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Calculation of forest biomass indices as a tool to fight forest fires

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Abstract

Wildfires are mainly responsible for economical and ecological disasters both in forests and forest resources all over the world. In this article, we report a method which allows the calculation of risk indices to be used in campaigns designed for preventing and/or fighting forest fires. The method is based on the determination of calorific values using a static bomb calorimeter in oxygen atmosphere following the procedure given by Hubbard et al. [in: F.D. Rossini (Ed.), Experimental Thermochemistry, Interscience Publishers, New York, 1956, p. 5] and flammabilities using the method proposed by Valette [Documentos del seminario sobre métodos y equipos para la prevención de incendios forestales, ICONA, Madrid, 1988]. A combined study of thermochemical data and bioclimatic parameters allowed the calculation of risk indices for the different species making up the forest vegetation of a zone situated in the coast of Galicia (NW Spain). These risk indices can be presented in the form of maps and, thus, be used to prevent and/or fight forest fires. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Forest fires; Calorific values; Flammability; Bioclimatic diagram; Xyloenergy; Risk index

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1. Introduction

Approximately 550,000 ha [1] of the coast of Galicia (NW Spain) are occupied by different forest species. The more abundant species, *Eucalyptus* (90,000 ha) and conifers (250,000 ha) are used mainly for production of wood pulp. The remaining forest biomass of the zone is composed of different bush species (190,000 ha) and hardwood species (20,000 ha).

In the last 25 years, the forest occupied surface of the zone was reduced by around 300,000 ha due to a huge number of forest fires which devastated total or partially different parts of the area. Approximately 95% of these forest fires were directly caused by accidental or deliberately performed anthropic activities. Because of these fires, the Atlantic coast of Galicia is suffering a desertification process.

This situation is common all over the world and for this reason, preventing and fighting forest fires became a main task. Calculation of risk indices of the different species which make up the woodland map of a given zone plays an important role in these kind of strategies [2,3]. In the present study, the risk indices of the different species which make up the woodland map of the coast of Galicia were calculated. The knowledge of risk indices; i.e. the energetic state of the forest species gives information about the possibility of these

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species to start and spread forest fires. A combined study of risk indices and forest inventories of the zone lead to the design of risk index maps to be used to prevent and/or to fight forest wildfires.

The method followed in this study can be extended all over the world providing the knowledge of the forest species fuel load, and bioclimatic parameters over the year of the different regions [4].

Calculation of risk index needs the knowledge of different factors; such as calorific values, flammability, physico-chemical parameters, bioclimatic parameters, and biological parameters characteristic of every species.

- Calorific value, i.e. the amount of energy released by each unit of combustible mass. Two calorific values must be differentiated. The higher heating value (HHV) is the amount of energy released by complete combustion of a mass unit of sample at constant volume in an oxygen atmosphere assuming that the final products of combustion consist of O_2, CO_2, SO_2, and N_2 in gas phase together with water that contained in the sample and that generated from the combined hydrogen, in liquid form. This calorific value can be determined experimentally in the laboratory and because of that is one of the two main parameters used for calculation of risk indices. For a given forest species, this value depends on the zone and season. The lower heating value (LHV) can be calculated assuming that the water in the products remains in the form of vapor. The knowledge of LHV gives a realistic idea about the magnitude of a fire and becomes an index to quantify both the spread to neighboring surfaces and the virulence of forest fires. Also, the knowledge of LHV is very helpful to evaluate forest resources and to choose the best moment for their rational energetic exploitation.

  Both calorific values are related through the equation

  $$\mathrm{LHV_d} = \mathrm{HHV_d} - 24.42(9H_\mathrm{d})$$

  where $\mathrm{LHV_d}$ (kJ kg^{-1}) corresponds to the lower calorific value of the dry sample, $\mathrm{HHV_d}$ (kJ kg^{-1}) 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 mass of water formed during combustion is nine times the hydrogen content.

  Fireline intensity can be calculated using the following equation [5,6]:

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

  where I (kW m^{-1}) is the fireline intensity, i.e. the product of the available heat of combustion per unit area of ground and the rate of spread of the fire, W (kg m^2) the fuel loading, i.e. the oven dry weight of fuel per unit area, and v (m s^{-1}) is the rate of spread.
- Flammability, i.e. the resistance of a given species to catch and spread fire. It depends on the nature of the fuel and the moisture level, both of the material and of the ambience. It is a key factor when planning fire extinction strategies.
- Physico-chemical parameters, such as moisture, density, ash percentage after bomb combustion, elementary chemical composition, heavy metal contents, etc.
- Bioclimatic parameters, such as environmental temperature, pluviosity, hydric availability, evapotranspiration, etc.
- Different species own biological parameters, such as blooming period, resin and/or essential oils content, age, etc.

The different parameters were measured using, a static bomb calorimeter (HHV), a standard epiradiator (flammability), a Carlo Erba elementary analyzer (elementary composition), and a Perkin-Elmer atomic absorption spectrophotometer (heavy metals).

