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Design of risk index maps as a tool to prevent forest fires in the humid Atlantic zone of Galicia (NW Spain)

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Abstract

In previous articles, we set the basis for the determination of risk indices of forest biomass of Galicia. With this aim, calorific values, flammability, density, moisture contents, ash percentage after combustion, elementary chemical composition, and heavy metal contents over the seasons of the year for the different species which make up the woodland map of a given zone were determined. In the present paper, these studies were applied to this humid Atlantic zone situated in Galicia (NW Spain). The special climatic characteristics of the humid Atlantic zone chosen for our study make its vegetal community singularly gifted.

The calorific values of combustion at 25°C were measured by static bomb calorimetry for the different forest species existing in the zone. These data were complemented with flammability values, measured by an epiradiator and completed with chemical analyzes. Some biological and climatic properties necessary for our calculations were taken from available literature.

A combined study of all these parameters led to calculation of risk indices of the forest species of the zone over the year. The knowledge of the seasonal risk indices can be very helpful to prevent and fight forest fires effectively, and also for a rational management and exploitation of the forest resources through the obtention of xyloenergy. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Calorimetry; Calorific values; Flammability; Risk index maps; Forest fire; Energy maps; Xyloenergy

1. Introduction

From the 80's, forests in Galicia (NW Spain) are suffering deep transformations due mainly to forest fires and to reforestation campaigns carried out with conifers and eucalyptus which have become very usual, thus causing a global change in the different ecosystems.

Conifers and eucalyptus species were chosen from an economical point of view and they are used mainly for extraction of raw materials for production of wood pulp. The introduction of these new tree species causes not only socio-economic changes but also ecological transformations due to the loss of forest biomass as a consequence of forest fires which at the same time originate soil degradation and thus desertification.

In the last years, campaigns have been developed to fight and/or to prevent forest fires. Among the measures to adopt for prevention of forest fires, the knowledge and calculation of risk indices can become very helpful. These indicators can be calculated by means of a combined study of different physical,

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thermochemical, and biological parameters such as:

- Calorific values, that is, the energy contained in 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. As it can be determined experimentally in the laboratory, is one of the two main parameters used for calculation of risk indexes. 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:

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

  where $(\mathrm{LHV})_{\mathrm{d}}$ corresponds to the lower calorific value of the dry sample, $(\mathrm{HHV})_{\mathrm{d}}$ is the higher calorific value of the dry sample, and H_{d} is 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 9 times the hydrogen content (%).

  The knowledge of LHV 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. The knowledge of LHV gives a realistic idea about the magnitude of a fire and leads to the calculation of the fireline intensity, sometimes called Byram's intensity. In this way, LHV becomes an index to quantify both the spread to neighboring surfaces and the virulence of forest fires. Fireline intensity can be calculated using the following equation [1]:

  $$I = (\mathrm{LHV})Wv \tag{2}$$

  where I is the fireline intensity, LHV, the lower heating value, W, the fuel loading, and v, the rate of spread. Using practical field units, the above equation is sometimes written as [1]:

  $$I = 0.007(\mathrm{LHV})Wv \tag{3}$$

  where I is measured in kW m^{-1}, LHV in cal g^{-1}, W in t ha^{-1}, and v in m min^{-1}.

  Fireline intensity is equivalent to the heat output of a unit length of fire front per unit time and is equal to the reaction intensity (i.e. the total heat release of a unit area of fuelbed divided by the burning time) multiplied by the depth of the fire front.
- Flammability, that can be considered as the ease with which a material catches fire, both spontaneously or through exposure to certain ambiences. Also, as the resistance of a forest species to starting and spreading wildfires.
- Chemical composition, both elementary (C, H, O, N, S, and Cl) and heavy metal contents (Pb, Cd, Zn, Cu, and Mn).
- Main bioclimatic characteristics and physico-environmental factors of the zone such as: winds in the zone, solar radiation, cloud cover, topography, and human activities (anthropic activity), temperature, pluviosity (rainfall), evapotranspiration, residual evapotranspiration, hydric availability, and free bioclimatic intensity (not depending on hydric deficiency, only limited by temperature), cold bioclimatic intensity (corresponding to temperature values less than 7.5°C), and potential bioclimatic intensity (surface between lines corresponding to mean monthly temperatures and the 7.5°C line in a bioclimatic diagram). Some of these factors are presented in the form of bioclimatic diagrams [2,3]. Forest fires start in a natural environment, not under a laboratory control. For this reason, the climatic parameters (temperature, pluviosity, water availability, evapotranspiration, etc.) of the zone have a determinative influence on the start and spreading of fires. All these parameters can be represented together in the form of bioclimatic diagrams. These diagrams describe the area to be studied and have a direct influence on all the above mentioned physicochemical parameters.
- Biological properties of the different tree species, such as: age, resin and/or essential oils contents, capacity to originate forest residues, etc.

For a better comprehension and use of risk indexes, they are presented in the form of maps which are designed using available data found in forest inventories. Risk indexes become key parameters for preventing and/or fighting forest fires.

All the studies were carried out over the year, in order to see how the evolution of the biological and bioclimatic characteristics influence the values obtained through the thermochemical parameters (HHV and flammability). For the present study, a humid Atlantic zone situated in Galicia (NW Spain) was chosen. In this zone, with an approximate surface area of 660,000 ha [4,5], two parts must be distinguished:

- A traditional marsh suffering scarce modifications in the last 100 years, thus keeping its autochthonous forest biomass.
- A modified marsh originated from forest fires and reforestations.

2. Experimental procedure

For collection and preparation of the samples, 1 ha of woodland was chosen. The plots were divided into 1 m^2 sites, five of which were randomly chosen. Bulk samples consisting of bark, branches having a diameter not greater than 6 cm, leaves, fallen fruits, etc., originated from pruning, cut of trees, and, in general, forestry works were collected. This sample corresponds to residues abandoned in the forest. Living parts of trees were also collected. With this aim, one standard representative tree corresponding to each forest species formation in the zone was chosen and then cut down. From this tree, samples consisting of fruits, if any, leaves, branches, and branches having a diameter not greater than 6 cm were collected. Living parts were used for infrared analysis, while residue samples were used for energetic evaluation. All bulk samples from the five sites and from the representative trees were reduced by a coning and quartering procedure to representative samples of about 1 kg.

Once collected, the samples were stored in hermetically closed polyethylene bags in order to avoid loss of moisture which is a key parameter in this kind of study. Part of this sample was used in the flammability experiments which were performed, following the standard UNE-23-721, using a standard epiradiator of 500 W constant nominal power. Flammability values reported in this article are average of 75 experiments carried out on each forest species using approximately 1 g samples according to the procedure proposed by Valette [6]. The remaining sample was used for physicochemical analyzes and for measuring calorific values. The material was weighed to 0.1 or 1.0 g using a double-scaled Salter EP-22KA balance and then heated to constant weight in a Selecta 200210 natural desiccating stove. Humidity of the sample was determined as the weight loss of the sample after treatment in the stove. Density was determined using routine methods (picnometer). The dry sample was ground using two mills, a Retsch SM-1 and a Taunus MS-50, in order to homogenize the sample as much as possible before pressing the pellets to be used in the calorimetric experiments.

Test samples were kept in a SAESA CH 50142 refrigerator in order to be checked in case of suspicious results.

