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# ENERGETIC STUDY OF RESIDUAL FOREST BIOMASS USING CALORIMETRY AND THERMAL ANALYSIS

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The European policy on energy focus on the search for alternative and renewable sources of energy where forest biomass plays a significant role.

In this article, calorific values of different kinds of forest residues (leaves, thin branches, barks, etc.) are reported. These values were measured by combustion bomb calorimetry with the objective of understanding, through different risk indices, the behaviour of forest waste in the case of wildfires, and also to study the use of forest residues as raw materials to be used as energy sources. The study was complemented with determination of elemental analysis, flammability using a standard epiradiator, thermodegradation analysis, and different mechanical tests trying to get relationships between thermal behaviour and some physical properties.

The study was carried out on *Eucalyptus globulus* Labill and *Pinus pinaster* Aiton, because these forest formations have both high economical and ecological interest in Galicia (NW Spain).

**Keywords:** *calorific value, calorimetry, flammability, forest fire, risk index, thermal analysis, xyloenergy*

## Introduction

In the last 150 years, the world forest surface was reduced in more than 65%, that is around $4.5\cdot10^9$ ha [1, 2].

One of most important causes of this considerable environmental deterioration corresponds to forest fires that, direct or indirectly, were originated in about 98% by man activities. In the Mediterranean zones, wildfires are the main and nearly exclusive responsible for the loss of forest covered surface. Since the last 90's, Spain lost more than 200 000 ha of forest surface [3], thus becoming the most affected Union European country, in front of Italy, Portugal, Greece and France.

Particularly, in Galicia (NW Spain) with a forest surface representing 11% of the whole Spanish one, forest fires devastated around 40 000 ha per year [3].

To understand the meaning of the bulk environmental deterioration, it is necessary to analyze the ecological damage through: loss of forest resources and fertile soil and also an economical loss of 240 million euros per year, that were spent to prevent and fight forest fires and also to recover degraded green spaces. To summarize, Spain has lost since the 1960's more than 6 400 000 ha with an economical damage of around $4.5\cdot10^{10}$ € [3].

One of the modern strategies to fight forest fires consists in the design of risk indices [1, 2, 4–6]. These risk indices try to guess the behaviour of the different forest species before forest fires, depending on their vegetative state and the environment in which they grow up. These indices can be elaborated by combination of many factors associated to the starting and spreading of forest fires and help to avoid or fight wildfires in the most effective way.

## Objectives

In the present study, forest fires were considered as physical processes depending on three basic factors [1, 2, 7]: a fuel, oxygen and temperature (without taking into account the accidental or planned cause). One of the main objectives of this study was the search for a new risk index that incorporate all the known risk indices basically based on physical environmental conditions, that up to now were used independently. A risk index can be defined as a numerical value that can be calculated from many parameters integrated into a cumulative final value that represents the physical state of a fuel to initiate and/or spreading forest fires. By integrated, we understand an interaction among many parameters that have influence both on the ignition or beginning of the wildfire (ignition risk index), and on the capacity to spread fire (spreading index), that have been for long studied separately. Cumulative means the fractional contribution of both of these indices to the final value of the risk index.

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With the development of this new risk index, still in experimental phase, it is aimed the elaboration of a numerical model that could be converted in a colour scale to be used for the design of a risk indices map that could be applied to prevent and/or fight forest fires.

In parallel with this study, an estimate was made of the economical benefit that could be originated by a rational and sustainable exploitation of the resources contained in the residual biomass resulting from different silviculture tasks carried out on the two most important forest species in Galicia: eucalyptus and pines [8–11].

## Experimental

### Material and methods

The different parameters that contribute either to the calculation of risk indices or to the design of a procedure for forest resources energy evaluation are considered in this section. For a better understanding of their particular role they are divided into different categories:

- material fuel own parameters
- surrounding zone parameters
- climatic parameters
- physical environmental parameters
- other parameters
- other risk indices depending only on climatic parameters that help to complement the index here presented

It must be pointed out that the risk index here reported was worked out after years of field and laboratory research. It is a model based on actual experimental data and, as an innovation, it combines both prevention and forest fires spreading studies.

The different parameters and categories are briefly reported.

