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# Determination of risk indices corresponding to eucalyptus in Galicia using bomb calorimetry

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**Abstract**

Forestry in Galicia has experienced a large change from the middle 1980s as a consequence of an aggressive forest exploitation due to the introduction of fast growing forest species to be used as raw material for production of pulp. Owing to its easy adaptability to Galician environment, eucalyptus is one of the forest species mostly used. Nowadays, the forest surface covered eucalyptus is close to 240 000 ha. Residues originating from forest exploitation of this species, together with changes experienced by the forest ecosystem cause important environmental problems, amongst them forest fires and environmental wildness.

This study was focussed on the determination of risk indices of the biomass originating from eucalyptus residues. These indices indicate the capability for these residues to start and spread forest fires and can be used to design campaigns to prevent and/or to fight forest fires.

The determination of risk indices includes measurements of flammability, using an epiradiator following the standard UNE-23-721, and caloric values using a static bomb calorimeter. Different parameters necessary for understanding these risk indices, such as elemental chemical composition (Carlo Erba elemental analyser), biological, and environmental parameters were also determined. The study was performed over 1 year, in three different zones situated in Galicia.


*Keywords:* Calorimetry; Caloric values; Flammability; Risk index maps; Forest fire

## 1. Introduction

Owing to forest fires and the abandonment of agricultural land, forestry in Galicia (NW Spain) has experienced a large change due mainly to reforestation campaigns carried out mainly with *Eucalyptus globulus* Labill.

This species was chosen from an economical point of view as it is used mainly for extraction of raw materials for production of wood pulp. This tree species was brought to Galicia some 100 years ago and it was used mainly for ornamental purposes. Nowadays, it covers approximately 240 000 ha [1], i.e., ∼10% of the total forest surface in Galicia, and its use is increasing as a consequence of its adaptability to Galician environment and also to its economical importance.

Recently, campaigns have been developed to fight and/or to prevent forest fires. Among the steps adopted for prevention of forest fires, the knowledge and calculation of risk indices, i.e., the capability of a material (tree) to start and/or spread forest fires, can become very helpful. These indicators can be calculated by means of a combined study of different

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physical, thermochemical, and biological parameters such as

- Caloric values, i.e., the energy contained in the forest biomass. Two caloric 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, this 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 vapor. Both caloric values are related through the equation:

$$\mathrm{LHV} = \mathrm{HHV}(1 - W) - 24.42(W + 9H_{\mathrm{d}}) \quad (1)$$

where LHV corresponds to the lower caloric value of the dry sample, HHV the higher caloric value, $W$ the moisture percentage content, and $H_{\mathrm{d}}$ 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 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 [2] can be calculated using the following equation:

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

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 [2]:

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

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

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. LHV of the trees species is a realistic indicator of the energetic state of the forest biomass of the zone and its knowledge helps to plan a rational exploitation of the energetic resources.
- Flammability can be considered as the ease with which a material catches fire, both spontaneously or through exposure to certain environmental conditions, or as the resistance of a forest species to starting and spreading wildfires.
- Elemental chemical composition (C, H, O, N, S, and Cl).
- 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). Forest fires start in a natural environment, not under a laboratory control. For this reason, the climatic parameters 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 [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, these 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 1 year in order to see how the change of the biological and bioclimatic characteristics influence the values obtained through the thermochemical parameters (HHV and flammability).

## 2. Experimental procedure

The first stage of 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 three forest stations owned by a reputable private wood company, Maderas Villapol (Trabada, Lugo, Spain). These forest stations are well characterized, and are located: No. 1 in Cedeira (A Coruña), No. 2 in As Pontes (A Coruña), and No. 3 in Ferreira (Lugo). Samples were collected from these stations coinciding with cutting programs developed by Maderas Villapol, sometimes in response to our needs. These programs 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, to analyze the possible influence of strong climatic changes in the zones (high temperature and decrease of rain) on caloric values and, to study the relationship between forest residues and forest fires, very common in this season, which will be the subject of a future analysis.

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 *E. globulus* Labill. 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 are 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 then reduced by a coning and quartering procedure to a representative bulk sample of 5–6 kg each. The rest of the residues were abandoned, on the forest surface with the object of periodical samplings to study the evolution of caloric values and flammability of the dead biomass and to compare these with those corresponding to live biomass.

Once 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 then 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 [8].

Once the humidity was determined, the dry sample was ground using two mills of different power, a Retsch SM-1 blade mill and a Taunus MS-50 grinder, in order to homogenize the sample as much as possible, thus making easier the preparation of the sample pellets to be used in the calorimetric experiments.