2. Experimental

For all the species studied, the samples were collected from a previously chosen 1 ha of forest. The plot was divided into 1 m^2 sites, five of which were randomly chosen. From every site, bulk samples consisting of branches having diameters not greater than 6 cm, bark, leaves, fallen fruits, etc. originated from pruning, cuts of trees, and, in general, forestry works were collected. All bulk samples from the five sites were reduced by a coning and quartering procedure to a representative sample of about 1 kg. This sample corresponds to residues abandoned in the forest.

Living parts of the different forest species were also collected. In the case of *Eucalyptus globulus* Labill. and *Pinus pinaster* Aiton, one standard representative tree corresponding to each species formation in the zone was chosen and then cut down. From this tree, samples consisting of fruits, leaves, long branches having a diameter greater or equal than 6 cm, and branches having a diameter not greater than 6 cm were collected. After grinding, the samples were mixed and then reduced by a coning and quartering procedure to a final representative sample of about 1 kg. Living parts were used for infrared analyses, while residue samples were used for energetic evaluation.

Once collected, the samples were stored in hermetically closed polyethylene bags in order to minimize loss of moisture which is a key parameter to determine calorific values.

Part of the sample was used for flammability experiments, following the procedure proposed by Valette [7], using a standard epiradiator of 500 W constant nominal power (UNE-23-721). Flammability values are average of 75 measurements performed on samples of same species.

The remaining sample was dried in a natural convection Selecta 200210 stove for 12 h at 105°C. Moisture was determined as the weight loss after the drying process, the material was weighed to 0.1 or 1.0 g using a double-scaled Salter EP-22KA balance.

After drying, the 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. A first part of this ground sample was used to determine density and average chemical composition of each of the species being studied. Elementary composition (C, H, O, N, and S) was determined using a Carlo Erba analysis equipment. Heavy metals (Cd, Cu, Zn, Pb, Mn, and Cl) were determined by a Perkin-Elmer atomic absorption spectrophotometer. A second fraction of the ground sample was used to determine calorific values and ash percentages after combustion of the different species.

Calorimetric experiments were performed according to the procedure described by Hubbard et al. [8]. Sample pellets of about 1 g size [9] were situated in a stainless steel crucible introduced into a Parr-1108 sealed static bomb calorimeter made of a special stabilized stainless steel. This material can successfully resist the attack of the acids originated during the

Table 1
Main characteristics [4] of the coast of Galicia

Altitude (m)	0–300
Annual rainfall index (mm)	1100–1427
Summer rainfall index (mm)	550–141
Mean annual temperature (°C)	13–14.2
Mean daily maximun temperature of the warmest month (July) (°C)	28–32
Hydric deficiency (mm)	130–174
Mediterraneanity index	1.93–2.24
Representative species [1] of the zone	
North coast	
Conifers	*P. pinaster* Aiton, *P. sylvestris* L. and *P. radiata* D.
Principal hardwoods	*Q. robur* L. and *E. globulus* Labill.
Other hardwoods	*A. pseudoplatanus* L., *C. sativa* Miller, *A. glutinosa* (L.) Gaertner, *B. pendula* Roth, *S. atrocinera* L., and L. *nobilis* L.
Bushes	Heath *U. europaeus* L., *R. fructicosus* L., *P. aquilinum* L. and *S. scoparius* Link.
South coast	
Conifers	*P. pinaster* Aiton, *P. sylvestris* L. and *P. radiata* D.
Principal hardwoods	*Q. robur* L. and *E. globulus* Labill.
Other hardwoods	*A. pseudoplatanus* L., *A. glutinosa* (L.) Gaertner, *B. pendula* Roth, *S. atrocinera* L., and *F. Excelsior* L.
Bushes	Heath, *U. europaeus* L. *R. fructicosus* L., *P. aquilinum* L. and *S. scoparius* Link.

combustion reactions taking place in the bomb. The solid samples, in pellet form, were ignited at (298.150 ± 0.001) K in oxygen 99.99995% pure at 3.04 MPa with 1 ml of water added to the bomb. The electrical energy for ignition was determined from the change in potential difference across a 2900 μF capacitor when discharged from 40 V through the platinum ignition wire. Samples, different wires, cotton thread, and crucible were weighed using a Sartorius R200D balance (sensitivity 0.01 mg). 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 calorimeter water was measured to 10^{-4} K at intervals of 15 s using a stable and sensitive platinum resistance 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 temperature controller (TRONAC PTC-41) with a precision of 0.003°C over a week.

Calorific values shown in different tables are average of four experiments carried out using each forest species samples.

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 Ltd., having a specific energy of combustion under standard bomb conditions of $26431.8 \pm 3.7\ \mathrm{J\ g^{-1}}$. From five calibrations done with the bomb, the energy equivalent of the calorimeter was determined to be $E_{\mathrm{calor}} = 22402.5 \pm 1.9\ \mathrm{J\ K^{-1}}$ (0.0085%) where the uncertainty quoted is the standard deviation of the mean.

The rise in temperature was corrected for stirring and exchange heating.

3. Results and discussion

The main bioclimatic characteristics of the coast of Galicia, as well as the representative forest species existing in the zone are shown in Table 1. For a better comprehension, due to bioclimatic differences, the coast zone was divided in two parts: north and south coast. All the data reported in Table 1 are represented in the form of the bioclimatic diagram [10] shown in Fig. 1, where 7.5°C is the temperature below which no stable vegetative production is possible.