### Fuel material own parameters

These parameters are defined as those directly depending on own characteristics of the forest species exposed to potential forest fires. Among them one must mention:

- thermochemical characteristics such as: calorific values, flammability and behaviour before thermodegradation [12–14]
- physico-chemical characteristics such as: density, humidity, chemical composition and ash percentage after combustion
- biological characteristics: vegetative activity, essential oils and/or resins content, age, perennial or deciduous leaves, and blooming period

The role of each of these characteristics on the risk index is next described:

- Calorific value, that is, the energy contained in a mass unit of forest biomass. Two calorific values must be pointed out, the higher heating value (*HHV*), that is determined experimentally in the laboratory [15], and the lower heating value (*LHV*) that can be calculated, from *HHV*. Both calorific values are related through the equation:

$$(LHV)=HHV(1-W)-24.42(W+9\mathrm{H_d}) \qquad (1)$$

where (*LHV*) corresponds to the lower heating value of the dry sample, (*HHV*) is the higher heating value, *W* is the moisture percentage content, and $\mathrm{H_d}$ is the hydrogen percentage of the dry sample. The heat of vaporization of water is taken as 2441.8 kJ $\mathrm{kg^{-1}}$, and the water formed during combustion is 9 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 in 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 [16]. *HHV* is determined by combustion of the forest sample in a static bomb calorimeter under an oxygen atmosphere.

- Flammability can be considered either 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. It is determined, following the standard UNE-23-721, using a standard epiradiator of 500 W constant nominal power [17].
- Thermodegradation. The behaviour of a forest species before thermodegradation supplies information about three very important and different items that help to evaluate the response of a forest fuel faced to a forest fire [7]. In the first place, the 'resistance' of a forest species to be degraded and because of this to withstand the fire attack. In the second place, the maximum temperature that can tolerate and thus the temperature that the different kinds of forest biomass can generate when subjected to fires and also showing the devastation power and the potential time for the activity of the wildfire. In the third place, the thermodegradation stability supplies information about the homogeneity of the response of a forest formation before wildfires [12–14]. The study of this part was carried out using an infrared spectrophotometer using the Fourier transformed (FTIR from Perkin Elmer, system 2000).
- Density. It was determined using the picnometric method. It complements thermodegradation studies supplying data for a better understanding of the process, as woods with high densities exhibit different behaviour as those with low densities regarding both to flammability and calorific values.
- Moisture [18]. It is a key parameter for *LHV* determination. It was determined as the mass loss after

drying of the sample in a Selecta 200210 natural desiccating oven, at 105°C, to constant mass.

- Chemical composition. Wood chemical composition, mainly in the case of mineralized compounds, could have an influence on delaying combustion as it affects directly on flammability [7]. Elemental chemical composition was determined by a Carlo Erba analysis equipment.
- Ash after combustion. Gives information about the virulence of a fire, because the smaller the amount of ash after combustion, the greater the temperature achieved, thus indicating a more complete combustion. Ash content was determined from the remains of wood inside the calorimetric bomb after combustion of the sample. In a forest fire, ash percentage is greater than in a bomb combustion because of the 'ideal' conditions in the last case.
- Vegetative activity. It has as an influence on wood moisture content, as in vegetative stop periods (autumn and winter), the own moisture of wood is smaller, thus increasing the possibility of catching fire in case of propitious environmental conditions.
- The existence of essential oils and/or resins, that are compounds with low ignition temperature and high heating value (30 000 kJ kg$^{-1}$), have a direct influence on the starting and spreading of forest fires. These compounds can achieve 15% of the forest species whole composition [7]. This type of compounds are specially dangerous in the summer when environmental temperature creates a highly flammable atmosphere, specially in conifer formations that because of the existence of terpenes highly increase the risk of wildfires owing to the enormous flammability of these compounds.
- Age. As a tree grows, its content in cellulose (a carbohydrate with a calorific value of approximately 16 100 kJ kg$^{-1}$) is gradually substituted by lignin (an aromatic polymer with a calorific value of about 24 500 kJ kg$^{-1}$) [7]. For this reason, the greater the age of forest formations the greater the devastating effects of forest fires. Moreover, young individual trees have a great percentage of young tissues with high water content thus showing both lower calorific values and flammability.
- Perennial or deciduous leaves. Deciduous leave trees go through periods particularly sensible to wildfires, as the end of summer and the end of autumn. In these periods, tissues moisture content is practically null and because of this the *LHV* shows its maximum value. In these periods, the risk index is very high.
- In the blooming period, plant tissues moisture content is maximum (and because of this the vegetative activity). The emergence of young and green tissues make the calorific value to significantly decrease.

