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Using bomb calorimetry for determination of risk indices of wildfires originating from pine residues

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Abstract

Pine trees, mainly *Pinus pinaster* Aiton, now cover 640,000 ha of the forest occupied surface in Galicia. The possibility of using the residues originating from pine tree exploitation as an alternative energy source could yield to gross benefit around 2.8×10^8 euros per year, together with ecological advantages.

The object of the present study is the evaluation of the energy contained in these residues through the measurement of their caloric values using a static bomb calorimeter. At the same time, flammabilities were measured by a standard epiradiator thus allowing the calculation of risk indices. This latter is very important to fight and prevent the start and spreading of forest fires.

Elementary chemical composition was also determined using an elementary chemical analyser. Biological and bioclimatic parameters, which are very useful for the evaluation of caloric values and flammabilities over the year, were used for discussion of results.

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1. Introduction

Only 50 years ago most of the forest surface of Galicia, approximately 2,500,000 ha, was covered by pine trees (mainly *Pinus pinaster* Aiton). However, owing to different factors such as changes in land policy, according to which terrains formerly dedicated to agriculture moved to forest exploitation, abandonment of land, thus favouring the scrubland expansion, and forest wildfires (10,000 ha of trees devastated per year), the agroforest sector in Galicia has undergone important alterations. Nowadays, Galicia has more than 640,000 ha covered by pine trees [1], mainly *P. pinaster* Aiton (≅500,000 ha). There are also *Pinus sylvestris* L., and *Pinus radiata* D.

It is expected that in the next 10 years, the forest sector will become one of the most important factors in the economical development of Galicia. Pine is mainly used in the furniture trade, but sometimes it is used as a raw material, together with eucalyptus, for production of pulp.

As a consequence of massive wood exploitation, a large amount of forest residues consisting mainly of leaves, little branches with a diameter less than 6 cm, and bark, is generated. To date, most of these forest residues are abandoned in situ, thus causing important environmental problems, among them, soil

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acidification (due to the accumulation of organic matter) and the increase in risk for the start and spreading of forest fires, specially in months when dryness and temperatures are high.

The intent of this study is to point out the importance of combining forest exploitation programs with rational silviculture works in order to preserve the environment by leaving on the forest soil only the necessary amount of dead matter, thus ensuring environmental fertilization and preventing forest fires. With this aim, risk indices are defined in terms of caloric values and flammability. These indices are a measure of the ease of a material to initiate and/or to spread forest fires or the resistance of a forest species to starting and spreading wildfires, both spontaneously or through exposure to certain environmental conditions.

Two caloric values must be considered:

- 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, it is one of the two main parameters used for the calculation of risk indexes.
- The lower heating value (LHV) can be calculated, through HHV, by assuming that the water in the products of combustion remains in the form of vapour. Both caloric values are related through the equation:

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

  where $(\mathrm{LHV})_\mathrm{d}$ ($\mathrm{kJ\,kg^{-1}}$) corresponds to the lower caloric value of the dry sample, $(\mathrm{HHV})_\mathrm{d}$ ($\mathrm{kJ\,kg^{-1}}$) the higher caloric value of the dry sample and H_d the hydrogen percentage of the dry sample. The heat of vaporization of water is taken as $2441.8\,\mathrm{kJ\,kg^{-1}}$, and the water formed during combustion is nine times the hydrogen content (%). The knowledge of LHV for the different tree species making up the forest vegetation becomes a realistic indicator of the energetic state of the forest biomass of a zone. The knowledge of LHV also gives a realistic idea about the magnitude of a fire and leads to the calculation of the fireline intensity, sometimes called Byram's [2] intensity. In this way, LHV becomes an index to quantify both the spread to neighbouring surfaces and the virulence of forest fires.
- Flammability can be defined as the ease with which a material will catch fire, both spontaneously or through exposure to certain ambient conditions or as the resistance of a forest species to starting and spreading of wild fires.

  These parameters are key for calculation of risk indices.

Some other interesting parameters in this kind of studies are:

- Elemental chemical composition (C, H, O, N, S and Cl).
- Main bioclimatic characteristics and physico-environmental factors of the zone having a determinative influence on the start and spreading of fires. All these parameters can be represented together in the form of bioclimatic diagrams [3].
- 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, all the key parameters used for preventing and/or fighting forest fires are presented in the form of maps which were designed using available data found in forest inventories. All the studies were carried out over 1 year. The sampling was made in seven well-differentiated zones of Galicia.

2. Experimental

The first stage of the experimental work begins with sampling. This is one of the most important stages because the usefulness of the experimental measurements depends greatly on the samples being representative. For our study, sampling was made in seven forest stations. All these stations are owned or managed by a reputable private wood company, Maderas Villapol (Trabada, Lugo, Spain). These forest stations, situated in the north, and south of Galicia, show general climatic characteristics making them representative of the whole forest surface of Galicia. Because of this, though sampling was made in different zones, only north, and south bioclimatic diagrams were considered. Samples were collected from these stations coinciding with wood cutting by Maderas

Villapol, sometimes at our request. These studies were carried out in November (autumn), January and February (winter), May (spring), and July, August, and September (summer). The reason for choosing the three summer months was, on the one hand to analyse the possible influence of strong climatic changes in the zones (high temperatures and decrease of rains) on caloric values and, on the other hand, to study the evolution and the relationship between forest residues and forest fires, very common in this season. This relationship will be the subject of a future analysis.