Chemical analysis of the samples of this study are listed in Table 2. In this table, elementary analysis (C, H, O, N, S, and Cl) important for HHV calculation, and heavy metals content (Cu, Cd, Zn, Pb, and Mn) are reported. High contents in Mn, compared to the other elements studied are observed. Highest Mn contents

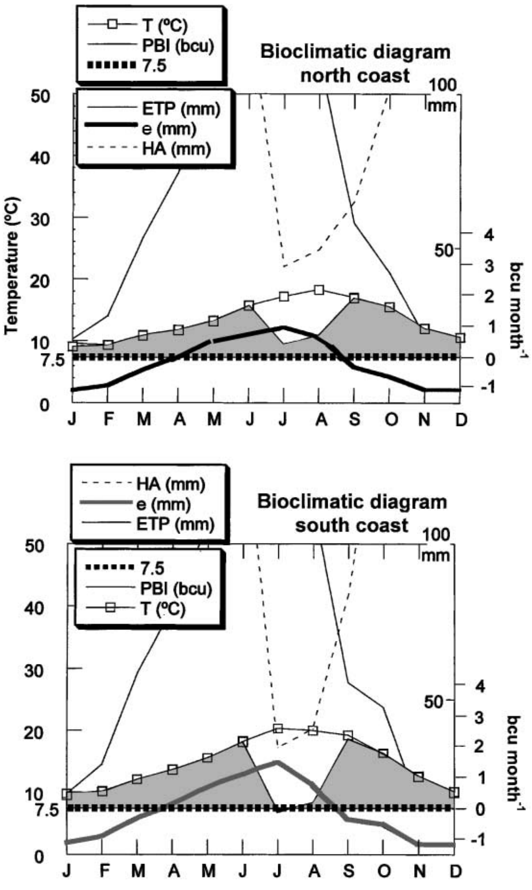


Fig. 1. Bioclimatic diagrams showing the main environmental characteristics of the two coast zones of Galicia (NW Spain): T (temperature in °C), ETP (evapotranspiration in mm), e (residual evapotranspiration in mm), HA (hydric availability in mm), and PBI (potential bioclimatic intensity in bcu). Shaded areas correspond to vegetative production periods (1 bcu = 5°C × 1 month).

Table 2
Chemical analysis and volatile metals [15–18]

	Chemical analysis (percentage of total composition)						Volatile metals (ppm)				
	N	C	H	O	S	Cl	Cu	Cd	Zn	Pb	Mn
Acer 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
Alnus 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
Betula 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
Castanea 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
Eucalyptus 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
Laurus nobilis L.											
Spring	2.14	49.99	6.52	41.31	<0.01	0.03	21.11	1.92	86.36	24.95	32.63
Summer	2.04	50.76	6.51	41.11	<0.01	0.03	15.67	2.94	88.16	<1.00	1.96
Autumn	1.52	46.19	6.35	45.91	<0.01	0.03	258.69	<0.01	21.32	6.49	70.46
Winter	2.04	48.82	6.64	42.46	0.01	0.03	27.25	2.02	126.17	11.10	34.32
Pinus 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

Table 2 (*Continued*)

	Chemical analysis (percentage of total composition)						Volatile metals (ppm)				
	N	C	H	O	S	Cl	Cu	Cd	Zn	Pb	Mn
Pinus 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
Pinus 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
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
Pinus 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
Quercus 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
Rubus 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
Salix 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
Sarothamnus 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
Ulex 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

correspond always to the blooming period of the different forest species. This may be understood by the need for this ion in the electron transfer from the water as electron donor to the photosystem II (for the formation of one oxygen molecule, four electrons must be separated from two water molecules). This process needs the presence of Mn^{2+} and chloride ions [11].

Moisture, density, and bomb ash after combustion are shown in Table 3. These data are very valuable for

Table 3
Mean high heating values (HHV), mean low heating values (LHV), moisture in percentage (*M*), density in kg m^{-3} (*D*), ashes in bomb after combustion in percentage (AB), and flammability (*F*) of the different species over the seasons of the year [15–18][a]

	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
Laurus nobilis L.						
Spring	20276.01 ± 88.13 (0.43)	4620.31 ± 29.24 (0.63)	66.82	800	1.28	4
Summer	20810.72 ± 46.82 (0.22)	4857.66 ± 15.66 (0.32)	66.55	760	1.49	5
Autumn	19668.90 ± 76.83 (0.39)	6155.12 ± 31.88 (0.52)	58.50	780	0.97	5
Winter	20082.60 ± 131.02 (0.65)	6976.18 ± 58.58 (0.84)	55.29	760	0.79	4
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

Table 3 (*Continued*)

	HHV (kJ kg^{-1}) (%)	LHV (kJ kg^{-1}) (%)	*M*	*D*	AB	*F*
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
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
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

Mean heat value ± standard deviation of the mean = 20488.22 ± 81.39 (0.40%)