*Own environmental parameters*

These parameters are key for determination of the capacity of the environment to spreading forest fires. They are based on the habitat configuration (presence of continuous horizontal and/or vertical fuel and woodland density):

- Habitat configuration. The two forest species here studied, and their arrangement in the different strata, have an important influence on fire spreading. Trees with large content in essential oils and/or resins, such as conifers, originate a propitious environment for fires.
- The presence of forest residues, compounds with high calorific values and high flammability, caused by the very low content in cellulose due to a fast degradation, high lignin content and low moisture content favour the starting and spreading of forest fires.
- Wooded density has influence on fire spreading, because the excess of forest fuel load existing in a dense forest may cause an oxygen deficiency that slows down the forest fire advancing.

*Climatic parameters*

These parameters have a direct influence on the starting and spreading of forest fires. The following parameters must be cited: rainfall (quantity and regularity), mean environmental temperature, hydric availability and moisture. They can be analyzed all together. As a rule, dry periods and high mean temperatures (summer) originate high risk indices in forest formations. These parameters were analyzed as a whole using the different climatic dependent risk indices existing nowadays such as: Nesterov index, Angström index, Australian south-eastern index, Orieux index, and Mediterranean France index. A brief mention of these indices is reported:

- Nesterov index. This index analyzes the excess of temperature over the dew point and its dependence on the rainfall days,

$$P=\sum_{\mathrm{i}=1}^{\mathrm{n}}(T_{\mathrm{i}}-D_{\mathrm{i}})T_{\mathrm{i}}$$

where $P$ is the ignition index, $T$ is the temperature in °C, $D$ is the dew-point temperature in °C, and $n$ is the number of days since the last rainfall greater than 3 mm. There is virtually nil risk if the index value is under 301, moderate risk, for a value from 301 to 1000, high risk, from 1000 to 4000, and extremely high risk for values over 4000. This index is limited in the sense that is not daily but, to be effective, it must be determined from abundant weather data daily supplied. The calculations are begun in the spring on the first day the temperature exceeds freezing (0°C) after the snow has melted. The ignition index increases each day until a rainfall of more than 3 mm occurs at which time the index drops back to zero and the process begins again.

- Angström index. This index relates environmental temperature with relative humidity through $I=H/20+(27-T)/10$, where $H$ is the percentage of relative humidity and $T$ is the air temperature in °C. Risk index is low for values >4.0, moderate risk for values from 4.0 to 2.5, high risk between 2.5 and 2.0, and extremely high for values <2.0. The index ignores the effects of precipitation and wind, and does not accurately reflect the relationship between relative humidity, temperature, and fuel moisture.
- Australian southeastern index. Similar to the previous one,

$$P=\sum_{i=1}^{n}(0.6T_i-0.3H_i-30)$$

  where $n$ is the number of days since the last rainfall, $T$ is the maximum temperature in °F, and $H$ the relative humidity percentage (%). Risk index is low for values <7, moderate between 7 and 50, high risk in the range from 51 to 99, and extremely high for values >99. This index is not indicated in the case of climates similar to the Galician one.
- Mediterranean France index. $I_{85}=(r^{0.5}H_n/v_b)C$, where $r$ is the hydric deficiency (100 mm according to Thornthwaite), $H_n$ is the minimum relative humidity expressed as %, $v_b$ is the wind speed in °Beaufort, and $C$ is the phenomenological coefficient of vegetation. Risk index is virtually nil for values >450, low risk for values between 450 and 300, moderated risk in the range from 300 to 150, high risk from 150 to 50, and extremely high for values <50.
- Orieux index is very similar to previous indices, $D=Cd^{[-\Sigma(E/C)]}$, where $D$ is the drought index, $C$ the available water capacity of the soil and $E$ the potential evapotranspiration according to Thornthwaite.
- Tellysin index. Similar to Nesterov. It calculates the logarithm of the difference between the actual temperature and the dew-point temperature,

$$T=\sum_{i=1}^{n}\log(t-r)$$

  where $n$ is the number of days since last significant rainfall, $t$ is the actual temperature in °C, and $r$ is the dew-point temperature in °C. Null risk index for $T\leq2.0$, low risk in the range $2.0<T\leq3.5$, middle risk for $3.5<T\leq5.0$, and high risk $T>5.0$. Owing to its enormous dependence on climatic conditions, this risk index suffers same limitations as Nesterov index.