Sampling operations were carried out in different zones. The reason for this change was twofold. On the one hand, our sampling being of a destructive type, we had to stop sampling after all trees of a zone were cut down. On the other hand, most of the land where sampling was done was private, and cutting by the wood company was carried out under temporary contracts. Moreover, sampling was made not only in different zones with different climatic parameters, but also on different species, such as *P. radiata* D., to check the influence of zone and climatic conditions on heat value evaluation.

Samples were collected from a previously chosen 1 ha of forest located in a zone of a total forest surface greater than 10 ha. In this zone, the predominant forest species is *P. pinaster* Aiton. The zone 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.

Once the sampling zone was chosen, the average height of the trees was estimated by using a hypsometer, and then two of the trees were marked for analysis after being cut down. These two trees must be representative of the whole so the selection of young, old, ill, or any other irregular tree was avoided. Also, trees situated at the border of the zone should be considered as non-representative. Usually, the trees chosen for analysis were located in the middle of the exploitation zone. After all the trees were cut down, the two previously marked were taken for extraction of the residues usually abandoned on the forest surface after forestry works. These residues were divided into three well-differentiated classes: leaves, branches having a diameter less than 3 cm, and branches with a diameter between 3 and 6 cm. All other kinds of residues originated from forestry tasks, such as bark and branches with a diameter between 6 and 8 cm usually collected either by forestry workers or by land owners.

After division of the three mentioned groups, residues of each of them were carefully mixed and the two kinds of branches were cut to small pieces. They were then reduced by a coning and quartering procedure to a representative bulk sample of 5–6 kg each.

This sampling operation was also performed in March and August by collecting the dead biomass originating from residues abandoned in station 1 after cutting carried out in November. The objective was to study the change of caloric values and flammability as a consequence of the degradation caused by the exposure to wind and weather. These residues were abandoned on the forest soil and could originate environmental damages.

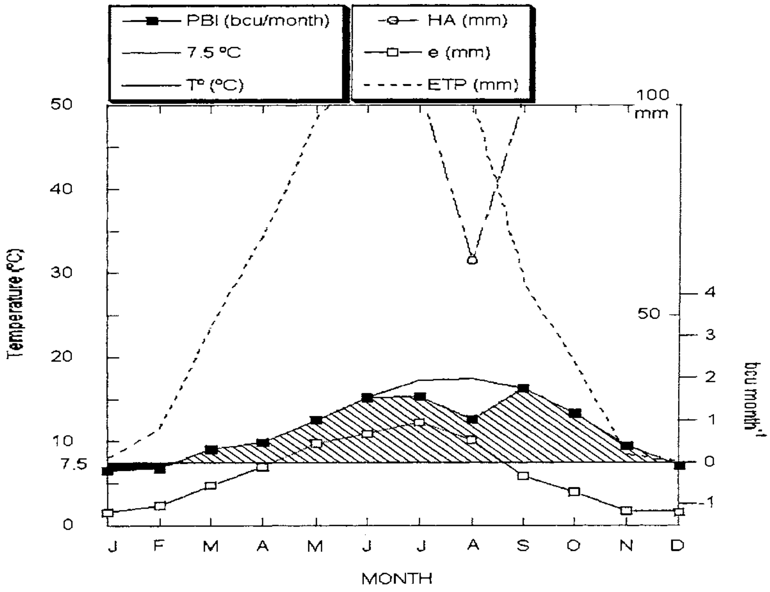
After being collected, the samples were stored in hermetically closed polyethylene bags to avoid loss of moisture, and sent to the laboratory in less than 10 h. Once in the laboratory, samples were weighed to 0.1 or 1.0 g using a double scaled Salter EP-22KA balance and dried in a Selecta 200210 natural desiccating oven at 105 °C to constant weight to determine moisture content as the weight loss.

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 were obtained according to the tables proposed by Valette [4].

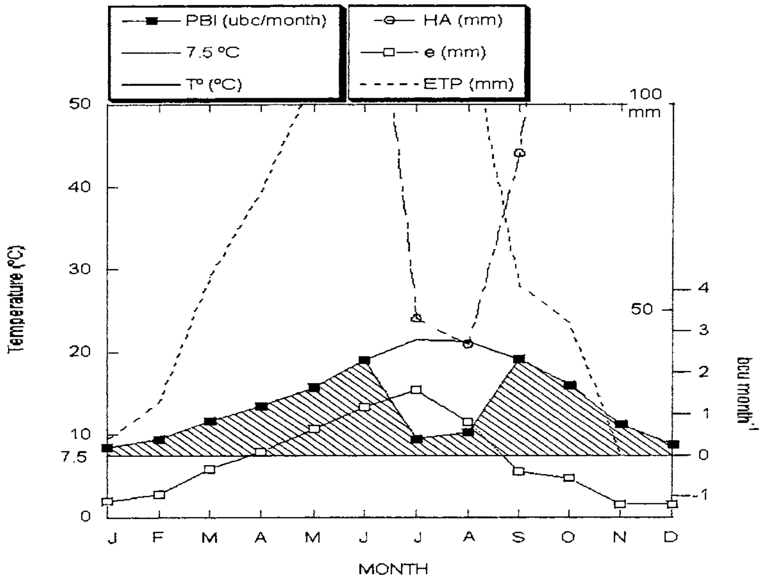
Once the humidity was determined, the dry sample was ground using two mills of different power, a Retsch SM-1 blade mill and a Taunus MS-50 grinder, in order to homogenize the sample as much as

Table 1
Main bioclimatic [3] and biological parameters corresponding to the main forest zones where sampling was made