The samples were analyzed by a Perkin–Elmer atomic absorption spectrophotometer to determine their Cu, Cd, Zn, Pb and Mn contents and a Carlo Erba analysis equipment for determination of elementary composition C, H, O, N, S and Cl. The calorimetric experiments were performed as follows: sample pellets of about 1 g size [7] were placed in a stainless 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. [8]. HHV reported are average of 4 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. 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 a 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 $-\Delta_c U_0$=16250 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-ISOP standard reference sample) from the Bureau of Analyzed Samples, having a specific energy of combustion under standard bomb conditions of 26431.8±3.7 J g^{-1}. The temperature rise measured in every experiment was corrected for stirring and exchange heating.

From five calibrations done with the bomb, the energy equivalent of the calorimeter was determined to be E_o=22402.5±1.9 J K^{-1} (0.0085%), where the uncertainty quoted is the standard deviation of the mean.

3. Results and discussion

The most representative average bioclimatic characteristics of the zone [9] are shown in Table 1. For a better understanding, these parameters are presented in the form of bioclimatic diagrams, as can be seen in Fig. 1. Mean values were calculated from analysis of data recorded during more than 25 years by the different weather stations situated in the zone.

Table 2 shows values of: moisture contents (*M*), density (*D*), ash after bomb combustion (AB), and flammability (*F*).

Elementary chemical composition (C, H, O, N, S, and Cl) and heavy metal contents (Cu, Cd, Zn, Pb, and Mn) are shown in Table 3. The interest of chemical analysis knowledge is based on:

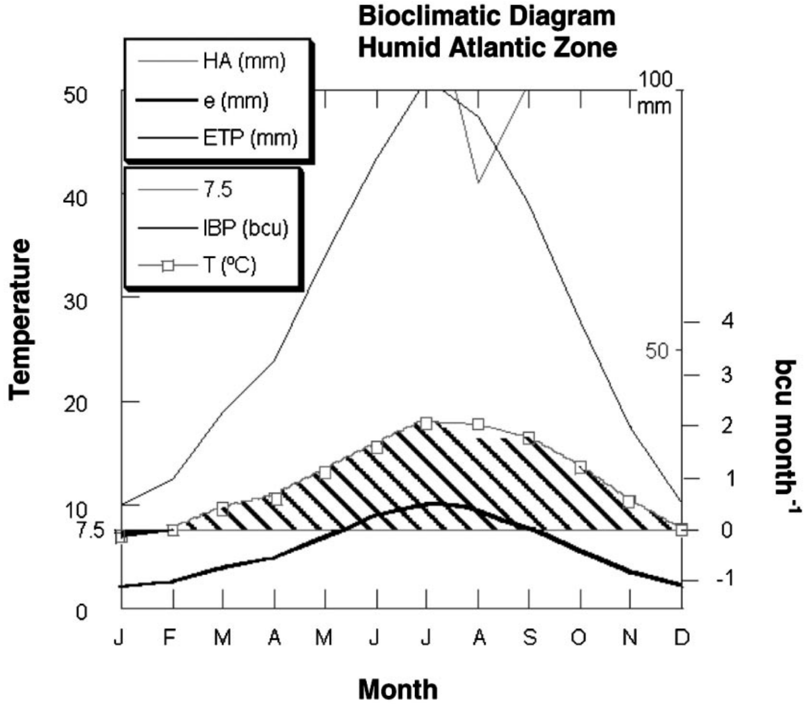
- Elementary composition is important for calculation of HHV.
- Heavy metals concentration, very helpful for:

  The study of environmental pollution evolution, because plants fix heavy metals along their vital cycles. Changes in heavy metals concentration reflect changes in environmental pollution.

  The high contents in Mn detected in the samples after the blooming period, as opposite to the rest of the elements to be studied, can be explained by the fact that this ion is necessary for the electronic transportation from the water to the photosystem

Table 1
Main characteristics [10] of the Atlantic humid zone in Galicia

Altitude	200–500 m
Annual rainfall index	1568 mm
Summer rainfall index	204 mm
Mean annual temperature	12.3°C
Mean daily maximum temperature of the warmest month (July)	32.5°C
Hydric deficiency	65 mm
Mediterraneanity index	1.4
Representative species (ICONA, 1993) of the zone:	
Traditional marsh	
Conifers	*P. pinaster Aiton, P. sylvestris L.,* and *P. radiata D.*
Principal hardwoods	*Q. robur L.*
Other hardwoods	*A. pseudoplatanus L., C. sativa Miller, A. glutinosa (L.) Gaertner, B. pendula Roth, S. atrocinera L., P. avium (L.) L.,* and *F. excelsior L.*
Bushes	Heath, *U. europaeus L., R. fructicosus L., P. aquilinum L.,* and *S. scoparius Link*
Modified marsh	
Conifers	*P. pinaster Aiton, P. sylvestris L.,* and *P. radiata D.*
Principal hardwoods	*Q. robur L.*
Other hardwoods	*A. pseudoplatanus L., E. globulus Labill., A. glutinosa (L.) Gaertner, B. pendula Roth,* and *S. atrocinera L.*
Bushes	Heath, *U. europaeus L., R. fructicosus L., P. aquilinum L.,* and *S. scoparius Link*



	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 (•C) E: evapotranspiration (mm) e: residual evapotranspiration (mm)
HA: hydric availability (mm) PBI: potential bioclimatic intensity (bcu)
FBI: free bioclimatic intensity (bcu) CBI: cold bioclimatic inte nsity (bcu)

Fig. 1. Bioclimatic diagram [3,4,10] of the studied humid Atlantic zone showing the most important bioclimatic indexes.

II (for the formation of an oxygen molecule, four electrons must be detached from two water molecules, i.e., dehydrogenation) [10].

Calorific values, HHV and LHV, are also in Table 2 in which can be seen:

- Conifers, *P. pinaster Aiton* (summer), *P. radiata D.* (autumn), and *P. sylvestris L.* (winter), show their maximum HHV in different seasons along the year. This can be understood as a natural self-defense mechanism. If HHV's of these species, taking up a surface of approximately 225,000 ha, should coincide in the same season the effects of fire would be catastrophic. These species are particularly dangerous in spring and summer because of their high flammabilities (4–5) and large HHV due to the presence of resins and essential oils with very high calorific values, around 40,000 kJ kg^{-1} [11].
- Bush species, taking up 253,000 ha, present their maximum HHV's distributed along the year.

Table 2
Mean high heating values (HHV)[a], mean low heating values (LHV)[a], moisture[b] in % (M), density in kg m^{-3} (D), ashes[c] in bomb after combustion in % (AB), and flammability (F) of the different species over the seasons of the year [13–15]