It was theoretically proved that the value obtained for our risk index corresponding to the sections climatic characteristics and parameters depending on physical environmental conditions is very close to the values obtained using any of the indices previously mentioned. These risk indices can be modified after application in order to improve results. However, they will always strongly depend on climatic features. Furthermore, the index here presented is the one fitting best the environmental conditions of the zone where the study was carried out.

### *Physical environmental parameters*

These parameters complement the surrounding own parameters and climatic parameters and have a decisive influence on the land adaptation to make forest fire motion easier or more difficult. Among these parameters one can cite: winds (strength and regularity), clouds (quantity and regularity), sun radiation (quantity and periodicity), topography of the zone (orientation, slope and location) and studies about Byram equation [16]. As it was previously mentioned, this last parameter is related to *LHV*. 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. The fireline intensity [1, 2, 16] can be calculated using the following equation:

$$I=(LHV)Wv \qquad (2)$$

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

$$I=0.007(LHV)Wv \qquad (3)$$

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

The 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 (that is, the total heat release of one unit area of fuelbed divided by the burning time) multiplied by the depth of the fire front.

### *Other parameters*

From the scientific point of view, these parameters are difficult to control, but its actual influence is crucial for starting forest fires. Among these parameters: man activities on environment, economical–ecological interest and recent history of the zone (intensity and regularity of fires and interval since the last fire).

- Man activities modify considerably the response of the environment to an external aggression. In the case of forest fires, these activities could be either, a direct and uncontrollable cause, or a key agent to prevent and fight these fires. Silviculture, forest resources exploitation, infrastructure creation, etc. are some of these parameters.

- The economical-ecological interest of the zone is nowadays the cause of the most part of forest fires and, from the scientific point of view, it is the most uncontrollable parameter. In the last years in Galicia, and same in any other country, mean density of forest fires happen in zones close to places where building land is in a great demand and, because of this, have an immediate high economical value, a very small ecological value, and is defined as a 4–5 model of fuel (zones with plentiful bushes and forest waste originated from silviculture tasks and wood exploitation) [3].
- The recent history of the zone allows on the one hand, to make more flexible the assignment of risk indices to zones that, because of recent fires, have not enough wood fuel load to generate a new fire in period of at least 5 years and, on the other hand, to design fire prevention models for the zone.

## Results and discussion

Table 1 shows the main climatic and environmental physical parameters having a strong influence on the physical characteristics of the fuel, in our case eucalyptus forest formations situated in North Galicia, a zone

**Table 1** Main bioclimatic and biological parameters [19] corresponding to the main forest stations where sampling was made

| Galician north zone | |
|---|---|
| altitude | 400–600 m |
| annual rainfall index | 1062–1684 mm |
| summer rainfall index | 137–187 mm |
| mean annual temperature | 11.7–12.9°C |
| mean daily maximum temperature of the warmest month (July) | 22.5–31.3°C |
| hydric deficiency | 9–105 |
| mediterraneanity index | 1.77–2.39 |