Parameters	North zone	South zone
Altitude	100–900 m	100–500 m
Annual rainfall index	1062 mm	1485 mm
Summer rainfall index	137 mm	123 mm
Mean annual temperature	12.9 °C	14.6 °C
Mean daily maximum temperature of the warmest month (July)	22.5 °C	38.2 °C
Hydric deficiency	105	180
Mediterraneanity index	2.39	3.28



As Pontes



Ponteareas

█ CBI: cold bioclimatic intensity (bcu) ▨ FBI: free bioclimatic intensity (bcu)

Fig. 1. Representative bioclimatic diagram showing the main environmental characteristics of the zone As Pontes (north zone) and Ponteareas (south zone): T (temperature in °C), 7.5 (minimum temperature for vegetal activity), ETP (evapotranspiration in mm), e (residual evapotranspiration in mm), HA (hydric availability in mm), PBI (potential bioclimatic intensity in bcu, where bcu is bioclimatic units) [3]. The striped zone corresponds with FBI (free bioclimatic intensity).

possible, thus making easier the preparation of the sample pellets to be used in the calorimetric experiments.

A part of this ground sample, labelled as fraction A, was used to measure the density and average chemical composition of each of the species being studied. The samples were analysed using Carlo Erba analysis equipment for determination of elemental composition (C, H, N, O and S). A second fraction named B was used to determine caloric values and ash percentage after combustion. All the combustion experiments were done in a static bomb calorimeter, a sealed Parr-1108, following the procedure described by Hubbard et al. [5]. Sample pellets of about 1 g size [6] were put in a stainless steel crucible and then inside the bomb. A cotton thread fuse of empirical formula

Table 2
Mean HHVs, mean LHVs, *M*, *D* and BA corresponding to the three groups and the different sampling stations for both live and dead matter

	HHV (kJ kg^{-1})	LHV (kJ kg^{-1})	*M* (%)	*D* (kg m^{-3})	BA (%)
Live matter					
Station 1—November (Abadín)					
Leaves	21695.33 ± 230.69 (1.06%)	6655.14 ± 92.05 (1.38%)	60.10	935	0.34
Thin branches	20531.98 ± 324.44 (1.58%)	10319.98 ± 193.04 (1.87%)	40.50	797	0.07
Thick branches	19740.71 ± 117.57 (0.60%)	4815.23 ± 40.56 (0.84%)	65.50	784	0.09
Station 2—January (Trabada)					
Leaves	20423.62 ± 106.59 (0.52%)	5832.42 ± 41.04 (0.70%)	61.50	1049	0.40
Thin branches	20290.50 ± 257.15 (1.27%)	12477.30 ± 179.24 (1.44%)	30.30	893	0.18
Thick branches	19363.55 ± 176.22 (0.91%)	7052.69 ± 81.77 (1.16%)	53.60	850	0.14
Station 3—March (Orol)					
Leaves	21144.85 ± 143.85 (0.65%)	5780.43 ± 50.70 (0.88%)	62.40	1087	0.69
Thin branches	20545.74 ± 206.27 (1.00%)	8433.23 ± 105.40 (1.25%)	48.90	947	0.24
Thick branches	19535.12 ± 82.97 (0.42%)	7128.01 ± 39.00 (0.55%)	53.00	878	0.15
Station 4—May (Oia)					
Leaves	20862.31 ± 264.43 (1.27%)	4073.03 ± 78.72 (1.93%)	70.20	1009	0.34
Thin branches	20329.23 ± 190.79 (0.94%)	7582.11 ± 89.23 (1.18%)	53.20	815	0.05
Thick branches	19857.28 ± 123.01 (0.62%)	9852.44 ± 72.02 (0.72%)	41.40	801	0.10
Station 5—July (Porriño)					
Leaves	20652.19 ± 246.94 (1.20%)	6332.57 ± 100.01 (1.58%)	59.50	1066	0.60
Thin branches	20304.13 ± 146.37 (0.72%)	7390.17 ± 67.18 (0.91%)	54.10	873	0.23
Thick branches	20148.62 ± 171.17 (0.85%)	7350.17 ± 78.74 (1.07%)	54.00	854	0.12
Station 6—August (Ponteareas)					
Leaves	21713.31 ± 83.80 (0.39%)	6289.29 ± 32.18 (0.51%)	61.60	1012	0.31
Thin branches	20188.12 ± 223.66 (1.11%)	7780.22 ± 107.51 (1.38%)	51.90	874	0.26
Thick branches	19685.73 ± 160.87 (0.82%)	7368.46 ± 75.93 (1.03%)	52.80	771	0.17
Station 7—September (Ferreira)					
Leaves	20747.03 ± 163.93 (0.79%)	5475.61 ± 59.67 (1.09%)	63.60	1069	0.52
Thin branches	21408.02 ± 319.93 (1.49%)	8165.82 ± 151.01 (1.85%)	52.80	888	0.16
Thick branches	20096.32 ± 271.87 (1.35%)	7513.67 ± 127.78 (1.70%)	53.00	856	0.09
Dead matter					
Station 1—March (Abadín)					
Leaves	20873.05 ± 210.89 (1.01%)	2345.41 ± 46.04 (1.96%)	78.20	909	0.22
Thin branches	22124.77 ± 59.86 (0.27%)	6898.66 ± 24.08 (0.35%)	59.80	868	0.14
Thick branches	19683.24 ± 117.61 (0.60%)	8234.76 ± 60.12 (0.73%)	48.90	822	0.08
Station 1—August (Abadín)					
Leaves	23079.44 ± 68.14 (0.30%)	9558.37 ± 33.87 (0.35%)	50.30	867	0.26
Thin branches	20824.64 ± 137.97 (0.66%)	12108.10 ± 91.61 (0.76%)	33.60	758	0.36
Thick branches	19026.47 ± 115.01 (0.60%)	5721.64 ± 46.68 (0.82%)	59.41	675	0.33