	HHV (kJ kg^{-1})	LHV (kJ kg^{-1})	M	D	AB	F
Acer pseudoplatanus L.						
Spring	17795.00±71.15 (0.40%)	6363.39±36.07 (0.57%)	49.31	890	4.62	3
Summer	17848.87±74.59 (0.42%)	5052.88±29.46 (0.58%)	60.50	820	2.67	5
Autumn	18436.86±27.10 (0.15%)	5498.27±11.86 (0.22%)	56.25	810	2.13	4
Winter	17834.93±12.05 (0.07%)	8747.26±7.11 (0.08%)	41.00	820	1.15	3
Alnus glutinosa (L.) Gaertner						
Spring	21090.77±121.96 (0.58%)	6051.73±46.89 (0.77%)	61.54	790	0.48	1
Summer	21073.82±90.45 (0.43%)	4020.92±26.54 (0.66%)	70.66	840	1.44	2
Autumn	20628.67±90.83 (0.44%)	5014.57±31.39 (0.63%)	65.44	800	0.24	1
Winter	19861.74±74.68 (0.38%)	6703.25±32.62 (0.49%)	56.32	800	0.24	1
Betula pendula Roth.						
Spring	20755.92±131.31 (0.63%)	6863.10±56.32 (0.82%)	57.14	770	0.46	1
Summer	21086.13±24.54 (0.12%)	6534.09±9.99 (0.15%)	59.30	850	0.86	2
Autumn	20522.94±64.04 (0.31%)	8668.47±32.97 (0.38%)	48.51	840	0.37	2
Winter	19837.35±147.49 (0.74%)	7696.54±71.36 (0.93%)	51.62	780	0.18	1
Castanea sativa Miller						
Spring	17460.78±58.86 (0.34%)	5363.19±24.68 (0.46%)	58.08	610	1.58	4
Summer	17436.71±86.35 (0.50%)	5458.14±36.71 (0.67%)	57.49	590	2.18	5
Autumn	17130.09±85.03 (0.50%)	8515.32±51.02 (0.60%)	40.00	590	1.71	5
Winter	18667.42±50.63 (0.27%)	7334.69±25.31 (0.35%)	50.00	600	0.30	4
Eucalyptus globulus Labill.						
Spring	18585.90±61.81 (0.33%)	6215.43±29.17 (0.47%)	52.80	640	1.37	4
Summer	20760.84±80.64 (0.39%)	6743.03±34.03 (0.50%)	57.80	620	1.56	4
Autumn	19142.75±81.41 (0.43%)	8210.82±42.66 (0.52%)	47.60	650	0.28	4
Winter	17539.08±64.72 (0.37%)	5510.48±28.01 (0.51%)	56.72	660	2.58	3
Fraxinus excelsior L.						
Spring	19303.09±65.97 (0.34%)	4705.13±23.17 (0.49%)	64.88	790	2.23	2
Summer	18975.23±69.62 (0.37%)	3644.84±21.14 (0.58%)	69.63	810	2.50	1
Autumn	18721.65±62.30 (0.33%)	6072.54±26.76 (0.44%)	57.05	810	0.86	1
Winter	18701.18±74.16 (0.40%)	8027.66±39.36 (0.49%)	46.93	800	1.09	1
Heath						
Spring	22728.69±200.97 (0.88%)	11217.66±115.33 (1.03%)	42.60	1030	0.36	2
Summer	21653.12±129.04 (0.60%)	13530.29±90.95 (0.67%)	29.52	990	0.21	5
Autumn	21981.18±144.32 (0.66%)	11370.59±86.59 (0.76%)	40.00	990	0.79	5
Winter	21636.56±68.73 (0.32%)	11853.58±43.62 (0.37%)	36.54	900	0.49	3
Pinus pinaster Aiton						
Spring	19480.91±35.41 (0.18%)	6524.59±15.47 (0.24%)	56.30	650	1.04	4
Summer	20658.80±61.11 (0.30%)	7645.81±28.42 (0.37%)	53.50	640	0.84	5
Autumn	20463.05±103.76 (0.51%)	5867.91±39.95 (0.68%)	61.50	640	0.91	4
Winter	20398.48±79.11 (0.39%)	6028.61±31.28 (0.52%)	60.46	630	0.71	3
Pinus radiata D.						
Spring	21047.31±48.04 (0.23%)	7885.54±22.42 (0.28%)	53.33	850	0.69	2
Summer	20203.93±52.38 (0.26%)	5995.51±20.81 (0.35%)	60.27	790	1.06	4
Autumn	21833.44±119.89 (0.55%)	7740.45±53.57 (0.69%)	55.32	870	0.78	3
Winter	21402.49±96.59 (0.45%)	7876.39±44.34 (0.56%)	54.09	910	0.61	3
Pinus sylvestris L.						
Spring	21965.26±50.21 (0.23%)	8074.83±23.08 (0.29%)	54.03	890	0.53	4
Summer	21653.86±48.38 (0.22%)	6994.47±20.12 (0.29%)	58.41	840	0.29	4

Table 2 (*Continued*)

	HHV (kJ kg^{-1})	LHV (kJ kg^{-1})	*M*	*D*	AB	*F*
Autumn	21619.80±61.44 (0.28%)	6332.93±23.78 (0.38%)	61.29	890	0.58	3
Winter	22155.57±41.72 (0.19%)	8452.04±19.69 (0.23%)	52.81	870	0.51	3
Prunus avium (L.) L.						
Spring	20074.46±130.24 (0.65%)	5856.94±51.19 (0.87%)	60.70	790	1.56	1
Summer	19724.55±8.58 (0.04%)	5568.44±3.31 (0.06%)	61.36	830	1.44	1
Autumn	19689.15±103.39 (0.53%)	8267.65±53.01 (0.64%)	48.73	880	1.84	1
Winter	19635.38±83.81 (0.43%)	7950.76±42.16 (0.53%)	49.70	800	0.85	1
Pteridium aquilinum L.						
Spring	17625.89±60.07 (0.34%)	3470.82±18.90 (0.54%)	68.53	760	2.26	1
Summer	18967.45±26.40 (0.14%)	7043.96±12.46 (0.18%)	52.80	750	2.16	5
Autumn	18420.05±65.90 (0.36%)	7827.05±34.52 (0.44%)	47.62	780	1.18	5
Winter	18639.07±56.54 (0.30%)	2749.46±15.53 (0.56%)	72.53	700	2.74	3
Quercus robur L.						
Spring	17627.15±45.37 (0.26%)	4297.04±17.53 (0.41%)	61.36	640	0.66	5
Summer	18541.90±78.72 (0.42%)	7794.56±41.09 (0.53%)	47.80	620	2.28	5
Autumn	17468.03±10.70 (0.06%)	6654.84±5.24 (0.08%)	51.00	630	1.42	4
Winter	18112.93±54.09 (0.30%)	5451.04±22.63 (0.42%)	58.16	640	2.53	4
Rubus fructicosus L.						
Spring	17777.51±11.11 (0.06%)	5490.01±4.67 (0.09%)	57.97	940	1.96	4
Summer	18059.86±30.88 (0.17%)	4141.73±10.60 (0.26%)	65.66	930	0.84	5
Autumn	18478.28±95.62 (0.52%)	4969.06±36.14 (0.73%)	62.20	950	1.23	4
Winter	19466.00±57.75 (0.30%)	6810.34±25.99 (0.38%)	55.00	880	1.44	2
Salix atrocinera L.						
Spring	20185.41±113.20 (0.56%)	7012.40±50.42 (0.72%)	55.46	810	1.18	1
Summer	21341.49±142.28 (0.67%)	7001.01±60.27 (0.86%)	57.64	800	0.75	2
Autumn	19670.47±106.03 (0.54%)	6952.53±48.12 (0.69%)	54.62	790	0.47	2
Winter	19030.75±115.67 (0.61%)	6694.03±52.27 (0.78%)	54.81	720	0.22	1
Sarothamnus scoparius Link.						
Spring	20533.91±46.04 (0.22%)	4698.03±15.34 (0.33%)	66.68	860	0.77	1
Summer	19019.07±93.92 (0.49%)	5031.57±35.07 (0.70%)	62.66	900	0.74	1
Autumn	20520.97±51.88 (0.25%)	8859.71±27.21 (0.31%)	47.55	870	0.15	2
Winter	20681.97±96.94 (0.47%)	5999.86±39.75 (0.66%)	59.00	640	0.32	2
Ulex europaeus L.						
Spring	20182.37±64.15 (0.32%)	5724.23±24.81 (0.43%)	61.32	830	0.68	1
Summer	20680.74±73.71 (0.36%)	6327.61±29.86 (0.47%)	59.49	860	0.73	2
Autumn	20950.41±87.82 (0.42%)	6901.04±37.33 (0.54%)	57.50	900	0.78	2
Winter	20488.22±81.39 (0.40%)	5726.12±30.93 (0.54%)	62.00	840	1.14	1

[a] Mean heat value±standard deviation of the mean.
[b] Moisture (%)=100×(initial weight of collected sample-weight of sample after drying)/initial weight of collected sample.
[c] Bomb ashes (%)=100×(weight of crucible and contents after combustion-weight of empty crucible)/weight of pellet.