A part of this ground sample, labeled as fraction A, was used to measure the density and average chemical composition of each of the species being studied. The samples were analyzed 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 $CH_{1.686}O_{0.843}$ 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 discharge from 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. 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 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., after 20 min 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 $26\,431.8 \pm 3.7\,\text{kJ}\,\text{kg}^{-1}$. From five calibration experiments $E(\text{calor}) = 21\,182.28 \pm 0.22\,\text{J}\,\text{K}^{-1}$ (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 and physical parameters of the three main forest stations 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). For a better understanding, these parameters are presented in the form of bioclimatic diagrams, as can be seen in Fig. 1 (only one of three main forest stations is shown, as the bioclimatic characteristics of the remaining two zones are very similar). Mean values were calculated from

Table 1
Main bioclimatic and biological parameters [7] corresponding to the main forest stations where sampling was made

| |
|---|
| Station 1: Cedeira |
| Altitude: 500 m |
| Annual rainfall index: 1062 mm |
| Summer rainfall index: 137 mm |
| Mean annual temperature: 12.9 °C |
| Mean daily maximum temperature of the warmest month (July): 22.5 °C |
| Hydric deficiency: 105 |
| Mediterraneanity index: 2.39 |
| Station 2: As Pontes |
| Altitude: 600 m |
| Annual rainfall index: 1684 mm |
| Summer rainfall index: 173 mm |
| Mean annual temperature: 11.7 °C |
| Mean daily maximum temperature of the warmest month (July): 31.6 °C |
| Hydric deficiency: 58 |
| Mediterraneanity index: 1.91 |
| Station 3: Ferreira |
| Altitude: 400 m |
| Annual rainfall index: 1345 mm |
| Summer rainfall index: 187 mm |
| Mean annual temperature: 12.5 °C |
| Mean daily maximum temperature of the warmest month (July): 31.3 °C |
| Hydric deficiency: 9 |
| Mediterraneanity index: 1.77 |

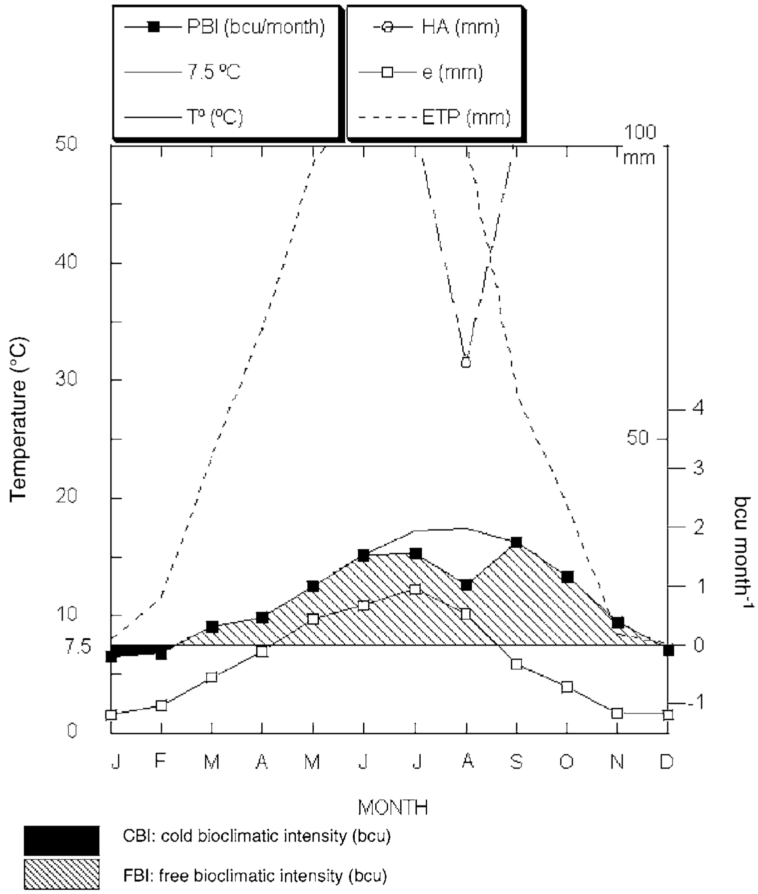


Fig. 1. Representative bioclimatic diagram showing the main environmental characteristics of the zone As Pontes (other zones were similar): *T* (temperature in °C), 7.5 (minimum temperature for vegetal activity), ETP (evapotranspiration in mm), *e* (residual evapotranspiration in mm), HA (hydric availability in mm), and PBI (potential bioclimatic intensity in bcu). The striped zone corresponds with FBI (free bioclimatic intensity).

analysis of data recorded during more than 25 years by the different weather stations situated in the zone [7]. Analysis of Table 1 shows, in fact, that climatic conditions in these three forest stations are very close and, thus, their influence on energy data will not differ. One thing to point out is the possible vegetative stop in winter as a consequence of low temperatures.