$CH_{1.686}O_{0.843}$ was attached to the platinum ignition wire and placed in contact with the pellet. In all the experiments the bomb was filled with C-45 oxygen 99.99995% pure from Carburos Metálicos (Spain) at 3.04 MPa. Ignition was at 298.15 K with 1.0 cm^3 of water added to the bomb. The calorimeter was placed in an isothermal jacket with an air-gap separation of 10 mm between all surfaces. The electrical energy for ignition was determined from the change in potential across a 1256 or 2900 μF capacitor when discharged at about 40 V through a platinum wire.

The bomb calorimeter was submerged in a calorimeter can filled with 4631 g of distilled water weighed by a Mettler P-11 balance (sensitivity ±0.1 g). A correction to the energy equivalent was made for the deviation of the mass of water to 4631 g.

Table 3
Elementary analysis corresponding to dry samples of the three groups of residues, and to the seven main sampling stations for both live and dead matter

	Chemical analysis (% of total composition)				
	N	C	H	O	S
Live matter					
Station 1—November (Abadín)					
Leaves	2.06	55.23	6.04	36.01	0.66
Thin branches	0.23	55.42	6.94	37.19	0.22
Thick branches	0.16	54.92	5.22	39.48	0.22
Station 2—January (Trabada)					
Leaves	1.53	49.40	6.25	42.32	0.50
Thin branches	1.59	52.63	6.04	40.25	0.45
Thick branches	1.33	48.33	6.11	43.98	0.25
Station 3—March (Orol)					
Leaves	1.40	55.12	7.82	35.32	0.34
Thin branches	0.26	55.29	7.76	36.48	0.21
Thick branches	0.16	54.67	7.35	37.68	0.14
Station 4—May (Oia)					
Leaves	1.81	50.29	6.46	41.08	0.36
Thin branches	1.48	50.25	6.09	41.97	0.21
Thick branches	1.24	48.67	5.92	43.97	0.20
Station 5—July (Porriño)					
Leaves	1.81	50.54	6.50	40.78	0.37
Thin branches	1.10	50.20	6.03	42.47	0.20
Thick branches	1.16	48.59	5.93	44.10	0.22
Station 6—August (Ponteareas)					
Leaves	1.13	51.11	6.45	40.88	0.43
Thin branches	1.56	51.68	6.21	40.30	0.25
Thick branches	1.21	49.58	6.11	42.87	0.23
Station 7—September (Ferreira)					
Leaves	1.96	50.29	6.54	40.88	0.33
Thin branches	1.42	53.57	6.26	38.48	0.27
Thick branches	1.21	50.48	6.17	41.89	0.25
Dead matter					
Station 1—March (Abadín)					
Leaves	2.15	50.96	6.30	40.02	0.57
Thin branches	1.02	53.13	6.11	39.41	0.33
Thick branches	1.59	49.01	5.64	43.51	0.25
Station 1—August (Abadín)					
Leaves	2.15	52.40	6.26	38.71	0.48
Thin branches	1.48	52.55	6.16	39.52	0.29
Thick branches	1.34	48.42	6.17	43.86	0.21

Table 4
Mean flammability values and LHV class[a]

	LHV class[b]	Flammability class[c]
Station 1—November (Abadín)	5	1
Station 2—January (Trabada)	5	0
Station 3—March (Orol)	4	0
Station 4—May (Oia)	4	0
Station 5—July (Porriño)	4	5
Station 6—August (Ponteareas)	4	0
Station 7—September (Ferreira)	4	0
Dead matter		
Station 1—March (Abadín)	2	1
Station 1—August (Abadín)	5	4

[a] This table was worked out taking into account the percentage of each of the three groups of residues in the final bulk sample.

[b] Class 1: LHV $< 4500\,\mathrm{kJ\,kg^{-1}}$; class 2: LHV ≥ 4500 and LHV $< 5500\,\mathrm{kJ\,kg^{-1}}$; class 3: LHV ≥ 5500 and LHV $< 6500\,\mathrm{kJ\,kg^{-1}}$; class 4: LHV ≥ 6500 and LHV $< 7500\,\mathrm{kJ\,kg^{-1}}$; class 5: LHV $\geq 7500\,\mathrm{kJ\,kg^{-1}}$.

[c] 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) and class 5: extremely flammable (<12.5 s).