- Usually, the lower the moisture content the higher the LHV. The energetic exploitation of forest resources is advisable coinciding with maximum LHV's. Taking into account the characteristics of the zone and based on rational exploitation criteria such as:

Bushes: 253,000 ha, 15 t ha^{-1}, 5 years between consecutive cuts, average LHV of 1910 kcal kg^{-1} (8000 kJ kg^{-1}).
Eucalyptus: 5000 ha, 15 years between consecutive cuts, 3500 trees per hectare, dry residues (leaves, branches less than 6 cm, and 3–6 cm in

Table 3
Chemical analysis and volatile metals [13–15]

	Chemical analysis (% of total composition)						Volatile metals (ppm)				
	N	C	H	O	S	Cl	Cu	Cd	Zn	Pb	Mn
A. pseudoplatanus L.											
Spring	2.66	45.45	13.04	38.70	0.15	–	13.12	1.13	28.15	1.01	891.32
Summer	1.77	45.00	5.99	46.93	0.23	0.08	18.13	1.65	39.00	1.65	2044.50
Autumn	1.95	47.92	12.42	37.61	0.10	–	17.12	1.10	41.80	4.10	160.30
Winter	2.01	46.96	5.97	44.88	0.18	–	7.82	1.06	24.37	7.20	90.00
A. glutinosa (L.) Gaertner											
Spring	2.07	51.65	6.59	39.62	<0.01	0.06	15.75	1.97	111.24	29.53	63.98
Summer	3.10	50.98	6.77	39.09	<0.01	0.06	17.90	0.99	84.55	6.96	13.93
Autumn	1.22	50.92	6.80	41.00	<0.01	0.05	9.77	<0.01	45.92	8.79	6.84
Winter	1.48	50.25	6.22	41.99	<0.01	0.05	14.19	2.03	95.39	19.26	49.67
B. pendula Roth.											
Spring	1.21	56.64	6.77	35.33	<0.01	0.05	14.11	2.02	109.86	21.17	36.28
Summer	1.99	51.54	6.71	39.71	<0.01	0.04	11.50	2.87	158.18	1.92	103.53
Autumn	0.81	47.59	6.31	45.25	0.01	0.03	9.36	<0.01	37.46	10.41	4.16
Winter	0.68	46.92	6.02	46.32	<0.01	0.04	39.12	1.86	149.95	18.63	37.25
C. sativa Miller											
Spring	0.86	45.60	5.84	47.49	0.16	0.05	8.03	3.20	35.33	2.10	63.70
Summer	1.98	45.71	5.89	45.97	0.26	0.19	160.72	1.96	25.50	3.92	4704.00
Autumn	2.53	47.16	5.96	44.24	0.11	–	9.31	1.35	30.21	3.21	1931.10
Winter	2.26	48.28	7.08	42.29	0.10	–	4.70	–	18.32	1.40	2212.31
E. globulus Labill.											
Spring	2.11	46.65	12.42	38.68	0.13	0.08	46.31	2.38	12.35	1.12	795.12
Summer	2.25	50.13	6.54	40.46	0.10	0.52	52.34	1.94	19.40	6.78	6390.00
Autumn	1.90	44.64	5.71	47.46	0.22	0.07	6.13	2.30	17.48	1.86	83.12
Winter	1.65	48.10	7.31	42.83	0.06	0.05	4.32	2.88	11.53	0.90	92.24
Fraxinus excelsior L.											
Spring	2.15	46.93	6.35	44.51	<0.01	0.05	20.66	1.97	122.99	13.77	5.90
Summer	2.45	47.18	6.26	44.07	<0.01	0.05	8.87	1.97	26.63	5.92	2.96
Autumn	1.42	47.18	6.09	45.25	<0.01	0.04	12.03	<0.01	24.05	1.01	22.05
Winter	1.16	46.67	6.44	45.66	<0.01	0.05	14.79	0.98	93.67	3.94	4.93
Heath											
Spring	1.63	53.26	6.23	38.71	0.12	0.05	31.00	<1.00	42.00	6.00	130.00
Summer	1.41	53.23	6.52	38.74	0.07	0.03	23.00	<1.00	17.00	13.00	172.00
Autumn	1.00	53.74	6.38	38.75	0.10	0.03	51.00	<1.00	117.00	20.00	59.00
Winter	1.68	55.51	7.06	35.64	0.08	0.03	14.00	<1.00	28.00	4.00	138.00
P. pinaster Aiton											
Spring	3.02	46.96	6.39	43.41	0.22	–	0.29	1.60	25.60	2.10	1206.30
Summer	1.88	49.74	6.40	41.57	0.15	0.26	36.55	1.00	38.90	1.80	1754.40
Autumn	2.01	50.26	6.01	41.58	0.14	–	13.10	3.21	28.30	1.61	1730.10
Winter	1.86	52.89	6.45	38.69	0.08	0.03	5.71	4.28	18.57	0.90	54.28
P. radiata D.											
Spring	1.35	49.50	6.19	42.84	0.12	<0.01	20.00	<1.00	59.00	1.00	167.00
Summer	1.47	48.72	6.41	43.33	0.07	<0.01	19.00	<1.00	44.00	9.00	86.00
Autumn	1.26	51.59	6.76	40.30	0.09	<0.01	31.00	<1.00	57.00	11.00	83.00
Winter	1.76	51.45	6.23	40.46	0.10	<0.01	22.00	<1.00	57.00	10.00	129.00
P. sylvestris L.											
Spring	1.44	51.55	6.96	39.94	0.11	>0.01	20.00	<1.00	109.00	4.00	86.00

Table 3 (*Continued*)