Table 2 shows caloric values, moisture content (*M*), density (*D*), and ash content (BA) after combustion in the bomb for the three groups of residues mentioned above, i.e., leaves, and two kinds of branches. It can be seen that caloric values are very similar for the three forest stations. One thing to point out is the trend of HHV of leaves to be larger than those of the two kinds of branches. The same is observed for M, D and BA. This trend could originate from the concentration of essential oils (eucalyptus oil) or any other type of volatile compounds (tannin) having larger HHV [4] (40 000 kJ kg$^{-1}$) in the leaves. It can be also observed that thin branches have larger HHV than thick ones. However, from the energy exploitation point of view this difference is not significant. In the case of LHV, there is not a marked trend since these values depend very much on moisture content. In this table are also shown results corresponding to the part of forest residues abandoned in station 1 during the sampling carried out in November. These residues are usually abandoned in situ after forestry

Table 2
Mean high heating values (HHV) and mean low heating values (LHV), moisture (*M*), density (*D*), and ash percentage after combustion in the bomb (BA) corresponding to the three groups of residues and the seven samplings live matter and two of dead biomass collected in the same zone but in different months

| | HHV ($kJ\,kg^{-1}$) | LHV ($kJ\,kg^{-1}$) | *M* (%) | *D* ($kg\,m^{-3}$) | BA (%) |
|---|---|---|---|---|---|
| Station 1: November (Cedeira) | | | | | |
| Leaves | 21165.08 ± 165.31 (0.78%) | 6151.90 ± 64.47 (1.05%) | 61.00 | 1070 | 1.67 |
| Thin branches | 18931.47 ± 184.27 (0.97%) | 7657.38 ± 93.79 (1.22%) | 49.10 | 1060 | 0.32 |
| Thick branches | 18574.57 ± 191.08 (1.03%) | 8189.68 ± 104.52 (1.28%) | 45.30 | 990 | 0.46 |
| Station 1: January (Cedeira) | | | | | |
| Leaves | 21581.24 ± 238.11 (1.10%) | 6912.29 ± 98.34 (1.42%) | 58.70 | 1106 | 0.70 |
| Thin branches | 18589.44 ± 77.82 (0.42%) | 7141.53 ± 37.67 (0.53%) | 51.60 | 993 | 0.74 |
| Thick branches | 18204.28 ± 145.81 (0.80%) | 6958.77 ± 71.01 (1.02%) | 51.30 | 949 | 0.19 |
| Station 1: March (Cedeira) | | | | | |
| Leaves | 21572.98 ± 157.80 (0.73%) | 7433.31 ± 69.59 (0.94%) | 55.90 | 1050 | 1.49 |
| Thin branches | 18818.44 ± 145.27 (0.77%) | 7369.54 ± 72.64 (0.99%) | 50.00 | 990 | 0.14 |
| Thick branches | 18166.85 ± 11.72 (0.27%) | 7113.07 ± 24.78 (0.35%) | 49.50 | 930 | 0.16 |
| Station 1: May (Cedeira) | | | | | |
| Leaves | 21513.14 ± 298.39 (1.39%) | 8003.57 ± 138.36 (1.73%) | 53.60 | 1038 | 1.28 |
| Thin branches | 18422.72 ± 14.79 (0.08%) | 7159.23 ± 7.52 (0.10%) | 49.10 | 1016 | 0.50 |
| Thick branches | 18459.39 ± 85.16 (0.46%) | 7565.08 ± 43.44 (0.57%) | 49.00 | 980 | 0.40 |
| Station 1: July (Cedeira) | | | | | |
| Leaves | 21355.42 ± 195.91 (0.92%) | 7559.99 ± 87.38 (1.16%) | 55.40 | 1089 | 0.66 |
| Thin branches | 18550.17 ± 111.25 (0.60%) | 8512.46 ± 61.97 (0.73%) | 44.30 | 1016 | 0.47 |
| Thick branches | 18539.16 ± 184.03 (0.99%) | 7626.87 ± 94.04 (1.23%) | 48.90 | 986 | 0.31 |
| Station 2: August (As Pontes) | | | | | |
| Leaves | 21218.75 ± 201.67 (0.95%) | 6209.67 ± 73.25 (1.26%) | 61.20 | 1033 | 1.52 |
| Thin branches | 18435.59 ± 135.44 (0.73%) | 6730.08 ± 63.39 (0.94%) | 53.20 | 912 | 0.52 |
| Thick branches | 18179.03 ± 242.05 (1.33%) | 7044.09 ± 118.85 (1.69%) | 50.90 | 825 | 0.21 |
| Station 3: September (Ferreira) | | | | | |
| Leaves | 22105.45 ± 239.39 (1.08%) | 7107.00 ± 98.98 (1.39%) | 58.70 | 1064 | 0.98 |
| Thin branches | 18659.97 ± 195.13 (1.05%) | 7441.93 ± 97.37 (1.31%) | 50.10 | 1037 | 0.41 |
| Thick branches | 17904.58 ± 95.08 (0.53%) | 8582.79 ± 55.05 (0.64%) | 42.10 | 1023 | 0.13 |
| Dead matter | | | | | |
| Station 1: March (Cedeira) | | | | | |
| Leaves | 21810.65 ± 111.69 (0.51%) | 2823.76 ± 25.80 (0.91%) | 76.90 | 940 | 1.17 |
| Thin branches | 18600.28 ± 159.78 (0.86%) | 8469.51 ± 87.72 (1.04%) | 45.10 | 885 | 0.61 |
| Thick branches | 18230.83 ± 84.01 (0.46%) | 8378.79 ± 46.71 (0.56%) | 44.40 | 848 | 0.48 |
| Station 1: Agosto (Cedeira) | | | | | |
| Leaves | 20006.01 ± 116.88 (0.58%) | 11172.36 ± 75.27 (0.67%) | 35.60 | 1000 | 1.32 |
| Thin branches | 18862.74 ± 251.37 (1.33%) | 13221.90 ± 197.08 (1.49%) | 21.60 | 982 | 0.32 |
| Thick branches | 18398.03 ± 315.03 (1.71%) | 10576.79 ± 209.81 (1.98%) | 33.40 | 979 | 1.29 |