Table 5
Mean HHV and LHV calculated as a function of the percentage of each of three groups of residues, both dry and wet, in the final bulk sample

	HHV ($\mathrm{kJ\,kg^{-1}}$)	LHV ($\mathrm{kJ\,kg^{-1}}$)
Station 1—November (Abadín)	20632.69	8230.37
Station 2—January (Trabada)	20076.31	8366.90
Station 3—March (Orol)	20572.79	7072.33
Station 4—May (Oia)	20410.76	7388.01
Station 5—July (Porriño)	20400.99	6999.02
Station 6—August (Ponteareas)	20571.40	7173.91
Station 7—September (Ferreira)	20860.94	6823.98
Dead matter		
Station 1—March (Abadín)	21084.47	4953.60
Station 1—August (Abadín)	21583.27	9734.67

The calorimeter jacket was maintained at constant temperature by circulating water kept at 25 °C by a Tronac PTC-41 temperature controller, with a precision of 0.003 °C per week, including a probe, a heater and cooling coil. The water temperature was kept homogeneous in the whole calorimeter by means of two

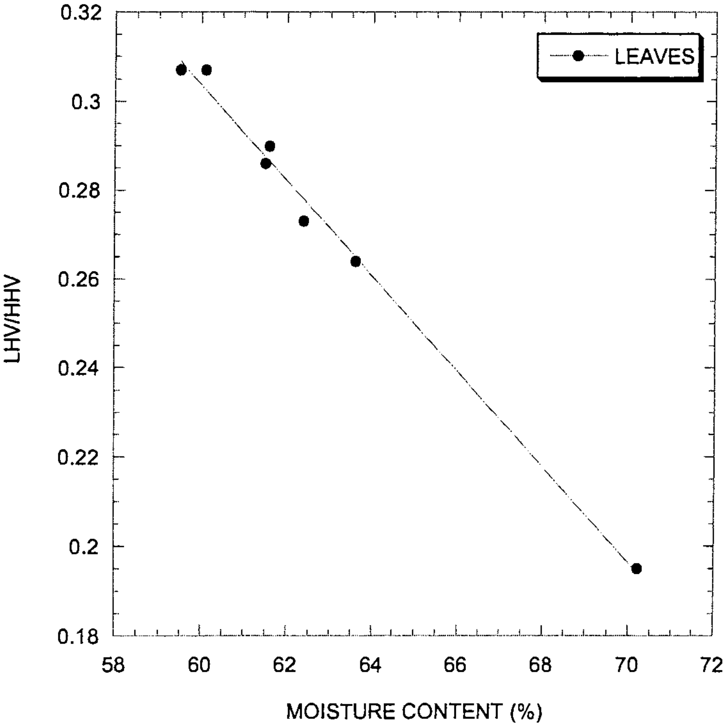


Fig. 2. Plot of LHV/HHV versus moisture content for the needles.

motors which continuously stirred both the calorimetric tank and the calorimeter. Temperature changes taking place in the calorimeter can during the experiments were followed by a Isotech 935-14-13 platinum resistance thermometer connected to an ASL F-26 resistance bridge. Temperature data were taken every 15 s and recorded by a 2086 Amstrad computer. The ignition of the sample was achieved on step 80, i.e., at minute 20, through the discharge of the capacitor. This ignition started the main period of the calorimetric run. The experiment ended, after 1 h, at step 240. The bomb calorimeter was removed from the can and after being carefully opened, ash and water resulting from the combustion were evaluated following routine procedures. The corrected temperature rise was obtained using a computer program and the measured data. Knowledge of this temperature rise allows calculation of caloric values.

The equivalent energy of the calorimeter was determined using the combustion of benzoic acid, BCS CRN-ISOP standard reference sample from Bureau of Analysed Samples Ltd., having an energy of combustion under standard bomb conditions of $26431.8 \pm 3.7\,\mathrm{kJ\,kg^{-1}}$. From five calibration experiments the heat capacity E (calor) $= 21182.28 \pm 0.22$ ($\mathrm{J\,K^{-1}}$) (0.000985%),where the uncertainty quoted is the standard deviation of the mean. The temperature rise was corrected for stirring and exchange heating.

3. Results and discussion

Main bioclimatic [7] and physical parameters of the two main forest zones (north and south) where sampling was made are shown in Table 1. 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 the bioclimatic diagrams [3] shown in Fig. 1, corresponding to the northern and southern zones. Owing to some climatic peculiarities, these sampling zones were purposely chosen to study the possible influence of environmental conditions on caloric values.

Table 2 shows caloric values, moisture content (M), density (D), and ash content after combustion in the bomb (BA) for the three groups of the residues mentioned above both for live and dead matter. It can be seen that caloric values show only small discrepancies among the seven main forest stations in spite of their various environmental conditions, the differences being less than 6% in HHV for the three groups of residues, and 18% in LHV owing to the high dependence of these values on moisture content. One thing to point out is the trend of HHV of leaves to show, in general, greater values than those corresponding to the two kinds of branches. This might be a consequence of the accumulation of turpentine in needles. As was pointed out in previous articles [8], leaves constitute sites for accumulation of essential oils in plants. Values for M, D and BA are also higher for leaves. Even so, HHV corresponding to the three fractions of residues are not very different.

From Table 2, it can be seen that thin branches have larger HHV than thick ones. Mean HHV and LHV corresponding to pine trees are sensibly higher than those measured for other forest species reported in the literature, as a consequence of the higher production of essential oils and resins by pine. Dead matter shows a similar behaviour.

Table 3 lists the elementary composition of samples from different forest stations. The main feature to be pointed out is the good agreement among similar values corresponding to the different samples. It can be observed that nitrogen content increases for dead matter as a possible consequence of material degradation. This same behaviour was observed in some other forest species such as *E. globulus* Labill.

Table 6
Risk index succession over the year for live biomass and dead forest residues

	Risk index[a]
Station 1—November (Abadín)	3
Station 2—January (Trabada)	2
Station 3—March (Orol)	2
Station 4—May (Oia)	2
Station 5—July (Porriño)	5
Station 6—August (Ponteareas)	2
Station 7—September (Ferreira)	2
Dead matter	
Station 1—March (Abadín)	1
Station 1—August (Abadín)	5

[a] 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 and class 5—risk index final value > 4.5: extremely high risk.