	Chemical analysis (% of total composition)						Volatile metals (ppm)				
	N	C	H	O	S	Cl	Cu	Cd	Zn	Pb	Mn
Summer	0.60	50.30	6.40	42.60	0.10	>0.01	14.00	<1.00	104.00	4.00	120.00
Autumn	1.04	50.61	6.34	41.91	0.10	>0.01	27.00	<1.00	75.00	10.00	42.00
Winter	1.65	53.09	6.88	38.30	0.08	>0.01	18.00	<1.00	52.00	8.00	87.00
Prunus avium (L.) L.											
Spring	2.09	50.43	6.37	41.06	<0.01	0.04	22.75	0.99	75.19	26.71	9.89
Summer	1.66	49.49	6.53	42.27	<0.01	0.04	12.67	1.95	64.34	7.79	2.92
Autumn	1.42	47.35	5.65	45.53	<0.01	0.04	12.37	<0.01	45.35	1.03	18.55
Winter	1.14	51.81	6.44	40.57	0.01	0.04	20.80	1.98	100.05	<1.00	5.94
P. aquilinum L.											
Spring	1.41	45.38	5.82	46.81	0.19	0.39	2.57	–	32.85	2.85	41.42
Summer	1.71	45.50	5.97	45.60	0.31	0.91	8.40	1.50	16.90	1.30	1963.10
Autumn	2.58	46.57	5.72	44.77	0.22	0.14	21.70	2.41	41.00	4.83	410.00
Winter	2.27	46.66	5.93	44.49	0.26	0.39	29.72	–	43.60	1.70	2140.00
Q. robur L.											
Spring	3.05	44.70	11.96	40.14	0.15	8.71	6.50	1.85	18.51	0.60	293.50
Summer	1.82	45.88	6.25	45.66	0.25	0.14	75.05	3.26	21.30	1.63	3100.00
Autumn	1.97	45.87	6.12	45.96	–	0.08	6.30	1.00	18.31	0.40	295.80
Winter	1.16	46.87	7.69	44.10	0.15	0.03	8.42	3.37	16.84	0.80	397.40
R. fructicosus L.											
Spring	1.73	47.22	6.13	44.58	0.16	0.18	16.71	1.67	16.71	0.80	10.00
Summer	1.71	45.64	6.05	46.23	0.14	0.23	44.30	1.00	26.30	1.10	1377.90
Autumn	2.97	46.21	5.98	44.53	0.13	0.18	18.00	–	24.00	54.00	1800.00
Winter	2.92	46.82	6.13	43.86	0.12	0.15	12.00	–	36.00	24.00	1840.00
S. atrocinera L.											
Spring	1.79	50.13	6.37	41.62	<0.01	0.07	17.18	2.02	119.27	40.43	44.47
Summer	1.89	52.00	6.79	39.25	<0.01	0.07	12.76	2.95	95.25	<1.00	62.85
Autumn	1.25	49.89	6.42	42.37	0.01	0.07	27.00	1.93	165.89	7.72	59.78
Winter	0.82	48.42	5.71	44.97	0.01	0.07	20.30	2.53	125.64	31.73	71.07
S. scoparius (L.) Link											
Spring	2.01	50.55	7.04	40.03	0.21	0.16	38.39	1.60	22.30	0.80	199.90
Summer	1.99	48.23	6.58	42.81	0.17	0.22	7.74	1.00	36.90	1.80	2756.70
Autumn	1.01	51.06	6.44	41.30	0.08	0.11	8.57	–	27.14	4.29	1600.00
Winter	4.84	46.20	11.53	37.34	0.09	0.11	4.30	–	44.00	1.43	3714.00
U. europaeus L.											
Spring	1.00	49.70	6.88	42.07	0.23	0.12	15.00	3.33	89.28	1.80	60.00
Summer	2.67	48.70	6.71	41.49	0.07	0.36	19.24	1.60	25.60	4.81	1218.00
Autumn	3.06	47.03	6.41	43.35	0.08	0.08	8.08	–	36.40	12.10	1778.50
Winter	2.80	48.96	6.53	41.41	0.12	0.18	32.00	–	42.00	6.00	1920.00

diameter branches): 56.12 kg per tree, average LHV of 1500 kcal kg^{-1} (6300 kJ kg^{-1}).

Pine trees: 223,000 ha, 17 years between consecutive cuts, 3000 trees per hectare, dry residues (leaves, branches with diameter less than 6 cm, 3–6 cm in diameter branches): 63.51 kg per tree, average LHV of 1600 kcal kg^{-1} (6700 kJ kg^{-1}).

Hardwoods: 130,000 ha, yearly cuts (forestry), 4000 trees per hectare, dry residues (only leaves): 2 kg per tree, average LHV of 1400 kcal kg^{-1} (5900 kJ kg^{-1}).

and assuming an efficiency of 25% for the total transformation from xyloenergy to electric energy, and US $0.1 kW h^{-1}, it could be obtained a yearly income of US $200 million which is approximately the total amount invested in Spain to prevent and fight forest fires. The disposal of the forest residues originated from different forestry campaigns must be performed in a rational way in order to avoid soil defertilization. For this reason, part of forest residues must be abandoned 'in situ'. This is of special interest in the case of hardwood formations which play an important role in the ecosystems. A controlled disposal of forestry remains, later turned into forest residues, leads both to an economic and to an ecological benefit. The ecological is a twofold benefit, on the one hand, bushes expansion could be controlled, on the other hand, the withdrawal of highly flammable materials, with high calorific values, mainly responsible for forest fires as they are easy to ignite and also easily spread fire.

- For calculation of fire risk indexes, the different bush and tree species were classified according to their HHV and flammabilities following the tables proposed by Doat and Valette [6], modified for our needs. The different HHV and flammabilities are shown in Table 2.

Related to HHV, the different forest species were classified as follows:

Class 1	HHV<18 500 kJ kg^{-1}
Class 2	18 500 kJ kg^{-1}<HHV<19 500 kJ kg^{-1}
Class 3	19 500 kJ kg^{-1}<HHV<20 500 kJ kg^{-1}
Class 4	20 500 kJ kg^{-1}<HHV<21 500 kJ kg^{-1}
Class 5	HHV>21 500 kJ kg^{-1}

Related to flammability:

Class 0	Very low flammability
Class 1	Low flammability
Class 2	Flammable
Class 3	Moderately flammable
Class 4	Very flammable
Class 5	Extremely flammable

The table corresponding to HHV was converted to the SI unit 'J' using 1 cal=4.1868 J. Original class limit numbers were also modified according to the characteristics of the different forest species existing in the zone.

Analysis of experimental data listed in Table 2 shows that species with large HHV such as: heaths, *U. europaeus L., S. scoparius Link*, and conifers present maximum HHV in spring, autumn, or winter coinciding either with minimum flammability values or with abundant rainfalls, medium temperatures, and high moisture contens, thus reducing the risk of fires. Table 2 shows also that the highest flammability values correspond to summer as a consequence of low environmental humidity and high temperatures.

Table 4 shows the different parameters used for calculation of the risk index [13–15] of one of the species studied (*E. globulus Labill.*). The study was made using 15 years old trees. The samples were collected in summer and winter. 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 depend on some other parameters. Again, the different numerical contributions are adscribed 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 $0.1\times0.8=0.08M$, 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 $0.5\times0.4\times0.5=0.1P$, 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

Table 4
Risk index calculation of one of the species (15 years old *E. globulus Labill.*) collected in summer and winter. For understanding of this table see the text

			Experimental values		Calculated values	
			Summer	Winter	Summer	Winter
Thermochemical parameters						
HHV class number			4	1		
Flammability class number			4	3	4	2
Physicochemical properties		10				
Density (kg m^{-3})		15	620	660		
Own moisture (%)		80	57.8	56.72		
Bomb ashes after combustion (%)		5	1.56	2.58		
					0.0197	−0.0443
Biological characteristics		20				
Physiological activity		10	Middle	Low		
Essential oils/resins		20	Middle	Middle-low		
Age		10	15	15		
Habit		10	Plantacion	Plantacion		
Forest waste generated		20	Low	Low		
Forest cover around		10	Middle	Middle		
Perennial/deciduous		10	P	P		
Blooming period		10	Summer	Summer		
					−0.0450	−0.0490
Climate characteristics		50				
Rainfall		40				
Monthly mean amount (mm)	50		12	241		
Periodicity	50		Low regular	Very regular		
Mean temperature (°C)		20	19.1	9.6		
Hydric availability (mm $month^{-1}$)		30	112	341		
Environmental humidity (% $month^{-1}$)		10	68	75		
					0.2315	−0.2535
Parameters depending on physical environmental conditions		20				
Zone wind		30				
Strength	50		Middle-low	Middle		
Periodicity	50		Regular-low	Regular		
Clouds		10				
Amount	50		Regular	Abundant		
Regularity	50		Low	Abundant		
Topography		20	Favorable	Favorable		
Sun radiation		10				
Sunshine (%)	50		Middle-high	Middle-low		
Sunny days	50		Middle-high	Middle-low		
Anthropic activity		30	Middle-low	Middle-low		
					0.0202	−0.0252
Risk index final value					4.23	1.63
Risk index class					4	2

consider the influence of own moisture content of *E. globulus Labill.* collected in summer. Analysis of Table 3 shows that moisture content for the different species in the zone goes from 70.70%, the most resistant to forest fire, to 29.50%, the most favorable to forest fire. The mean of these two values is 50.10% and the difference between them, 41.20%, which is normalized to unity. In our scale, 50.10% corresponds to zero, 70.70% corresponds to −0.5, the most resistant to forest fire, and 29.50% corresponds to +0.5, the most favorable to forest fire. Subtracting *E. globulus Labill.* summer moisture 57.80 from 50.10 renders −7.70 which in the normalized scale corresponds to −7.70/41.20=−0.19.