tasks without any control. Our aim is to study the possible influence of their proper transformations (degradation) and climatic agents on physicochemical properties of the residual materials, mainly caloric values and flammability, and also on the behavior of live biomass in the case of forest fires. As can be seen, HHV keeps practically constant. However, a decrease on HHV corresponding to the last sampling of dead matter can be observed. This drop could be understood as a consequence of a possible loss either by washing and/or evaporation of tannin and some other compounds of large caloric values. Changes in

LHV are more significant for dead matter than those corresponding to live matter. This means that dead biomass is more influenced by changes in climatic parameters than live biomass.

Table 3 lists elemental composition of samples from different forest stations. The main feature to be pointed out is the good agreement among values corresponding to the different samples. The elemental composition of dead matter is very similar to that of the different live samples, except for nitrogen contents that show higher values in the case of the dead matter as a consequence of the degradation of these residues after some months of exposure to wind and weather.

Table 4 shows LHV and flammability class values calculated taking into account the percentage of the three groups of residues in the final bulk sample. These data are very important. On the one hand, from the energy exploitation point of view, these residues should be processed when showing their larger LHV. However, LHV are not very different, thus allowing their use as an energy source all over the year. On the other hand, flammability is a key parameter for studying the start and spreading of forest fires. Raw residues of *E. globulus* Labill show very low values of flammability over the year as opposed to results shown in previous studies [9]. This is due to their large content of moisture. This makes these raw residues "pyro-resistant". In this same table it can be seen that LHV corresponding to dead matter collected in August (9 months after cutting) is class 5 (as a direct consequence of low moisture content, summer) while samples collected in March (high moisture content) are in class 2. This fact indicates that, as flammability is 5 in both cases, this dead matter constitutes a high risk agent for the start and spreading of forest fires in summer.

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, 62% leaves, 25% thin branches, 13% thick branches; for the dry sample, 57, 25 and 18 % respectively. Fig. 2 is a typical plot for the three types of residues of the ratio LHV/HHV versus moisture content (%). As expected, there is a linear relationship with a slight deviation caused by deviation of individual hydrogen content (%) from the mean value. This can be understood in terms of Eq. (1). Dead matter shows a similar behavior.

Table 3
Results of chemical analysis for dry sample corresponding to the three groups of residues and the seven samplings of live biomass and two of dead matter