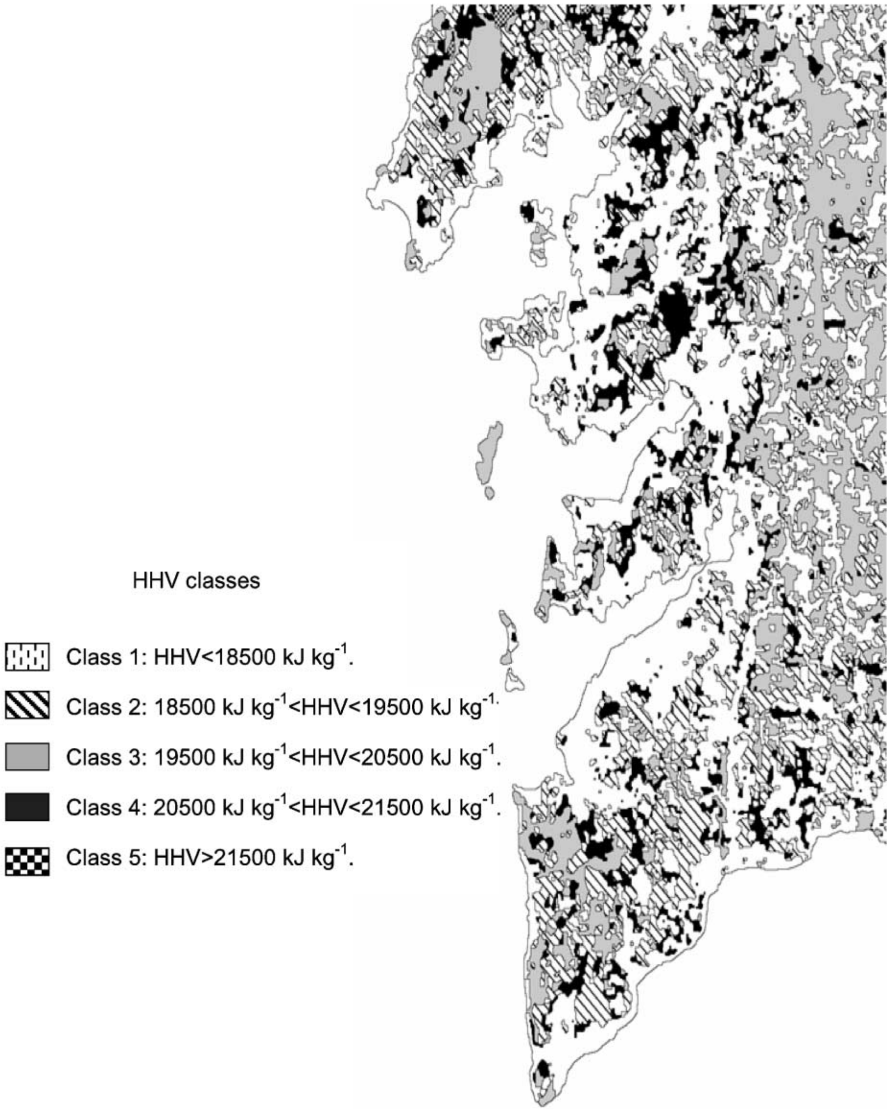
[a] Moisture (%) = 100 × (initial weight of collected sample − weight of sample after drying)/initial weight of collected sample. Bomb ashes (%) = 100 × (weight of crucible and contents after combustion − weight of empty crucible)/weight of pellet.

a better interpretation of calorific values. It can be seen, on the one hand, the close relationship between LHV and moisture content (the lower the moisture content the greater the LHV) and, on the other hand, HHV and ash content (the lower the ash content the greater the HHV).

Table 3 also shows average HHV and LHV over the seasons of the year corresponding to the different forest species in the zone. From this table, it can be concluded that