Table 4 shows LHV and flammability class values calculated as a weighted mean, taking into account the percentage of the three groups of residues in the final bulk sample. It can be observed that larger LHVs correspond to periods of low vegetal activity (end of autumn-end of winter). These large values could be caused by the lower vegetal activity in this season, thus diminishing the own moisture of vegetal tissues. Mean weighted moisture content is higher in samples 3–7 as deduced from LHV shown in Table 2. Flammability is a key parameter for studying the start and spreading of forest fires. It is apparent that raw residues of *P. pinaster* Aiton show very low values of flammability over the year (as opposed to results shown in previous studies) except for July, when flammability shows its maximum value, as reported in previous articles. The rest of the year, flammability remains very low as a consequence of the large moisture content of residues.

Table 7
Risk index calculation of one of the species (25 years *P. pinaster* Aiton) collected in autumn (November) [8–10]

	Experimental values	Calculated values
Thermochemical parameters		3
HHV class number	5	
Flammability class number	1	
Physico-chemical properties (20%)		−0.0230
Density (kg m^{-3}) (30%)	860.90	
Own moisture (%) (65%)	54.40	
Bomb ashes after combustion (%) (5%)	0.20	
Biological characteristics (25%)		−0.0067
Physiological activity (10%)	Low (0.38)	
Essential oils/resins (10%)	Very low	
Age (10%)	25	
Habit (10%)	Plantacion	
Forest waste generated (20%)	Low	
Forest cover around (20%)	Low	
Perennial/deciduous (10%)	P	
Blooming period (10%)	Spring–summer	
Climate characteristics (40%)		−0.0751
Rainfall (40%)		
Monthly mean amount (mm) (35%)	198	
Periodicity (65%)	Very regular	
Mean temperature (°C) (20%)	9.4	
Hydric availability (mm per month) (20%)	298	
Environmental humidity (% per month) (20%)	79.70	
Parameters depending on physical environmental conditions (15%)		0.0153
Zone wind (30%)		
Strength (60%)	Regular	
Periodicidity (40%)	Regular	
Clouds (10%)		
Amount (50%)	Abundant	
Regularity (50%)	Abundant	
Topography (20%)	Very favourable	
Sun radiation (10%)		
Sunshine (%) (50%)	Low	
Sunny days (50%)	Low	
Anthropogenic activity (30%)	Middle–low	
Risk index final value		2.91
Risk index class		3

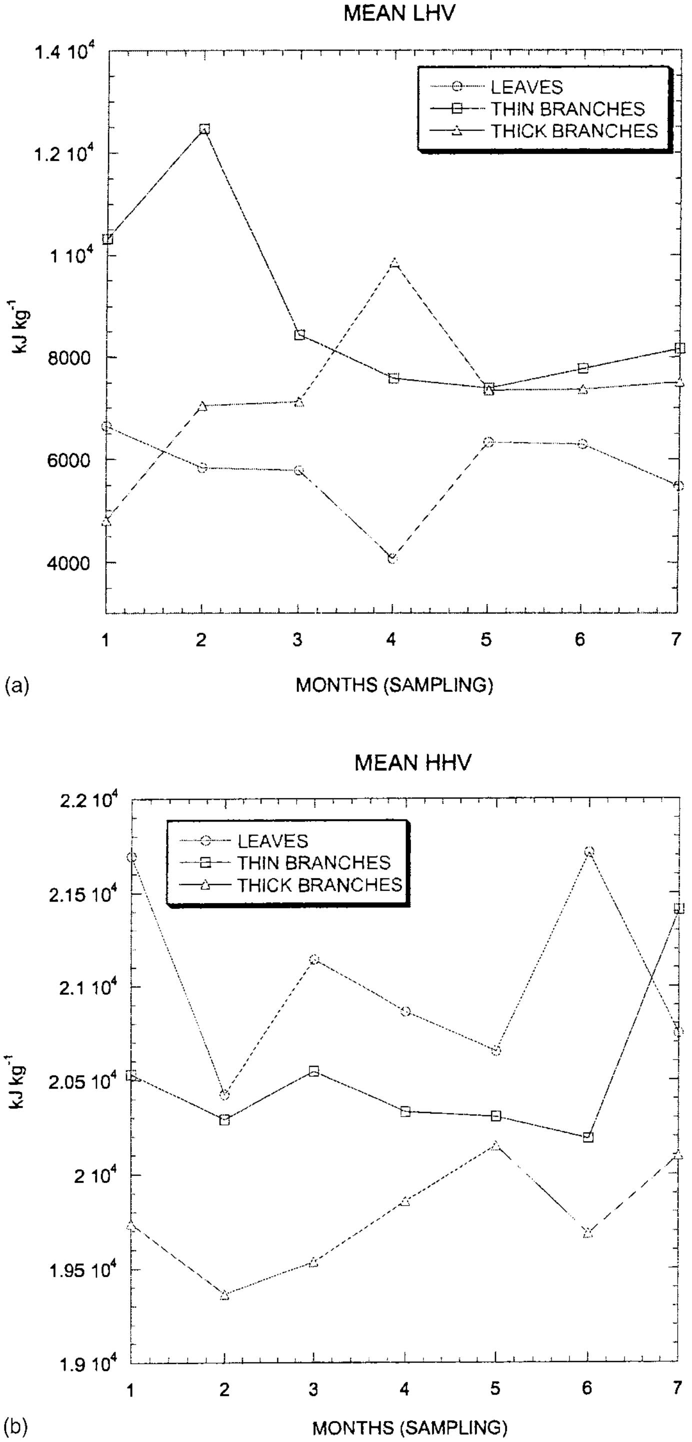


Fig. 3. (a) Mean LHV and HHV changes throughout the year. (b) Mean LHV and HHV changes throughout the year.