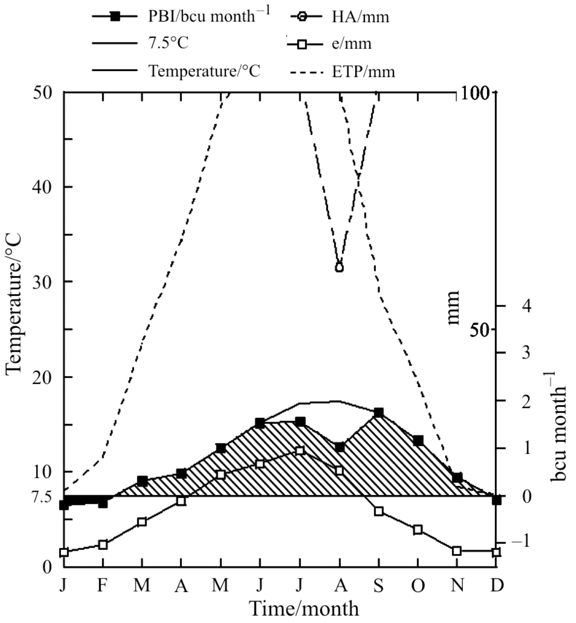

**Fig. 1** Representative bioclimatic diagram showing the main environmental characteristics of the north zone of Galicia: *T* – temperature in °C, 7.5 – minimum temperature for vegetal activity, *ETP* – evapotranspiration in mm,

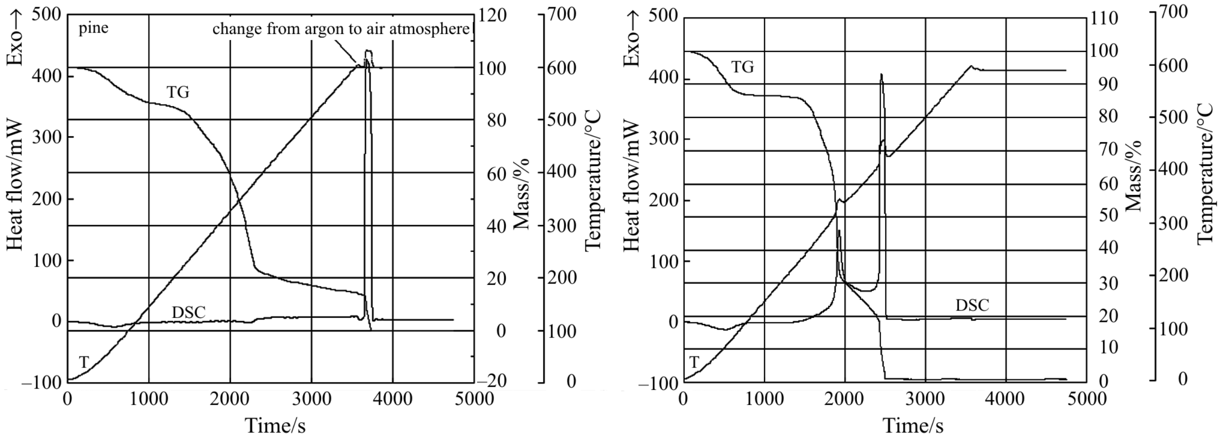

**Fig. 2** Plots showing thermal degradation of pine and eucalyptus species

| | Sample mass/ mg | Gas | Gas sweeping/ mL min$^{-1}$ | Heating rate from 25 to 600°C/ K min$^{-1}$ | Isotherm |
|---|---|---|---|---|---|
| Pine | 14.679 | air and argon | 50 | 10 | 600°C for 20 min |
| Eucalyptus | 14.447 | air | 50 | 10 | 600°C for 20 min |

**Table 2** Risk index calculation of one of the species (15 years old *E. globulus* Labill) collected in spring in north coast

| *Eucalyptus globulus* Labill<br>Age: 15 years | | | Experimental values | Calculated values |
|---|---|---|---|---|
| **Thermochemical parameters** | | | | |
| HHV class number | | **50** | 5 | |
| flammability class number | | **50** | 4 | 4.5 |
| **Physico-chemical properties** | | | | **20** |
| density/kg m$^{-3}$ | | **30** | 795.4 | |
| own moisture/% | | **65** | 46.3 | |
| bomb ashes after combustion/% | | **5** | 0.31 | –0.0011368382 |
| **Biological characteristics** | | | | **25** |
| physiological activity | | **10** | 0 | |
| essential oils/resins | | **10** | 2 | |
| age | | **10** | 15 | |
| habit | | **10** | 5 | |
| forest waste generated | | **20** | 5 | |
| forest cover around | | **20** | 5 | |
| perennial/deciduous | | **10** | 5 | |
| blooming period | | **10** | 0 | 0.001930502 |
| **Climate characteristics** | | | | **40** |
| rainfall | | **40** | | |
| monthly mean amount/MM | 35 | | 63 | |
| periodicity | 65 | | 5 | |
| mean temperature/°C | | **20** | 17.3 | |
| hydric availability/mm month$^{-1}$ | | **20** | 63 | |
| environmental humidity/% month$^{-1}$ | | **20** | 75.68 | 0.1205955 |
| **Parameters depending on physical environmental conditions** | | | | **15** |
| zone wind | | **30** | | |
| strength | 60 | | 4 | |
| periocidity | 40 | | 5 | |
| clouds | | **10** | | |
| amount | 50 | | 5 | |
| regularity | 50 | | 5 | |
| topography | | **20** | 7 | |
| sun radiation | | **10** | | |
| sunshine/% | 50 | | 5 | |
| sunny days | 50 | | 6 | |
| anthropic activity | | **30** | 5 | 0.00405 |
| risk index final value | | | | 4.615 |
| **Risk index class** | | | | **5** |