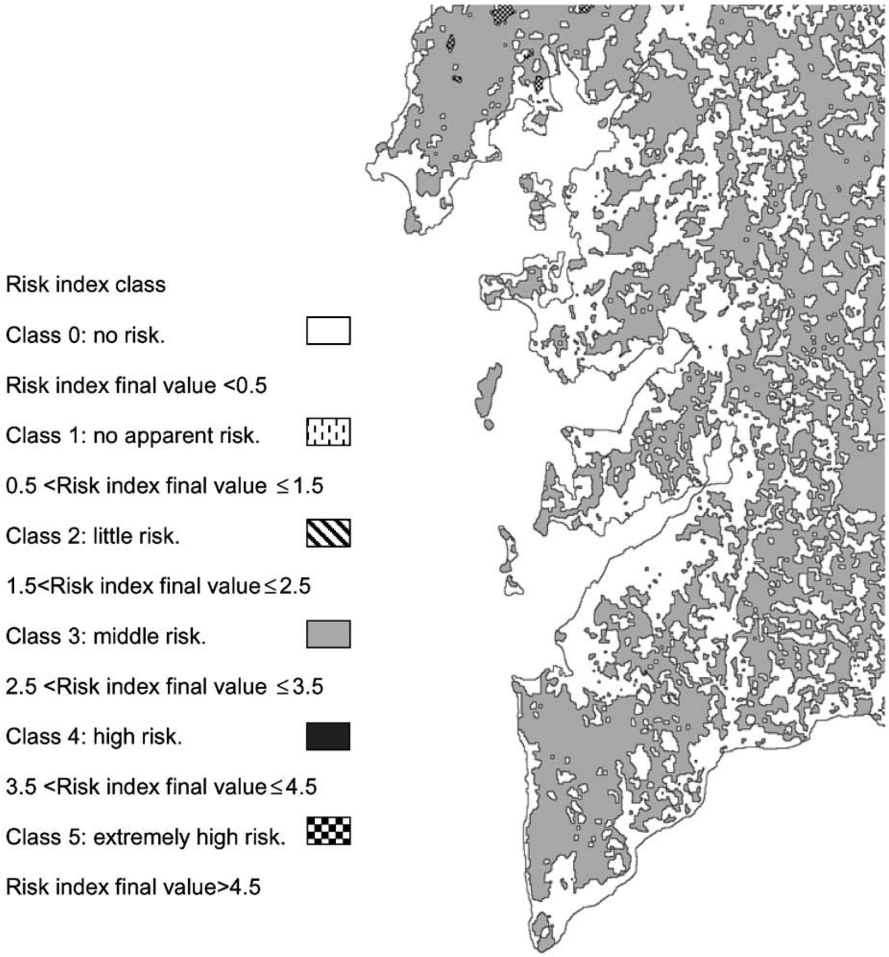
- Highest LHV correspond to lowest moisture contents. Usually these values are observed in autumn or winter. These seasons are the most favorable for energetic exploitation of forest resources.

This energetic exploitation would be mainly based on collection of the forest residues originated by different forestry works (bark, leaves and branches having diameters not greater than 6 cm) and also from periodical cuts of huge extensions of bushes with a yearly productivity of 3 t ha^{-1}. The collection of waste biomass must be done carefully to avoid damage to soil which could start defertilization and degradation of the zone. A rational exploitation of forest residues lead to a two-fold benefit, on the one hand, the disposal of forest residues which are



(a)

Fig. 2. Map of energy distribution in the coast zone of Galicia over the year.



Spring

(b)

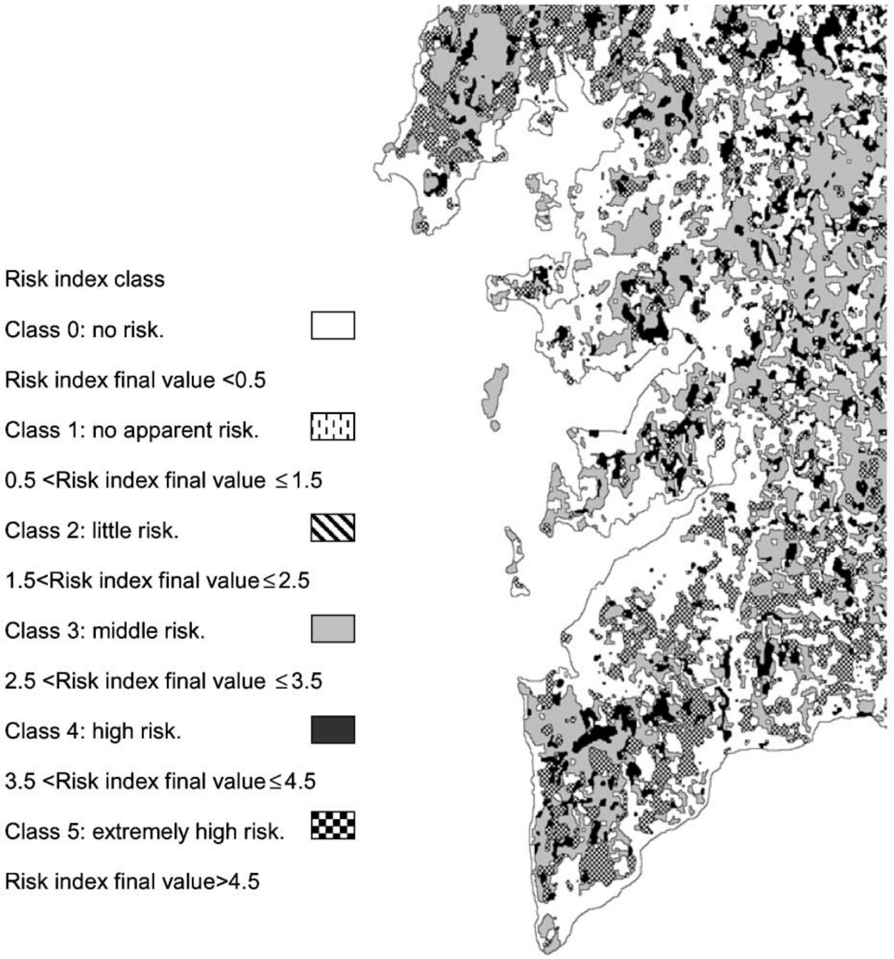
Fig. 2. (*Continued*)

mainly responsible for forest fires because they are easy to ignite and also rapidly spread fire. Nowadays, these forest residues having average LHV of 6800 kJ kg^{-1} (average HHV of 19759 kJ) and flammabilities close to 5 due to their low moisture content (30%) [12,13], as well as bush remains are abandoned on the forest without any control.