So the influence of *E. globulus Labill.,* in summer, to the risk index number is $0.08\times(-0.19)=-0.015$.

Same analyzes 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, 4.3, and this is the value used in our prevention studies. However, using the pessimistic point of view, this number could be rounded to the next higher 0.5-decimal number, 4.5.

In this study, the different forest species were arranged according to the following table:

Class 0 Risk index final value <0.5: no risk
Class 1 0.5<Risk index final value $\leq$1.5: no apparent risk
Class 2 1.5<Risk index final value $\leq$2.5: little risk
Class 3 2.5<Risk index final value $\leq$3.5: middle risk
Class 4 3.5<Risk index final value $\leq$4.5: high risk
Class 5 Risk index final value>4.5: extremely high risk

There are biological parameters with a strong influence on the risk index calculation. Some of them must be underlined such as:

- Age of the forest species. As the tree becomes old, part of the cellulose is progressively substituted by lignin with large HHV, approximately 26,000 kJ kg^{-1}.
- Generation of forest residues, with large HHV (19,000 kJ kg^{-1}), high flammability (4–5), and low moisture content (<30%) [12,13], very easy both to ignite and spread fire.
- Presence of resins and essential oils, with large HHV (40,000 kJ kg^{-1}), that in summer create highly flammable atmospheres.
- Blooming period, in which moisture contents are extremely high (young leaves, flowers, and abundant green parts), thus diminishing the risk of forest fires.

Combination of risk indexes and forest inventories leads to the design of risk index maps. These maps are

Table 5
General data used for calculation of risk indices [4]

Species	Surface (%)	HHV classes				Flammability				Risk indexes			
		Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
Traditional marsh													
P. pinaster Aiton	6	2	4	3	3	4	5	4	3	3	5	4	3
P. radiata D.	6	4	3	5	4	2	4	3	3	3	4	4	4
P. sylvestris L.	6	5	5	5	5	4	4	3	3	5	5	4	4
Conifers+Hardwoods	33	3	3	3	3	3	4	3	3	3	4	3	3
Other species	10	1	2	1	1	5	4	4	3	3	3	3	2
Bushes	39	4	4	4	4	1	3	3	2	3	4	4	3
Overall risk index of the zone										3	4	4	3
Total occupation=trees (54.9)+bushes (35.1)+no forestry (10)=100%													
Modified marsh													
E. globulus Labill.	1	2	4	2	1	4	4	4	3	3	4	3	2
P. pinaster Aiton	16	2	4	3	3	4	5	4	3	3	5	4	3
P. radiata D.	1	4	3	5	4	2	4	3	3	3	4	4	4
P. sylvestris L.	1	5	5	5	5	4	4	3	3	5	5	4	4
Conifers+Eucaliptus	20	2	4	3	3	4	5	4	3	3	5	4	3
Conifers+Hardwoods	3	2	4	2	3	4	5	2	3	3	5	4	3
Other species	13	1	2	1	1	5	4	4	3	3	3	3	2
Bushes	45	4	4	4	4	1	2	2	2	3	3	3	3
Overall risk index of the zone										3	4	3	3
Total occupation=trees (46.7)+bushes (38.3)+no forestry (15)=100%													

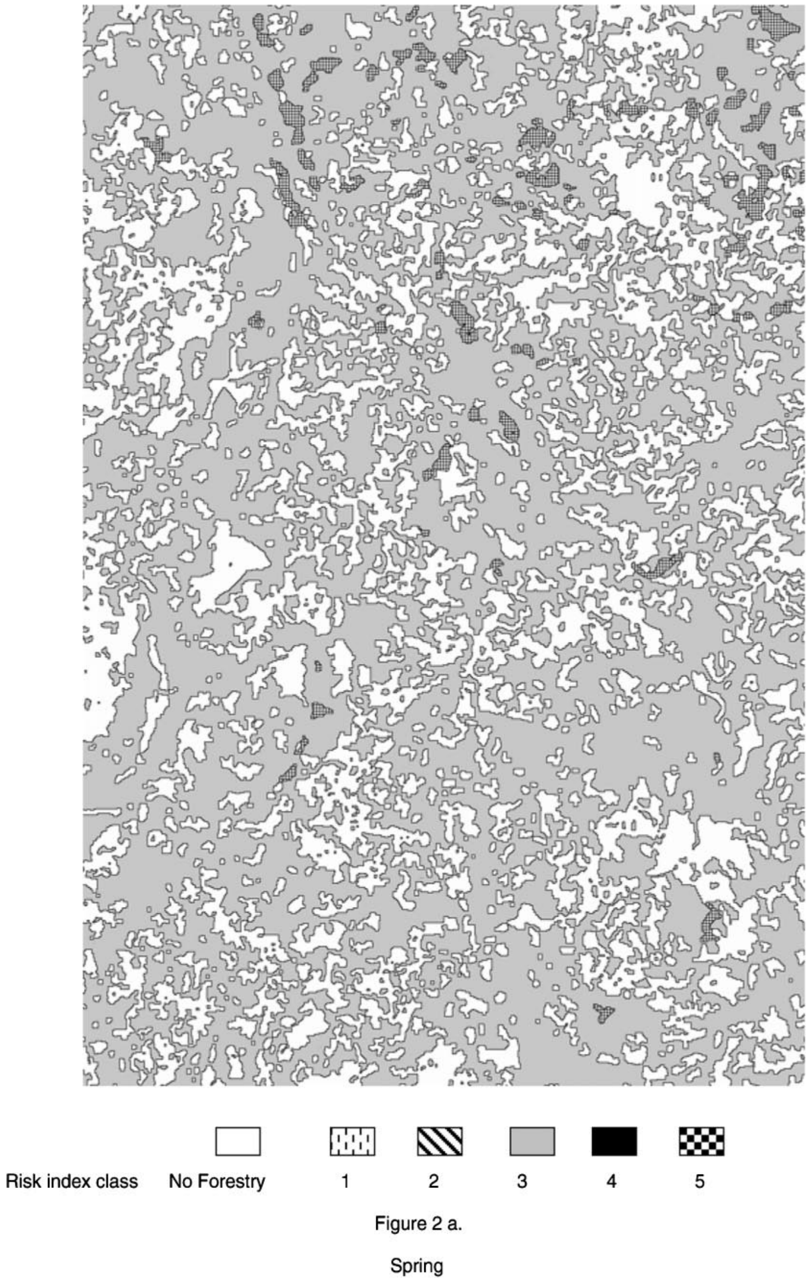


Fig. 2. Mean risk indexes evolution along the year of the humid Altantic zone of Galicia.

very easy understandable and they are very useful to prevent and/or fight forest fires effectively. Fig. 2 shows the risk index map evolution of the studied zones along the year.

Table 5 shows surface take up percentage, HHV, flammabilities, and risk indexes of the different forest formations existing in the studied zone.