**Table 3** Exploitation criteria and theoretical values of electricity production. For calculation of this table, it was consider a bulk dry sample consisting of 57% of leaves, 25% of thin branches, and 18% of thick branches in the case of eucalyptus, and 44% of leaves, 32% of thin branches, and 24% of thick branches in the case of pine [9, 10]

| Species | ha | Trees/ha | Forest waste (kg tree$^{-1}$) gross | Mean LHV/ kJ kg$^{-1}$ | KWh generated along the year | Efficiency/ % | Euros/year |
|---|---|---|---|---|---|---|---|
| *E. globulus* Labill | 240 000 | 2500 | 109 | 7228.4 | $3.28\cdot10^{10}$ | 25 | $0.7\cdot10^{8}$ |
| *P. pinaster* Aiton | 640 000 | 2200 | 165 | 7588.8 | $2.64\cdot10^{10}$ | 25 | $2.8\cdot10^{8}$ |

with strong Atlantic climate that favour the growth of eucalyptus and some other forest species. These data were supplied by the Spanish National Meteorological Institute and by different weather stations of Xunta de Galicia [19]. The data were recorded within the last 45 years and are presented in the form of bioclimatic diagrams as shown in Fig. 1 [20]. The most important data than can be analyzed in this kind of diagram is the evolution over the year of the vegetative potentiality of the zone as an index to assess forest biomass production. Analysis of these diagrams, together with temperature, rainfall and hydric availability, allows the prediction of periods specially sensible for the starting and spreading of forest fires as a response to the physical conditions of the fuel materials.

Figure 2 is a plot showing thermal degradation of eucalyptus that is compared to that of a very important forest species, *Pinus pinaster* Aiton, that in Galicia covers more than 650 000 ha what means a very important economical interest. Each thermodegradation experiment was repeated 4 times giving very close results. These plots have similar profiles that those reported by Liodakis *et al*. [12] showing that eucalyptus suffers thermal degradation in a shorter time than pine (3400 s eucalyptus while 4800 s pine). At the same time eucalyptus shows a sharp thermal degradation compared to pine and also this degradation happens at a temperature of 460°C while pine degradation needs 630°C. Also, ash percentage is higher in the case of eucalyptus, thus showing a lower flammability than pine. All these features indicate that fire in pine forest should be stronger (high temperature and low ash content) and also it will last for a larger time, thus making its control more difficult (its degradation is slower and needs of higher temperatures, because of this, its extinguishing originates serious problems). One other factor having influence on the pine to be a better quality fuel than eucalyptus is the greater amount of resins, and also the fact that pines are of greater age than eucalyptus and because of that their lignin/cellulose ratio is also greater.

Table 2 shows the contribution of every parameter to the risk index value corresponding to *Eucalyptus globulus* Labill, a forest species that covers in Galicia about 300 000 ha, that is 21% of the total Galician forest surface.

Table 3 shows, in a general way, the criteria used to carry out a rational and sustainable exploitation of the forest resources, as residual biomass, contained in pine and eucalyptus formations existing in Galicia.

## Conclusions

Risk indices based on experimental data can be the basis for the design of effective campaigns to prevent and fight forest fires.

The energy exploitation of forest residues originated from cutting of *Eucalyptus globulus* Labill and pine trees in Galicia (Spain) can yield an economical gross benefit of about 350 million euros [9, 10]. To avoid defertilization of soil, an amount, around 10%, of residues, mainly bark, must be left on the soil.

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