On the other hand, the energetic exploitation of this resources could lead in Galicia to a yearly production of 2.70×10^8 kW h; i.e. 120 millions dollars which is approximately 60% of the investment to fight forest fires in Spain.

The knowledge of LHV and forest inventory allows the design of energetic maps. Fig. 2 shows the energetic map of the coast zone of Galicia over the year.

- Conifers showed the highest HHVs as a consequence of the great amount of resins generated by these species mainly in spring and summer. These resins have large HHV (40,000 kJ kg^{-1}) and high flammability (5) [14]. Forest species were classified according to their HHV following the tables proposed by Valette [7] which were modified taking into account the realistic values of calorific



Summer

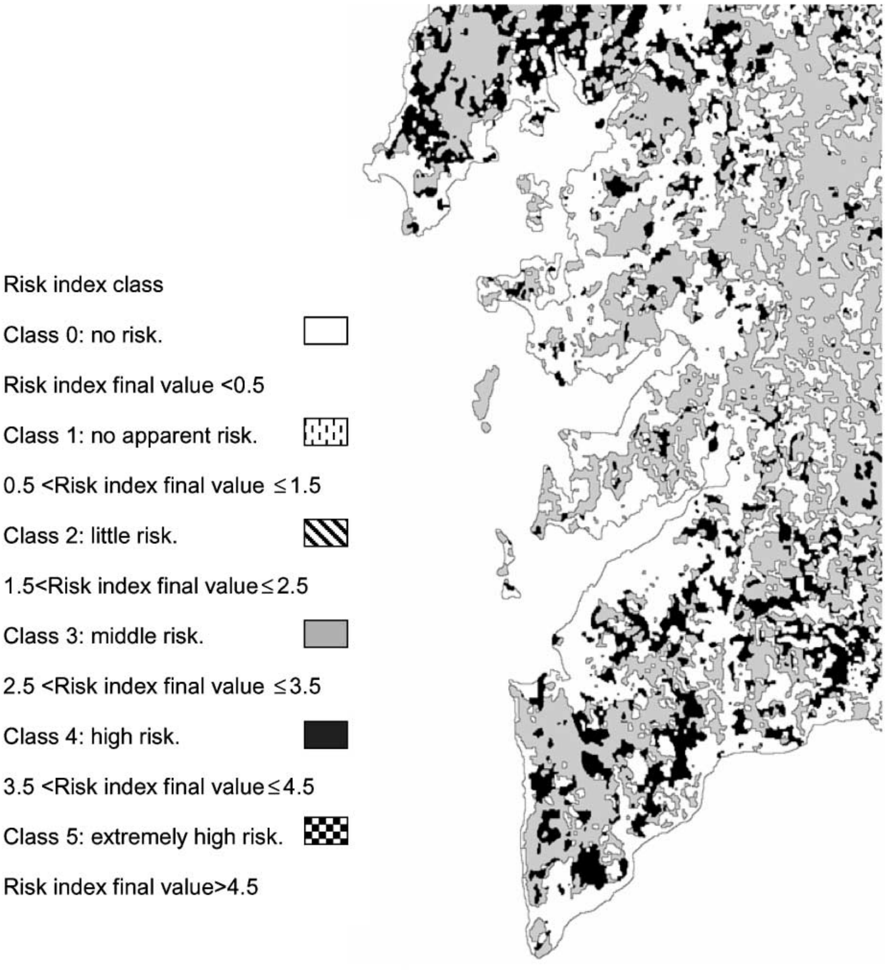
(c)

Fig. 2. (*Continued*)

values and flammability of the forest species existing in this zone of Galicia.

Table 3 also reports values of flammability. It can be seen that highest values, mainly for conifers, correspond to summer when rain is not frequent and average temperatures are high. This is the period in which wildfires are more probable to happen. For the most part of the species existing in the zone, their high HHV coincide with low values of flammability, thus, decreasing the risk of wildfires.

Combination of HHV, flammability, composition, and bioclimatic parameters allows the calculation of risk indices of the different species [2,3]. Table 4 shows an example of calculation of risk indices of *P. pinaster* Aiton corresponding to spring and summer. The influence of the different parameters on the risk indices are pointed out. The study was made using 50-year-old trees. 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



Autumn
(d)

Fig. 2. (*Continued*)

analysis of all these data, it was considered that numerical contributions were physico-chemical 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 ascribed through analysis of existing data. As an example, physico-chemical 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

Table 4
Risk index calculation of one of the species (50-year-old *P. pinaster* Aiton) collected in spring and summer in north coast

