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Experimental investigation on the burning of shrubs

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Abstract

This study aims to improve the knowledge on the combustion of Maquis shrubland for providing scientific bases for landscape management. The combustion dynamics of natural and isolated shrub was investigated. A typical shrub of Mediterranean vegetation, rockrose (*cistus monspeliensis*), was considered. This work was conducted in two steps. A structural characterization of shrubs of rockrose was firstly performed. The masses of the different class of particles composing the shrub, classified by range of thickness, were determined. Attention was paid to the composition of the crown and particularly to the thin particles (leaves, 0-2 mm diameter, more than 2 mm of diameter), which participate the most in the combustion process. The average mass distribution of these classes of particles along the height as well as their mass proportion in the crown were obtained. Then, the combustion dynamics of shrubs of rockrose was studied experimentally. Fire experiments were carried out with a Large Scale Heat Release apparatus which allows the measurement of the Heat Release Rate based on oxygen consumption principle. Two sets of two radiant panels were used to preheat and perform the ignition of the vegetation. The combustion study was based on the flammability criteria previously defined in the literature. The four criteria composing the flammability (ignitability, sustainability, combustibility and consumability) and their associated measurable parameters were investigated distinctively. New measurable parameters were proposed to study the combustibility and consumability. The study highlighted the influence of the moisture content and the ignition position on the parameters associated to the four criteria. Finally, the flammability was investigated as the combination of these criteria. A principal component statistical analysis was performed that revealed the relationships between the studied parameters. This analysis highlighted the presence of four flammability regimes depending on the position of ignition, time to ignition and the proportion of the thin particles within the crown.

Keywords: Wildland fire, calorimetry, flammability, vegetation characterization

1. Introduction

Different landscape managements are set-up to reduce the intensity and the impact of wildland fires. The treatment of these vegetation areas is based on the reduction of the amount of fuel at the ground level. However, the related practices are mainly performed from empirical knowledge and a quantitative approach relying on physical quantities is required by managers. Some experimental (Morvan and Dupuy 2004; Cruz *et al.* 2011) and numerical works have been devoted to the understanding of the combustion of shrubland but there remains a lack in measurement of physical quantities like the heat release rate to clearly understand their burning. More particularly the study of the combustion of isolated shrubs was poorly investigated (Tachajapong *et al.* 2014; Li *et al.* 2017). The influence of the Moisture content (MC) on the combustion dynamics was observed for Natural Douglas fir (Babrauskas 2006; Mell *et al.* 2009). A decrease of the effective heat of combustion was observed with an increase of MC. The effects of the ignition method, MC and bulk density on the rate of spread were studied for reconstructed chamise (Tachajapong *et al.* 2014; Li *et al.* 2017). An increase of the rate of spread within the crown was highlighted with increasing of bulk density or the decreasing MC.

In order to study the combustion dynamics of vegetative fuels, Anderson (Anderson 1970) introduced the flammability, which corresponds to the ability of vegetation to burn. The flammability was defined as a combination of three criteria: the ignitability, sustainability and combustibility. The ignitability is the capability of a material of being ignited. The sustainability represents how well the fire continues to burn once ignited. The combustibility is the intensity with which a fire burns. Martin et al. (Martin *et al.* 1993) added a fourth criterion to the flammability. The consumability corresponds to the mass of vegetation consumed during the combustion. Generally, the studies on the flammability focus on few criteria but they rarely consider all of them. Some physical quantities were used to characterize these four criteria. Thus, ignitability is usually studied with the time to ignition (Anderson 1970; Guijarro *et al.* 2002; Ganteaume *et al.* 2011). Sustainability is described by the flame duration (Plucinski and Catchpole 2001; Ganteaume *et al.* 2011). The flame temperature (Ganteaume *et al.* 2011; Santana and Marrs 2014), the flame height (Behm *et al.* 2004; Santana and Marrs 2014) and the rate of the fire spread (Guijarro *et al.* 2002; Ganteaume *et al.* 2011) are used to study the combustibility. Finally, the consumability is associated to the fuel consumption ratio (Guijarro *et al.* 2002; Santana and Marrs 2014) or the mass loss rate (Fonda *et al.* 1998; Santana and Marrs 2014). Various factors affect the parameters related to these criteria but the MC is the most influencing one. The increase of the time to ignition was observed with increasing MC (Weise *et al.* 2005; Pickett *et al.* 2010). Conversely, the decrease of consumption ratio (Dahale *et al.* 2013; Santana and Marrs 2014) and heat released (Babrauskas 2006) were observed with increasing MC. Furthermore, an increase in the proportion of thin particles, which participate actively in the combustion (Tihay *et al.* 2014; Barboni *et al.* 2017), lead to increases both the consumption ratio (Burrows 2001) and the heat released (Behm *et al.* 2004).