| | Chemical analysis (% of total composition) | | | | |
|---|---|---|---|---|---|
| | N | C | H | O | S |
| Station 1: November (Cedeira) | | | | | |
| Leaves | 0.69 | 57.66 | 7.15 | 34.17 | 0.33 |
| Thin branches | 0.18 | 52.75 | 6.97 | 40.01 | 0.09 |
| Thick branches | 0.17 | 52.63 | 7.19 | 39.58 | 0.43 |
| Station 1: January (Cedeira) | | | | | |
| Leaves | 1.32 | 50.09 | 6.25 | 42.18 | 0.16 |
| Thin branches | 1.29 | 45.04 | 5.60 | 47.97 | 0.10 |
| Thick branches | 1.34 | 45.70 | 5.95 | 46.86 | 0.15 |
| Station 1: March (Cedeira) | | | | | |
| Leaves | 1.57 | 57.85 | 7.38 | 32.89 | 0.31 |
| Thin branches | 0.14 | 53.04 | 7.45 | 39.24 | 0.13 |
| Thick branches | 0.15 | 52.19 | 7.68 | 39.82 | 0.16 |
| Station 1: May (Cedeira) | | | | | |
| Leaves | 1.25 | 52.30 | 6.50 | 39.74 | 0.21 |
| Thin branches | 1.36 | 45.67 | 5.82 | 47.02 | 0.13 |
| Thick branches | 1.22 | 45.94 | 5.84 | 46.94 | 0.06 |
| Station 1: July (Cedeira) | | | | | |
| Leaves | 1.20 | 50.56 | 6.24 | 41.83 | 0.17 |
| Thin branches | 1.44 | 44.19 | 5.64 | 48.48 | 0.25 |
| Thick branches | 1.12 | 45.29 | 5.81 | 74.60 | 0.18 |
| Station 2: August (As Pontes) | | | | | |
| Leaves | 1.23 | 50.61 | 6.20 | 41.72 | 0.24 |
| Thin branches | 1.28 | 45.73 | 5.82 | 47.07 | 0.10 |
| Thick branches | 1.54 | 45.89 | 5.92 | 46.50 | 0.15 |
| Station 3: September (Ferreira) | | | | | |
| Leaves | 1.23 | 51.57 | 6.49 | 40.27 | 0.44 |
| Thin branches | 1.48 | 47.26 | 5.89 | 45.20 | 0.17 |
| Thick branches | 1.06 | 45.41 | 5.94 | 47.38 | 0.21 |
| Dead matter | | | | | |
| Station 2: March (Cedeira) | | | | | |
| Leaves | 1.80 | 53.03 | 6.63 | 38.16 | 0.38 |
| Thin branches | 1.67 | 43.71 | 5.31 | 49.10 | 0.21 |
| Thick branches | 1.43 | 43.81 | 5.51 | 49.05 | 0.20 |
| Station 3: August (Cedeira) | | | | | |
| Leaves | 1.47 | 50.04 | 5.95 | 42.24 | 0.30 |
| Thin branches | 1.34 | 47.66 | 6.03 | 44.78 | 0.19 |
| Thick branches | 1.23 | 46.04 | 5.88 | 46.67 | 0.18 |

Figs. 3 and 4 show HHV and LHV, respectively, corresponding to bulk samples and to the three fractions. Mean caloric values correspond to the bulk sample and were calculated taking into account the

Table 4
Mean flammability values according to the model proposed by Valette [8], and LHV class[a]

| | LHV class[b] | Flammability class[c] |
|---|---|---|
| Station 1: November (Cedeira) | 4 | 1 |
| Station 1: January (Cedeira) | 4 | 0 |
| Station 1: March (Cedeira) | 4 | 0 |
| Station 1: May (Cedeira) | 5 | 2 |
| Station 1: July (Cedeira) | 5 | 1 |
| Station 2: August (As Pontes) | 3 | 0 |
| Station 3: September (Matamá) | 4 | 0 |
| Dead matter | | |
| Station 1: March (Cedeira) | 2 | 5 |
| Station 1: August (Cedeira) | 5 | 5 |

[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 kJ kg$^{-1}$; class 2: 4500 kJ kg$^{-1}$ $\leq$ LHV $\leq$ 5500 kJ kg$^{-1}$, class 3: 5500 kJ kg$^{-1}$ $\leq$ LHV $\leq$ 6500 kJ kg$^{-1}$; class 4: 6500 kJ kg$^{-1}$ $\leq$ LHV $\leq$ 7500 kJ kg$^{-1}$, class 5: LHV $\geq$ 7500 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)l 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 (kJ kg$^{-1}$) | LHV (kJ kg$^{-1}$) |
|---|---|---|
| Station 1: November (Cedeira) | 20081.72 | 6820.80 |
| Station 1: January (Cedeira) | 20559.55 | 6970.33 |
| Station 1: March (Cedeira) | 20065.90 | 7357.05 |
| Station 1: May (Cedeira) | 20194.46 | 7814.39 |
| Station 1: July (Cedeira) | 20353.08 | 7792.51 |
| Station 2: August (As Pontes) | 19947.18 | 6447.15 |
| Station 3: September (Matamá) | 20374.13 | 7396.66 |
| Dead matter | | |
| Station 1: November (Cedeira) | 20363.69 | 4957.35 |
| Station 1: November (Cedeira) | 19430.75 | 11607.32 |

contents (%) of the different fractions and, in the case of LHV, of their moisture contents. It can be seen that HHV keep constant over the year independently of the forest stations where samples were collected. Obviously, LHV behavior is not as regular, as it depends on moisture content which is different depending on the season and on the residue fraction.