However, it must be pointed out that these residues become highly flammable after abandonment on the forest surface. This increase in flammability could be a consequence of a natural drying process acting on these residues. LHV corresponding to dead matter depends greatly on environmental conditions. Because of this, moisture content of dead matter increases after being exposed to environmental humidity and rain. This moisture content is greater than that corresponding to live matter, i.e., before or immediately after cutting. As an example, in November the moisture content of residues originating from cutting is 54%, with 198 mm of rain and 76% of environmental humidity. Residues abandoned after cutting show a moisture content of 67% in March, with 112 mm of rain, and 76% of environmental humidity. For these reasons flammability reaches a class value of four in August.

Mean HHV and LHV are listed in Table 5. This table was calculated on the basis of the percentage of the different types of residues in the final bulk samples. The composition was for the wet sample, 48% leaves, 34% thin branches, and 18% thick branches, and for the dry sample, 37, 37 and 26%, respectively. Fig. 2 shows plots of the ratio LHV/HHV versus moisture content (%) corresponding to the three groups of residues. As expected, there is a linear relationship with a slight deviation caused by the deviation of individual hydrogen content (%) from the mean value. This can be understood in terms of Eq. (1). In the case of pines, as shown in Fig. 2, experimental measurements follow a behaviour very close to linearity as a consequence of the very small differences in hydrogen content. The example is given only for leaves, as all the other residues show similar behaviour. Analyses of data show that climatic conditions do not have an important influence on HHV. This can be seen by comparing data corresponding to the main forest stations (1–7) situated in different climatic zones. For LHV the differences are wider, reaching 18%, as a consequence of their dependence on water content. For dead matter, mean HHV and LHV show a great increase in August.

Risk index values over the different seasons of the year, both for live and dead matter, are shown in Table 6. Low risk index values, close to 2, can be seen except for July and August when they reach the

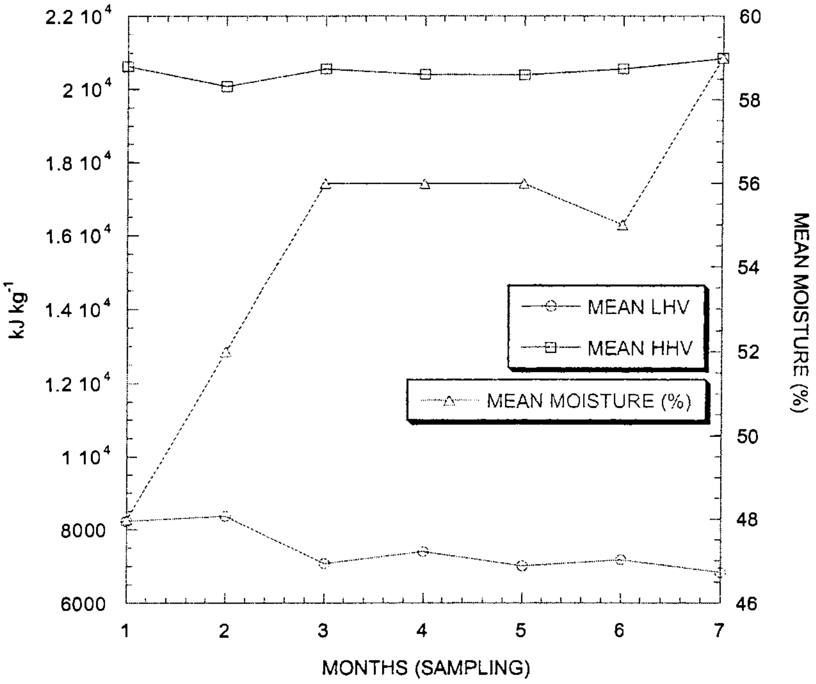


Fig. 4. Mean HHV, LHV and moisture content over the year (sampling number).

