 2441.8 kJ kg^{-1}, and the water formed during combustion is nine times the hydrogen content (%). The LHV calculated through Eq. (1) is one of the main parameters used for the calculation of risk indices.

The knowledge of LHVs of the different tree species making up the forest vegetation becomes a realistic indicator of the energetic state of the forest biomass of a zone and helps to plan a rational exploitation of the energetic forest resources.

Same as it was done with flammability, forest species were sorted into five classes according to an energy class arrangement set up by our research group, that consists of a modification of that proposed by Doat and Valette [5] adapted to Galician forest species. These classes are recorded in Table 4.

3. Results and discussion

Combination of LHV, flammability, composition, and bioclimatic parameters allows the calculation of risk indices of the different species. Table 5 shows an example of calculation of risk indices of *P. pinaster* Aiton 50 years old

Table 5
Risk index calculation of two of the species (A: 15-year-old *E. globulus* Labill. and B: 25-year-old *P. pinaster* Aiton) collected in summer

	Experimental values		Calculated values	
	A	B	A	B
Thermochemical parameters				
LHV class number	4	4		
Flammability class number	0	3	2	3.5
Physicochemical properties (10%)				
Density (kg mc^{-3}) (15%)	620	640		
Own moisture (%) (80%)	57.8	53.50		
Bomb ashes after combustion (%) (5%)	1.56	0.84	0.0197	−0.0007
Biological characteristics (20%)				
Physiological activity (10%)	Middle	Middle–high		
Essential oils/resins (10%)	Middle	Middle–high		
Age (10%)	15	Old		
Habit (10%)	Plantation	Conifers		
Forest waste generated (20%)	Low	Middle–high		
Forest cover around (20%)	Middle	Middle		
Perennial/deciduous (10%)	P	P		
Blooming period (10%)	May–July	April–May	−0.0450	0.0311
Climate characteristics (40%)				
Rainfall (40%)				
Monthly mean amount (mm) (50%)	12	−47.17		
Periodicity (50%)	Low regular	Low		
Mean temperature (°C) (20%)	19.1	17.47		
Hydric availability (mm month^{-1}) (30%)	112	52.83		
Environmental humidity (% month^{-1}) (10)	68	60	0.2315	0.1835
Parameters depending on physical environmental conditions (20%)				
Zone wind (30%)				
Strength (50%)	Middle–low	Middle–low		
Periodicity (50%)	Regular–low	Regular–low		
Clouds (10%)				
Amount (50%)	Regular	Regular		
Regularity (50%)	Low	Low		
Topography (20%)	Favorable	Unfavorable		
Sun radiation (10%)				
Sunshine (%) (50%)	Middle–high	Middle–high		
Sunny days (50%)	Middle–high	Middle–high		
Anthropogenic activity (30%)	Middle–low	Middle–high	0.0202	−0.0141
Risk index final value			2.22	3.70
Risk index class			2	4

For understanding of this table see the text.

corresponding to summer and *E. globulus* Labill 15 years old corresponding to winter. The influence of the different parameters on the risk indices are pointed out. The table shows the change in the risk index value due to changes in all the different parameters used for calculation. HHV and flammability were experimentally determined in our laboratory. For biological characteristics, climate characteristics, and parameters depending on physical environmental conditions, the study was made using available literature data of the zone for the last 40 years. After analysis of all these data, it was considered that numerical contributions were physicochemical properties (10% = 0.1), biological characteristics (20% = 0.2), climate characteristics (50% = 0.5), and parameters depending on physical environmental conditions (20% = 0.2).

At the same time, each of the mentioned factors depends on some other parameters. Again, the different numerical contributions are ascribed through analysis of existing data. As an example, physicochemical properties contribute 10% (0.1) to change the main risk index number. This contribution depends on density (15% = 0.15), own moisture (80% = 0.8), and bomb ashes after combustion (5% = 0.05). This means that, for instance, own moisture contribution to the final risk index is $0.1 \times 0.8 = 0.08M$, where M is the own moisture content in a normalized scale. Similar calculations can be made for all the different factors. Climate characteristics (50% = 0.5) depend, among other parameters, on rainfall (40% = 0.4), that in turn depends on monthly mean amount of rain (mm) (50% = 0.5) and periodicity contribution to change the risk index is $0.5 \times 0.4 \times 0.5 = 0.1P$, where P is the periodicity in a normalized scale.

To work out values of the different parameters in the normalized scales, we proceed as follows. Let us considerer the influence of own moisture content of *P. pinaster* Aiton col-