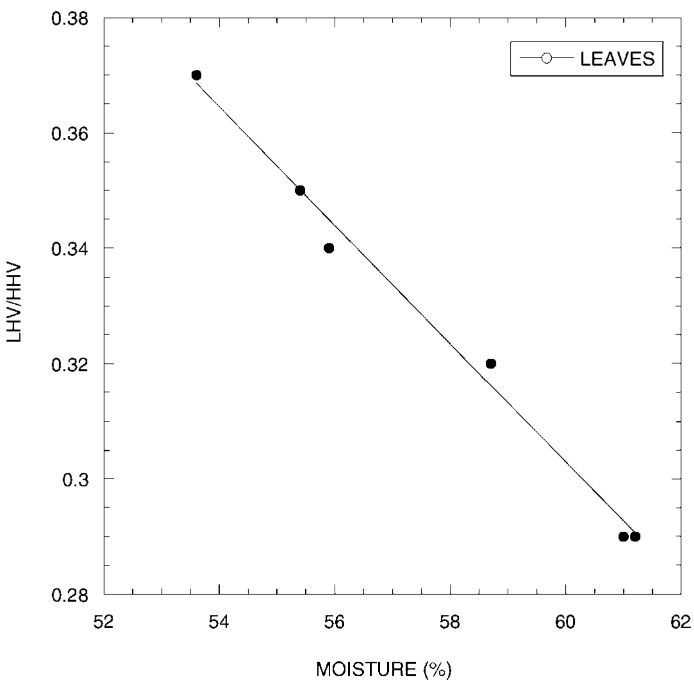


Fig. 2. Plot of LHV/HHV versus moisture content for the three kind of residues.

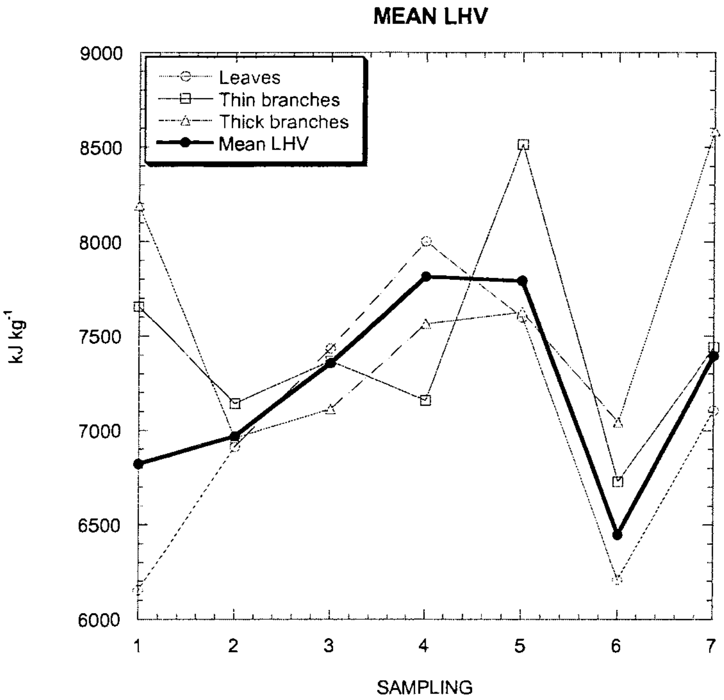


Fig. 3. Mean HHV changes throughout the year (sampling number).