		Experimental values		Calculated values	
		Spring	Summer	Spring	Summer
Thermochemical parameters					
HHV class number		2	4		
Flammability class number		4	5	3	4.5
Physico-chemical properties (10%)					
Density (kg m^{-3})	15	650	640		
Own moisture (%)	80	56.3	53.50		
Bomb ashes after combustion (%)	5	1.04	0.84	0.0026	−0.0007
Biological characteristics (20%)					
Physiological activity	10	High	Middle–high		
Essential oils/resins	20	Middle–high	Middle–high		
Age	10	Old	Old		
Habit	10	Conifers	Conifers		
Forest waste generated	20	Middle–high	Middle–high		
Forest cover around	10	Middle	Middle		
Perennial/deciduous	10	P	P		
Blooming period	10	April–May	April–May	−0.0113	0.0311
Climate characteristics (50%)					
Rainfall	40				
Monthly amount (mm)	50	54.83	−47.17		
Periodicity	50	Very low	Low		
Mean temperature (°C)	20	13.6	17.47		
Hydric availability (mm per month)	30	154.83	52.83		
Environmental humidity (% per month)	10	70	60	−0.0167	0.1835
Parameters depending on physical environmental conditions (25%)					
Zone wind	30				
Strength	50	Middle–strong	Middle–low		
Periodicity	50	Regular	Regular–low		
Clouds	10				
Amount	50	Abundant	Regular		
Regularity	50	Abundant	Low		
Topography	20	Unfavorable	Unfavorable		
Sun radiation	10				
Sunshine (%)	50	Middle–low	Middle–high		
Sunny days	50	Middle–low	Middle–high		
Anthropic activity	30	Middle–high	Middle–high	−0.0320	−0.0141
Risk index final value				2.90	4.70
Risk index class				3	5

consider the influence of own moisture content of *P. pinaster* Aiton collected in summer. Analysis of Table 3 shows that 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 0, 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 *P. pinaster* Aiton, in summer, to the risk index number is $0.08 \times (-0.08) = -0.0064$.

Same analyses and calculations were done over the different parameters affecting the various aforementioned 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.

In this study, the different forest species were arranged according to Table 5.

There are biological parameters having a strong influence on the risk index calculation. Some of them must be underlined.

Table 5
Risk index classes

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

- Age of the forest species: part of the cellulose is progressively subtituted by lignin with large HHV, approximately 26,000 kJ kg^{-1} [14].

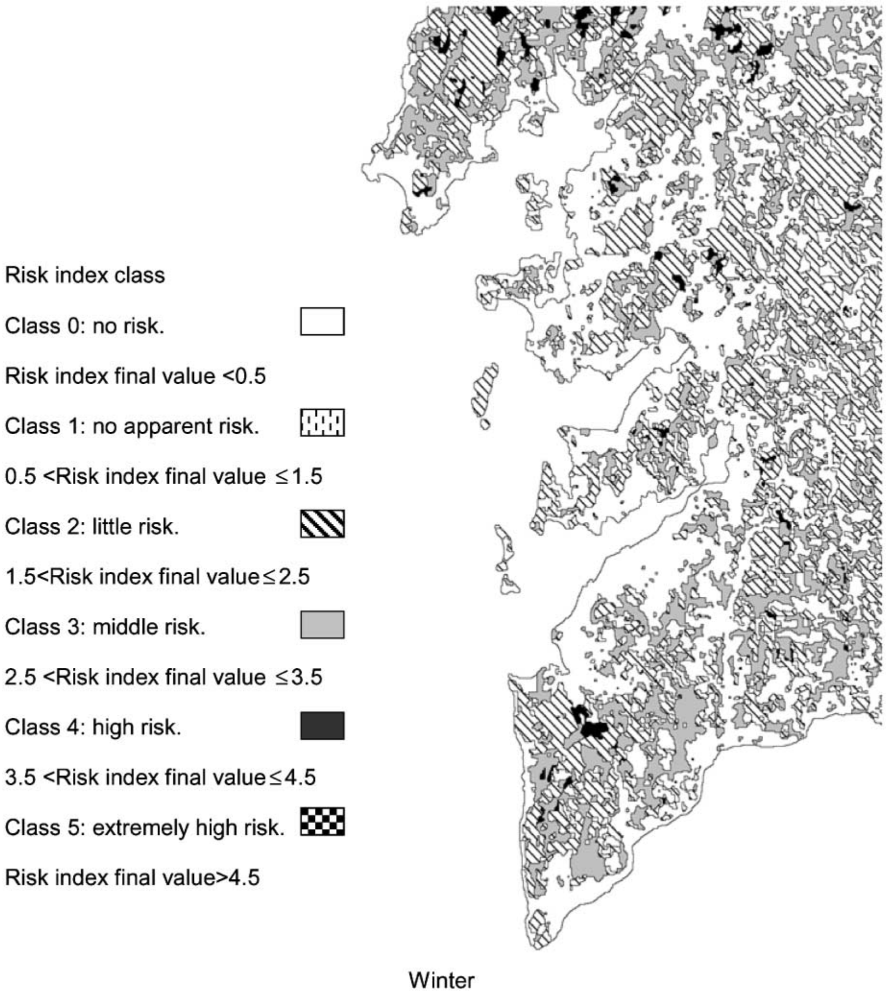


Fig. 3. Map of risk index distribution in the coast of Galicia over the year.