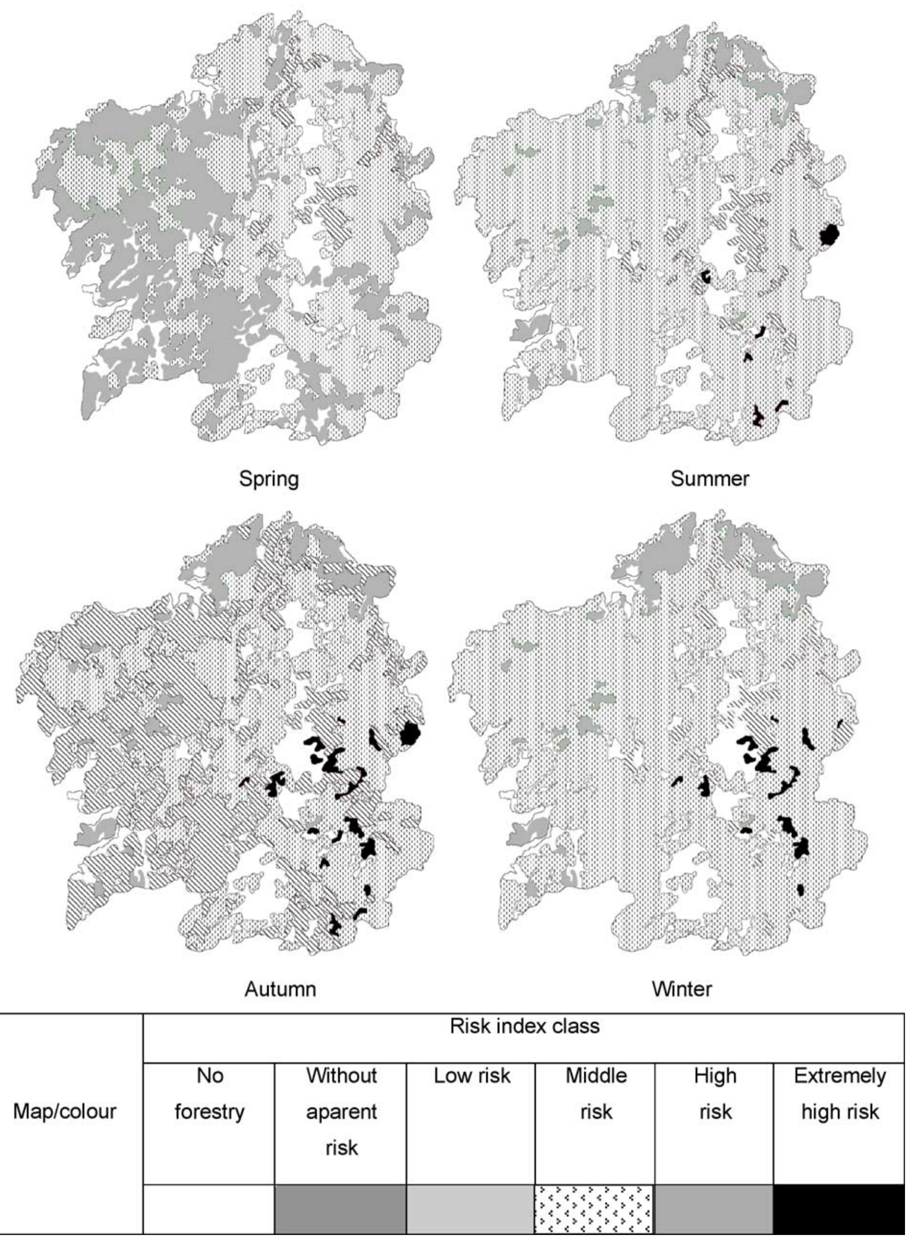


Fig. 2. Seasonal risk indices evolution maps for Galician forest species.

lected in summer. Moisture content for the different species in the zone goes from 70.66%, the most resistant to forest fire, to 29.52%, the most favorable to forest fire. The mean of these two values is 50.09% and the difference between them, 41.14%, which is normalized to unity. In our scale 50.09% corresponds to zero, 70.66% corresponds to −0.5, the most resistant to forest fire, and 29.52% corresponds to +0.5, the most favorable to forest fire. Subtracting *P. pinaster* Aiton summer moisture 53.50 from 50.09 renders −3.41, which in the normalized scale corresponds to −3.41/41.14 = −0.08.

So, the influence of the different parameters and properties on the risk index of *P. pinaster* Aiton, in summer, to the risk index number is 0.08 × (−0.08)= −0.0064.

Same analyses and calculations were done over the different parameters affecting the various afore-mentioned contributions.

The final risk index number is rounded to the next higher 1-decimal number, 4.7, and this is the value used in our prevention studies. However, to increase prevention, this number could be rounded to the next higher 0.5-decimal number, 5.

Table 6 shows an arrangement of different forest species according to their risk indices [7–13].

For a better comprehension and use of risk indexes, they are presented in the form of maps that were designed using available data found in forest inventories.

Fig. 2 shows a general risk index evolution map over the year of the more abundant Galician forest species.

Table 6
Risk indices for the different forest species studied

Specie	Spring	Summer	Autumn	Winter
A. pseudoplatanus L.	3	4	5	4
A. glutinosa (L.) Gaertner.	2	2	2	3
B. pendula Roth.	2	2	3	2
Bushes sp.*1	2	2	3	3
C. sativa Miller.	3	4	5	5
E. globulus Labill.	3	2	2	2
F. sylvativa L.	3	5	4	4
F. excelsior L.	2	2	3	3
L. nobilis L.	4	3	4	4
P. pinaster Aiton.	2	3	3	2
P. avium (L.) L.	3	3	3	3
P. aquilinum L.	1	3	5	4
Q. pyrenaica Willd.	3	5	5	4
Q. robur L.	4	4	5	5
R. fructicosus L.	3	4	3	3
S. scoparius Link.	2	2	2	2
S. atrocinera L.	2	2	3	3
S. aucuparia L.	4	4	4	4
T. baccata L.	4	4	4	3
U. europaeus L.	5	5	4	4

No risk: 1; low risk: 2; middle risk: 3; high risk: 4; extremely high risk: 5. The table corresponds to mix formations of high size *Erica* species, *U. europaeus* L., *S. scoparius* Link. and various herbaceous.

4. Conclusions

A method that describes the behaviour of forest formations with respect to forest fires is presented. This procedure can be used for all forest formations all over the world.

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