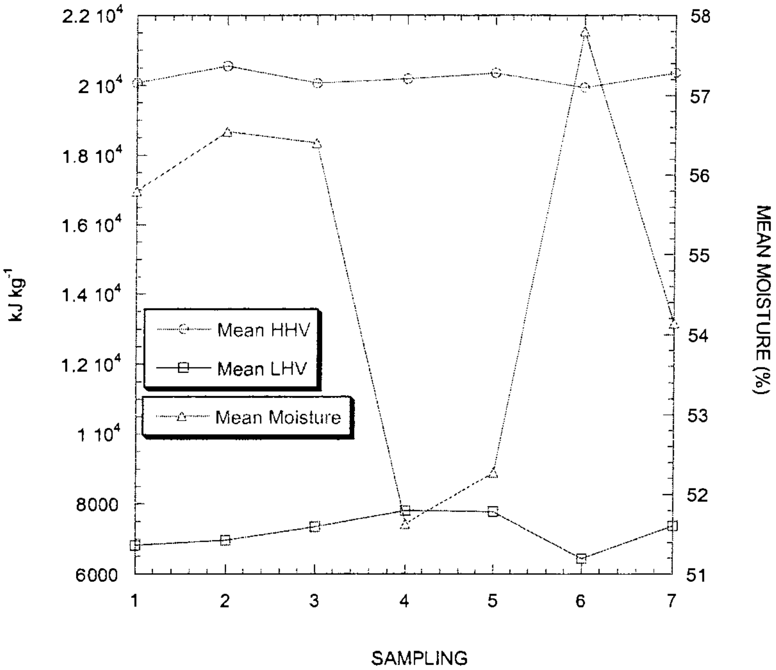


Fig. 4. Mean HHV, LHV, and moisture content along the year (sampling number).

Fig. 4 shows the behavior of mean HHV, mean LHV, and mean moisture content (%) as a function of the sampling period. LHV shows its highest value in May, that coincides with the blooming period, when plants show maximum vegetative activity, thus increasing oil and other volatile compounds production.

LHV is the main parameter to take into account as it is a real index of natural processes. Moreover, HHV keeps practically constant over the year. As it is known, there is an important relationship between caloric values and moisture content, as maximum values of LHV correspond to minimum moisture content.

Table 6
Risk index calculation of one of the species (15 years old *E. globulus* Labill.) collected in summer (August) for dead and live matter, respectively [9]

| | Experimental values | | Calculated values | |
|---|---|---|---|---|
| | Dead | Live | Dead | Live |
| Thermochemical parameters | | | 4 | 2 |
| HHV class number | 5 | 2 | | |
| Flammability class number | 5 | 5 | | |
| Physicochemical properties (20%) | | | 0.1445 | −0.0833 |
| Density (kg $m^{-3}$) (30%) | 991.7 | 909.7 | | |
| Own moisture (%) (65%) | 31.7 | 63.09 | | |
| Bomb ashes after combustion (%) (5%) | 1.06 | 0.91 | | |
| Biological Characteristics (25%) | | | −0.0632 | −0.0337 |
| Physiological activity (10%) | Middle–high (2.16) | 0 | | |
| Essential oils/resins (10%) | Middle–high | Low | | |
| Age (10%) | 15 | 15 | | |
| Habit (10%) | Plantation | Plantation | | |
| Forest waste generated (20%) | Low | Low | | |
| Forest cover around (20%) | Middle | Middle | | |
| Perennial/deciduous (10 %) | P | P | | |
| Blooming period (10%) | Spring–summer | Spring–summer | | |
| Climate characteristics (40%) | | | 0.1358 | −0.0579 |
| Rainfall (40%) | | | | |
| Monthly mean amount (mm) (35%) | 53 | 146 | | |
| Periodicity (65%) | Low regular | Very regular | | |
| Mean temperature (°C) (20%) | 18.3 | 9.7 | | |
| Hydric availability (mm per month) (20%) | 53 | 246 | | |
| Environmental humidity (% per month) (20%) | 66.1 | 65.2 | | |
| Parameters depending on physical environmental conditions (15%) | | | 0.0150 | 0.0075 |
| Zone wind (30%) | | | | |
| Strength (60%) | Middle–low | Middle | | |
| Periodicidity (40%) | Middle–low | Regular | | |
| Clouds (10%) | | | | |
| Amount (50%) | Low | Abundant | | |
| Regularity (50%) | Low | Abundant | | |
| Topography (20%) | Very favorable | Favorable | | |
| Sun radiation (10%) | | | | |
| Sunshine (%) (50%) | Middle–high | Low | | |
| Sunny days (50%) | Middle–high | Low | | |
| Anthropic activity (30%) | Middle–high | Middle–low | | |
| Risk index final value | | | 5.26 | 3.33 |
| Risk index class | | | 5 | 3 |

Analyses of data show that climatic conditions have not an important influence on HHV. For LHV the differences are wider, reaching 17%, as a consequence of their dependence on water content.

Table 6 shows the different parameters used for calculation of the risk index [9–11] of *E. globulus* Labill. The study was made both on dead and live matter and corresponds to samples collected in the same zone on August. The study was made using 15 years old trees. The samples were collected all over the year.

Table 7 shows risk index evolution over the year for live and dead matter. It can be observed the large increase in the risk index corresponding to dead matter as the consequence of the enormous increase in flammability (see Table 4). Fig. 5 shows risk index maps corresponding to November and August.