Table 6
General data used for calculation of risk indices [1]

	Surface (%)	HHV classes				Flammability				Risk indexes			
		Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
North coast													
P. pinaster Aiton	14	2	4	3	3	4	5	4	3	3	5	4	3
P. radiata D.	1.4	4	3	5	4	2	4	3	3	3	4	4	4
P. sylvestris L.	0.35	5	5	5	5	4	4	3	3	5	5	4	4
E. globulus Labill.	7	2	4	2	1	4	4	4	3	3	4	3	3
Conifers + hardwoods	3.5	3	4	3	3	3	4	4	3	3	4	3	3
Conifers + *Eucalyptus*	42.7	4	4	4	3	1	2	2	1	3	3	3	2
Other species	1.05	1	2	1	1	5	4	4	3	3	3	3	2
Bushes	30	4	4	4	4	1	3	3	2	3	4	4	3
Overall risk index of the zone										3	4	3	3
No forestry (35%) + bushes (22.5%) + forestry (42.5%) = 450000 ha													
South coast													
P. pinaster Aiton	24	2	4	3	3	4	5	4	3	3	5	4	3
P. radiata D.	2.4	4	3	5	4	2	4	3	3	3	4	4	4
P. sylvestris L.	1.8	5	5	5	5	4	4	3	3	5	5	4	4
E. globulus Labill.	5.4	2	4	2	1	4	4	4	3	3	4	3	3
Conifers + hardwoods	4.2	3	4	3	3	3	4	4	3	3	4	3	3
Conifers + *Eucalyptus*	20.4	4	4	4	3	1	2	2	1	3	3	3	2
Other species	0.6	1	2	1	1	5	4	4	3	3	3	3	2
Bushes	40	3	3	3	3	2	3	3	2	3	3	3	2
Overall risk index of the zone										3	4	4	3
No forestry (35%) + bushes (30%) + forestry (30%) = 400000 ha													
Related to HHV, the different forest species were classified as follows													
Class 1	$\text{HHV} < 18500\ \text{kJ kg}^{-1}$												
Class 2	$18500 < \text{HHV} < 19500\ \text{kJ kg}^{-1}$												
Class 3	$19500 < \text{HHV} < 20500\ \text{kJ kg}^{-1}$												
Class 4	$20500 < \text{HHV} < 21500\ \text{kJ kg}^{-1}$												
Class 5	$\text{HHV} > 21500\ \text{kJ kg}^{-1}$												
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												

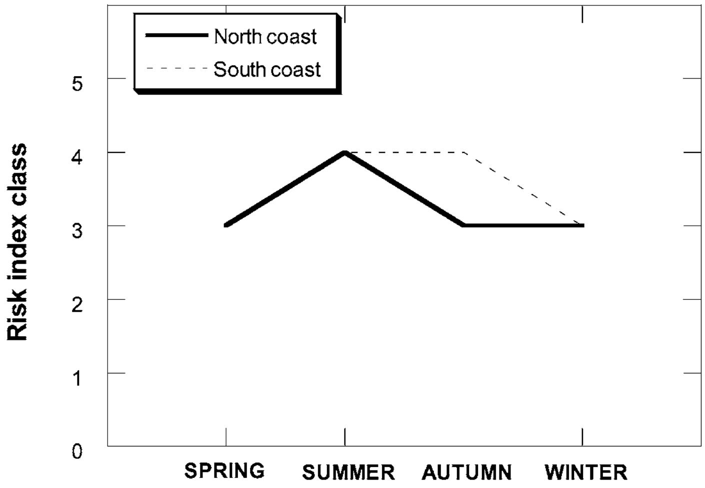


Fig. 4. Risk index evolution over the year of the two coast zones of Galicia.

- Blooming period, in which moisture content is extremely high (abundant green parts, flowers, young leaves, etc.).
- Generation of forest residues having large HHV (19,000 kJ kg^{-1}), high flammability (4–5), and low moisture content (<30%) [12,13], very easy to ignite and also to spread fire.
- Presence of essential oils and resins, with large HHV (40,000 kJ kg^{-1}) [14] that in summer created highly flammable atmospheres.

Combination of forest inventories and risk indices leads to the design of risk index maps. These maps are very understandable and very useful to prevent and to fight forest fires. As an example, Fig. 3 shows the risk index maps corresponding to the south coast of Galicia over the year.

Evolution of the average risk index of this zone is shown in Fig. 4. It can be seen that these risk indices show their maximun value in summer.

Table 6 shows the percentage of space taken up by the different plants, as well as their risk indices. Highest values of these indices correspond to periods with high temperatures and low environmental humidity commonly in summer. Conifers are the species with highest risk indices as a consequence of their capacity to originate resins. As a whole, the north coast present risk indices lower than the south coast. This is a consequence of the adverse weather conditions, and also to differences between both HHV and flammabilities corresponding to the two coast zones.

Finally, it can be observed that bushes and conifer species, because of their abundance, markedly influence on the behavior of the remaining biomass existing in the zone.

4. Conclusions

The calorific values and flammabilities of the different forest species making up the woodland map of the coast of Galicia were measured. These parameters together with some other experimentally measured or available from literature were used to design forest biomass indices maps very useful to fight and/or to prevent forest wildfires.

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