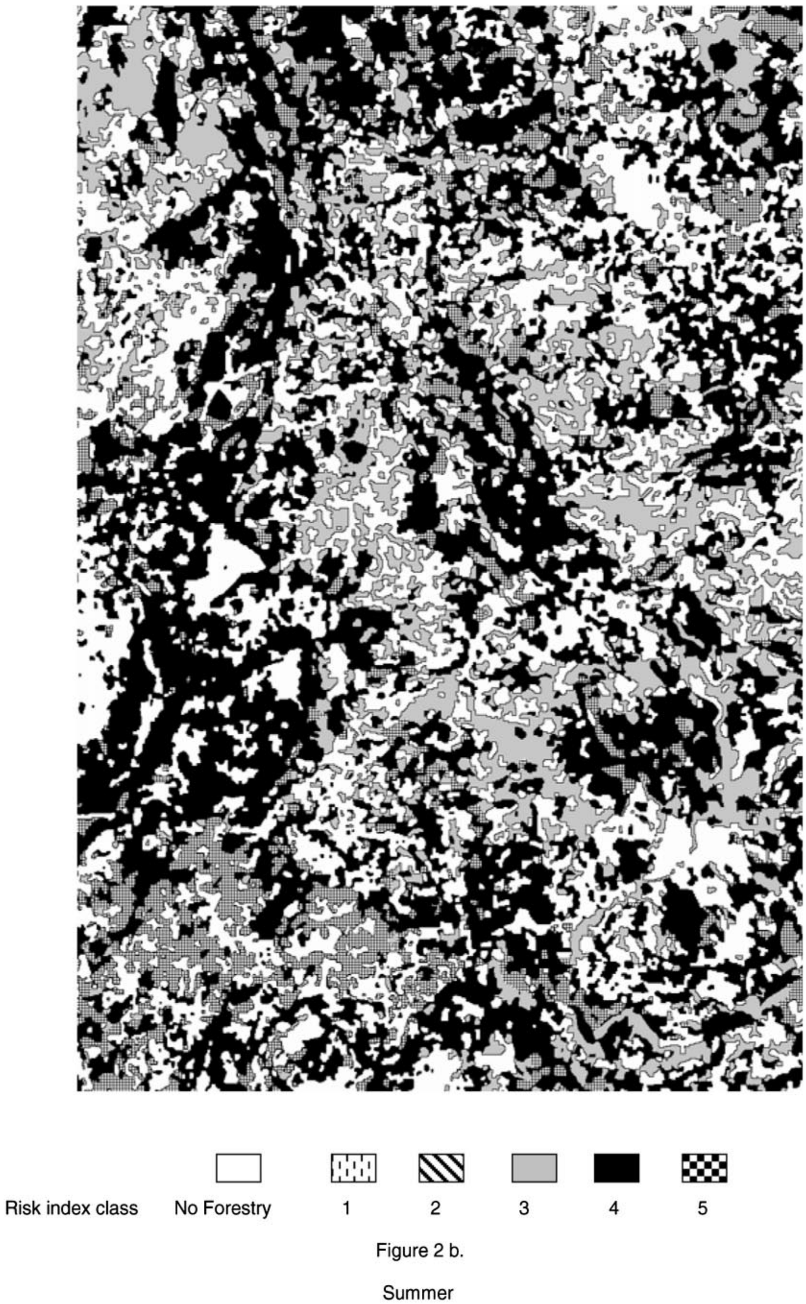


Fig. 2. (*Continued*)

In this table, it can be seen that bushes take up surface increased in the modified zone to the detriment of hardwood species. The cause of this transformation is the gradual abandonment both of farm work and forestry in favor of reforestation with species more important from the economical point of view. It can be seen also the significant increase of *P. pinaster Aiton* in the modified zone as a consequence of the impor-

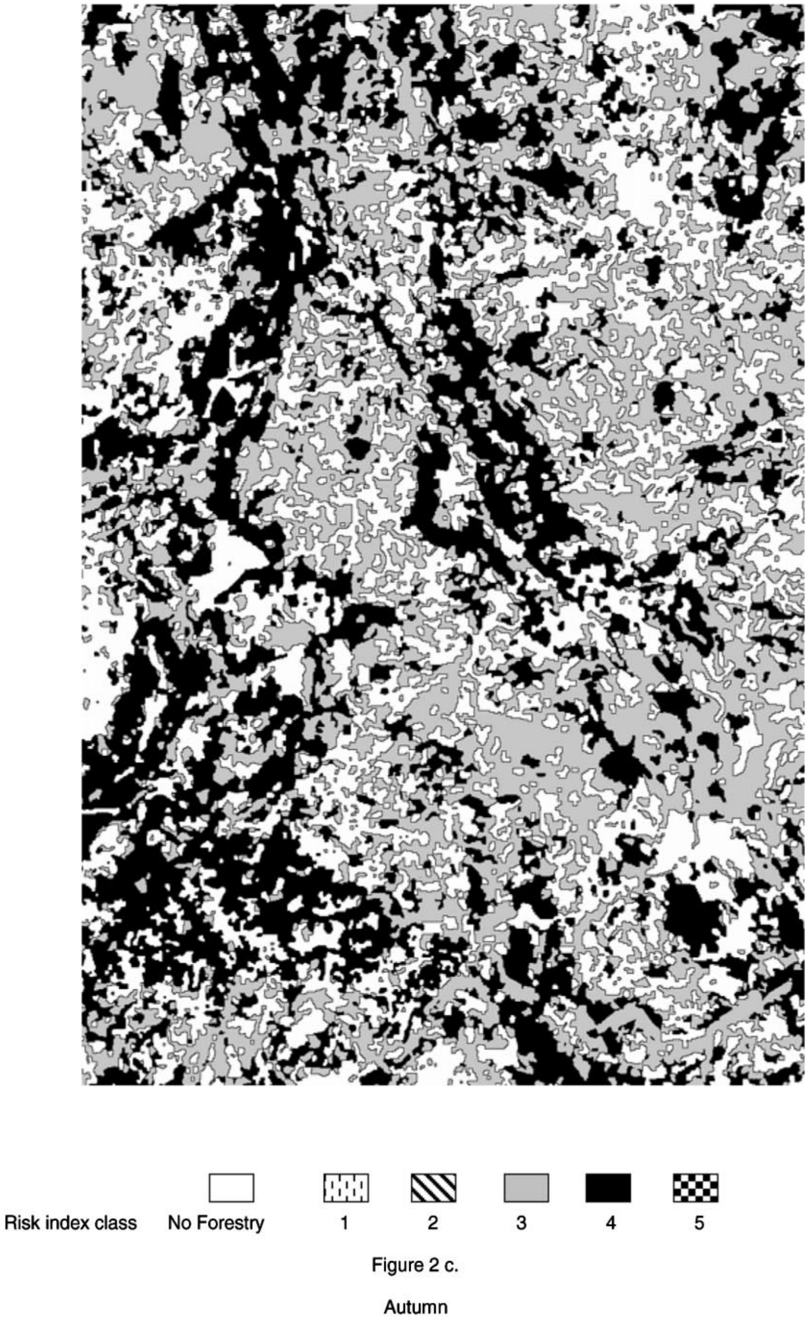


Fig. 2. (*Continued*)

tance of this species for wood pulp production. It must be noticed the appearance of *E. globulus Labill.* that has developed an important increase in the taking up surface.

Fig. 3 shows risk index evolution of the studied zones, traditional marsh and modified marsh, along the year.