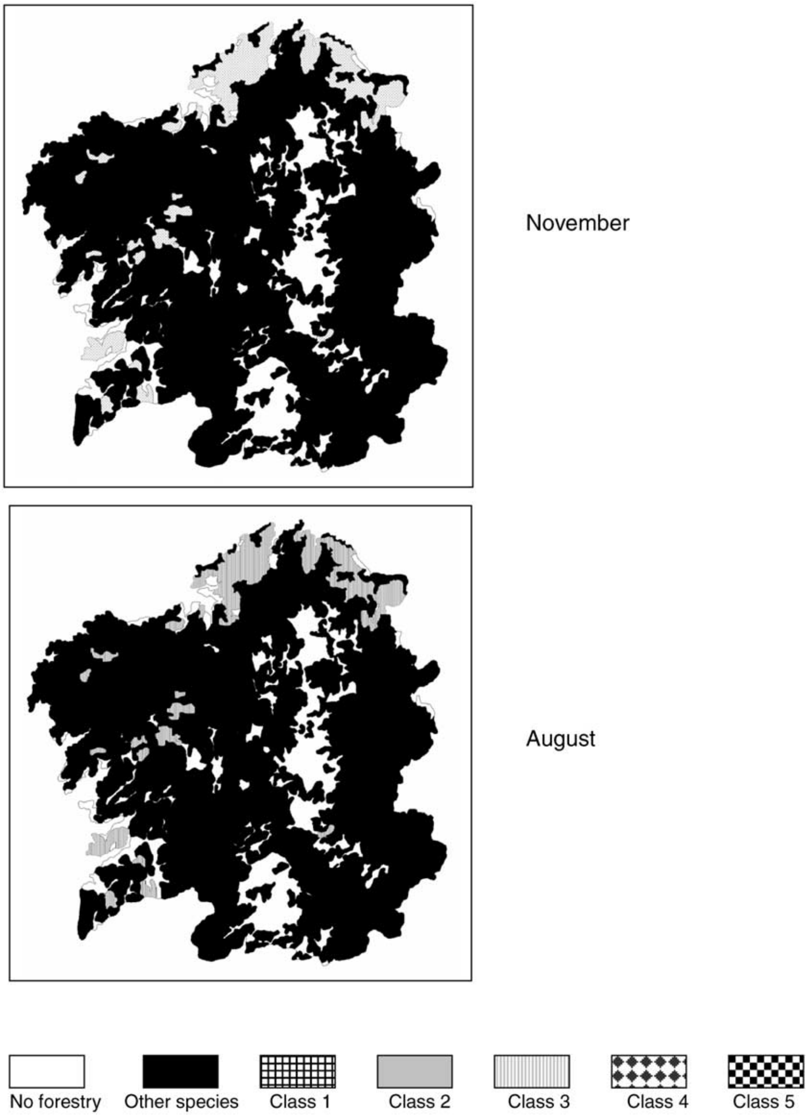


Fig. 5. Risk index maps corresponding to November and August.

Table 7
Risk index succession over the year for live and dead biomass residues[a]

| | Risk index |
|---|---|
| Station 1: November (Cedeira) | 2 |
| Station 1: January (Cedeira) | 2 |
| Station 1: March (Cedeira) | 2 |
| Station 1: May (Cedeira) | 3 |
| Station 1: July (Cedeira) | 3 |
| Station 2: August (As Pontes) | 2 |
| Station 3: September (Matamá) | 2 |
| Dead matter | |
| Station 1: March (Cedeira) | 3 |
| Station 1: August (Cedeira) | 5 |

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

## 4. Conclusions

LHV and mainly HHV remain reasonably constant though LHVs are more dependent on environmental moisture, specially in the case of the dead matter. As it can be seen HHVs are very close in all the zones studied. The fact that caloric values show very close values in all the zones is very important for energy exploitation and it allows extrapolation of these results for different zones and species.

HHVs are high over the year (mean class value 4). This means that, from the energetic point of view, *E. globulus* Labill. is a tree showing a high risk in a "non-clean" environment. However, its flammability (mean value $<$1) is very low, thus diminishing the risk of initiating forest fires. Because of this, *E. globulus* Labill. can be considered as a low risk tree regarding to forest fires.

However, residues originating from eucalyptus forestry can become very dangerous in initiating forest fires during seasons with high temperature and low environmental moisture mainly if they are abandoned on the forest without control. It can be seen that these residues show, in March, a risk index 3 higher than that showed by the live trees thus indicating an increase in the risk index. Because of this, a rational cleaning of the forest is a key measure to prevent and/or to fight forest fires. Obviously, this cleaning task must be done carefully to avoid soil defertilization. By doing this, eucalyptus cold be even considered as a natural firebreak species.

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