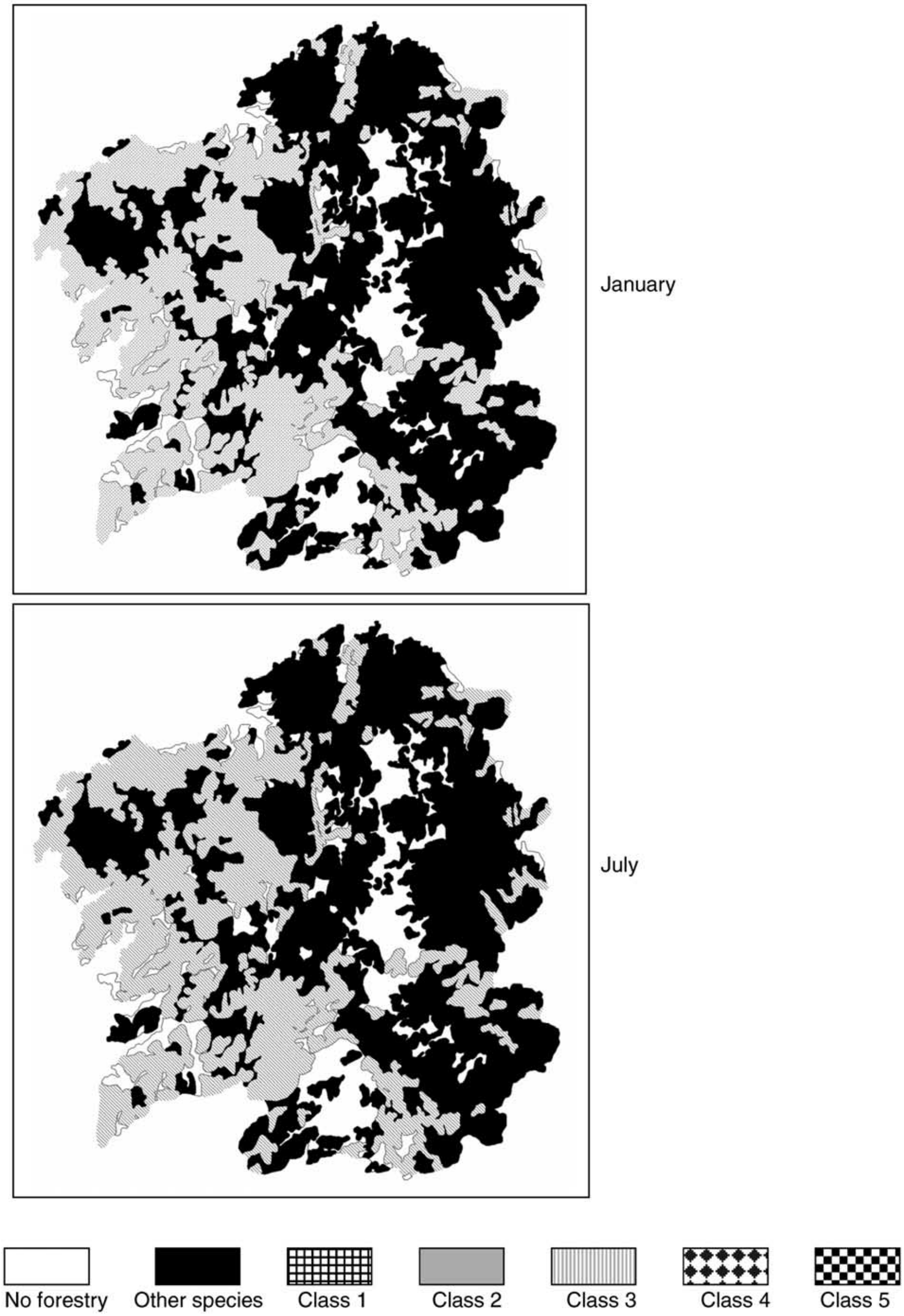


Fig. 5. Risk index maps corresponding to January and July, respectively.

maximum value 5. This shows the great influence of environmental and biological properties on the behaviour (risk index) of a forest species depending on the season of the year.

Table 7 shows the procedure followed for risk index calculation. The way this calculation was carried out was reported in previous papers [8–10]. It corresponds to sampling carried out in November. Figs. 3a and b and 4 show HHV and LHV, respectively, corresponding to bulk samples and to the three fractions. Mean caloric values correspond to the bulk samples and were calculated taking into account the content (%) of the different fractions and, in the case of LHV, also of their moisture content. It can be seen that, as stated above, HHV keep practically constant over the year independently of the forest station where samples were collected. Obviously, LHV behaviour is not as regular, as it depends on moisture content which is different depending on the season and on the residue fraction. Fig. 4 shows behaviour of mean HHV, mean LHV, and mean moisture content (%) as a function of the sampling period.

As previously stated LHV shows its highest value in November–January probably due to a vegetative activity stop. LHV is the main parameter to take into account for energy evaluation as it is a real index of natural processes. Moreover, HHV keeps practically constant over the year. There is an important relationship between caloric values and moisture content, as maximum values of LHV correspond to minimum moisture content. Fig. 5 shows a map of pine risk index evolution corresponding to January and July.

4. Conclusions

LHV and mainly HHV remain reasonably constant, thus allowing a sustainable exploitation over the year. A tree is stable energetically, even though its caloric value is very high. Because of this the behaviour of pine before a forest fire is very predictable, thus favouring fire extinguishing programs. This type of biomass needs a careful cleaning of environment, avoiding bush or residue accumulation in order to prevent wildfires. In the case of pine, it would be advisable to completely remove residues generated from forest tasks, as their abandonment in situ can originate not only problems related to forest fires, but also problems derived from the fact that these residues constitute a culture environment for parasites such as (coleoptera, *Hylobius abietis* L.) capable of ruining subsequent forestations. This behaviour is quite different from that showed by eucalyptus or hardwood species residues. For these it is recommended that 10% of the residues are left on the soil to facilitate its recovery through the nutrients contained in these residues.

Analysis of the behaviour of this forest species as a function of the different parameters studied shows that this kind of studies could be extrapolated to any zone. Results obtained from the present study are in good agreement with those reported in previous works [11,12], showing only certain discrepancies related to seasonal behaviour. In fact, as a consequence of changes introduced in the way of sampling and collection of residues, the final bulk sample is more homogeneous over the year. However, it must be considered that in those previous studies, sampling corresponded either to dead matter or to a mixture of dead matter, and a small contribution of live matter, collected as a whole. For the present study, we have done a rigorous sampling, choosing representative individuals, collecting the residues immediately after cutting and sorting the resulting residues into three groups based on the actual working carried out in the forest by a reputable wood company.

Risk indices are very low over the year except for summer months. This indicates that, provided a careful cleaning of residues is accomplished, with regard to forest fires this species can be dangerous only in the summer.

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