Due to the fact that no forestry works are performed in the traditional marsh zone, the accumulation of

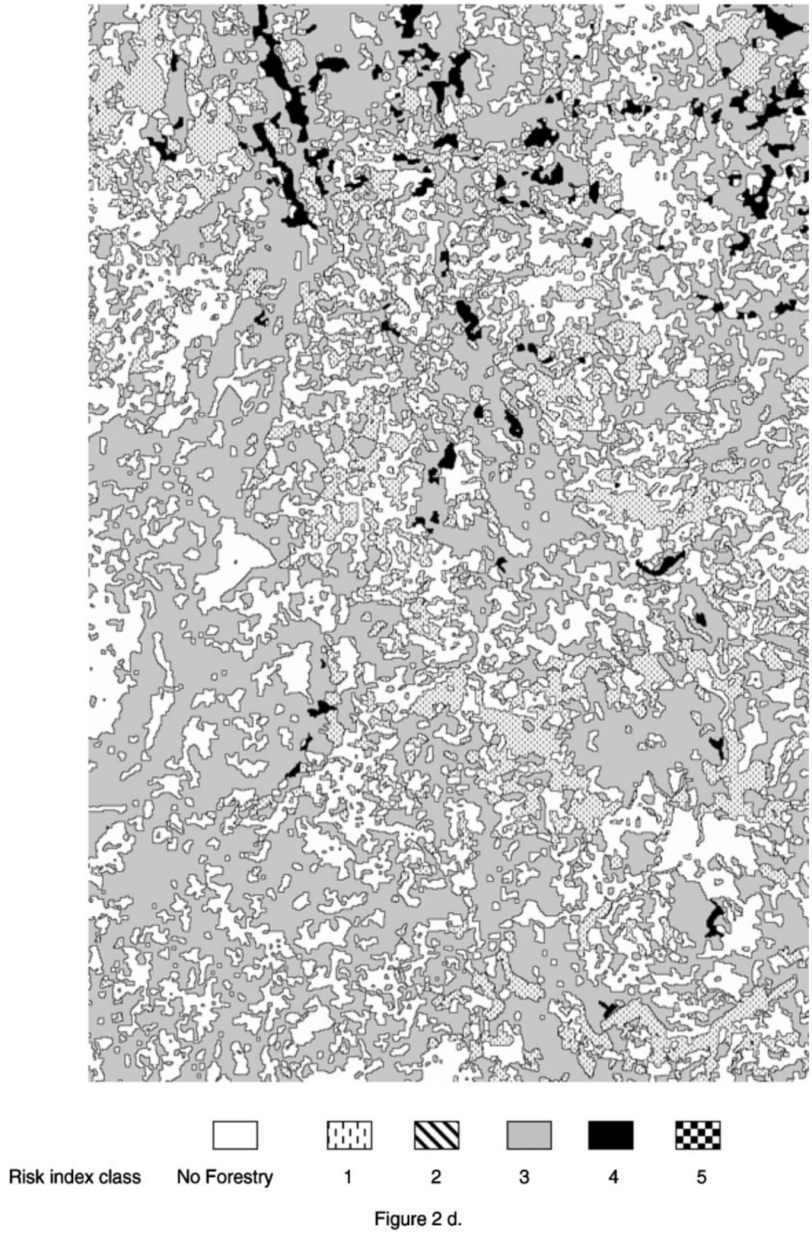


Fig. 2. (*Continued*)

forest residues, the abundance of hardwoods, and the presence of bushes mixed with trees, thus creating natural aeration channels, make this zone to present a risk index 4 in spring and autumn, while in the modified marsh zone, with scarcity of forest residues and controlled wood exploitation, the risk index in these seasons is 3.

In the whole zone, bioclimatic characteristics and bushes species distribution markedly influence the behavior of the forest biomass. As a conclusion, it can be said that this is a high risk zone for forest fires which should be protected through forestry prevention campaigns because, in case of fire, the consequences could be disastrous due to its heavy energetic load.

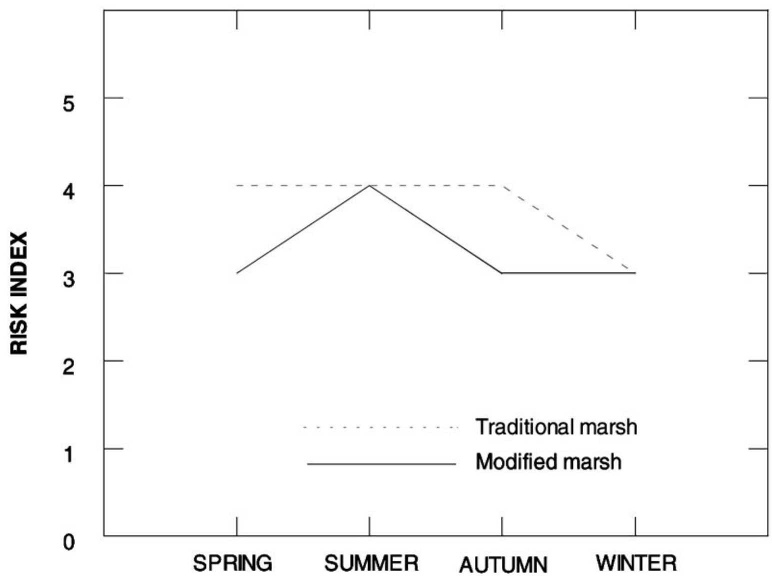


Fig. 3. Risk index evolution of the studied zones, traditional marsh and modified marsh, along the year.

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References

[1] C. Chandler, P. Cheney, P. Thomas, L. Trabaud, D. Williams, Fire in Forestry, Krieger Publishing Company, Malabar, FL, 1991.
[2] H. Water, E. Harnickell, D. Mueller-Dombois, Climate-diagram Maps, Springer, Berlin, Heidelberg/New York, 1975.
[3] J.L. Montero de Burgos y, J.L. González Rebollar, Diagramas Bioclimáticos, ICONA, Madrid, 1983.
[4] Ministerio de Agricultura, Pesca y Alimentación, Segundo Inventario Forestal Nacional, 1986–1995, ICONA, Madrid, 1993.
[5] Consellería de Agricultura, Gandería e Montes, Dirección xeral de montes e medio ambiente natural, plan forestal de Galicia, in: S.L. Sesfor (Ed.), Estudios e Iniciativas Forestales, Santiago de Compostela, 1992.
[6] J.Ch. Valette, Documentos del seminario sobre métodos y equipos para la prevención de incendios forestales, ICONA, Madrid, 1988.
[7] D. Wagman, W. Evans, V. Parker, R. Schumm, L. Halow, S. Bailey, K. Churney, R.J. Nuttall, Phys. Chem. Ref. Data 11 (1982) Supplement 2.
[8] W. Hubbard, D. Scott, G. Waddington, in: F.D. Rossini (Ed.), Experimental Thermochemistry, Interscience, New York, 1956, p. 5.
[9] Consellería de Agricultura, Gandería e Montes Xunta de Galicia, Resumo de Datos Climatolóxicos de Rede das Estacións do Centro de Investigacións Forestais de Lourizán 1955–1994, Xunta de Galicia, Santiago de Compostela, 1995.
[10] A. Lehninger, in: S.A. Omega (Ed.), Bioquímica, Barcelona, 1979.
[11] J.A. Rodríguez Añón, F. Fraga López, J. Proupín Castiñeiras, J. Palacios Ledo, L. Núñez Regueira, Bioresource Technol. 52 (1995) 269.
[12] J. Rodríguez Añón, M. González, F. Fraga, J. Palacios, L. Núñez, J. Thermal Anal. 41 (1994) 1393.
[13] L. Núñez-Regueira, J. Proupín Castiñeiras, J. Rodríguez Añón, Bioresource Technol. 57 (1996) 283.
[14] L. Núñez-Regueira, J. Rodríguez Añón, J. Proupín Castiñeiras, Bioresource Technol. 61 (1997) 111.
[15] L. Núñez-Regueira, J. Rodríguez Añón, J. Proupín Castiñeiras, Bioresource Technol. 69 (1999) 23.