In this paper, the flammability of shrubs of rockrose (*cistus monspeliensis*) was investigated. A characterization of the distribution of the thin particles was performed to identify the potential mass of fuel involved during the flaming combustion processes. A particular attention was paid to the composition of the crown which is mainly composed of leaves and small diameter twigs. Experiments were then carried out on 41 shrubs to assess their flammability. The criteria introduced by Anderson (Anderson 1970) and Martin et al. (Martin *et al.* 1993) were first studied independently. The flammability was then considered as the combination of the four criteria through a statistical analysis (Principal Component Analysis).

2. Materials and Methods

2.1. Vegetation Caracterization

A shrub of rockrose is composed of particles with different thickness which participate in different ways in the combustion. The thin particles (thickness and diameter thinner than 2 mm) are mainly involved in fires (Tihay *et al.* 2014) while larger particles (diameter greater than 6 mm) are less prone to the thermal degradation. A characterization of the composition of shrub of rockrose in terms of class of particle was necessary for a better understanding of the combustion. Three shrubs of rockrose (*cistus monspeliensis*) with similar mass and dimensions were characterized. These shrubs were collected at Corte (Corsica, France) during autumn. In this study, the bases of the rockroses (0.25 m above the roots) were not considered since they are composed of thick classes of particles that do not participate in the combustion (twigs with diameter in the range 6-25 mm) during wildfires. The mean height of the three rockroses was 1.23 ± 0.12 m, with a mean crown height of 0.35 ± 0.07 m for a mean diameter of 0.68 ± 0.06 m. The mean dry mass of the shrubs was 0.76 ± 0.03 kg. Then, in order to quantify the different size of classes of particles constituting the rockroses, the shrubs were placed within a 1.45 m high, 0.9 m long and 0.9 m wide metallic frame spatially divided into 252 small cubes with sides of

15 cm (Figure 1). The position of each cube was indexed following the height. The vegetation contained in these small cubes was cut and oven dried at 60°C for 48h. Finally, for each cube, the vegetation particles were ranged according to the following diameter classes (leaves, twigs with diameter in between 0 and 2 mm, 2 and 4 mm, 4 and 6 mm, 6 and 25 mm) and weighed.

Figure 1 - Characterization device for the class of particles

2.2. Combustion study

A series of 41 shrubs of rockrose with similar dimensions and weight were collected within the same vegetation stand during spring, summer and autumn. Their average properties were: a 1.25 m height, a crown height of 0.3 m, a crown diameter in the range of 0.6-0.8 m and a mass of 1.5 kg (excluding the 0.25 m base). The samples were conditioned 48h in a room with an ambient air temperature of about 25°C and a relative air humidity of about 50 % in order to obtain the required MC. This process allowed obtaining a leaf MC in the range of 3-20% depending on the initial moisture content of the samples. It should be noted that the MC of the other classes of particles was higher (10-45 % for the 0-2 mm diameter class).

The experiments were conducted with a 1 MW Large Scale Heat Release apparatus (LSHR). A layout of the experimental design is provided in Figure 2. Live shrubs were placed under a 3 m × 3 m hood with a 1 m^3/s smoke extraction system. Two set of two radiant panels, heated at 773 K, were used to preheat the vegetation samples up to ignition. To maximize the radiation impinging on the shrub samples, the two sets of radiant panels were used in orthogonal configuration. The emitted heat flux was close to 20 kW/m^2. The time to ignition was recorded for each test. The measurement of the heat release rate (HRR) was determined following the formulation derived by Parker (Parker 1984) using gas volume fraction and mass flow rate of exhausted gas. The samples were positioned on a load cell in order to record the mass loss during the thermal degradation. The measurements sampling rate was 1 Hz.

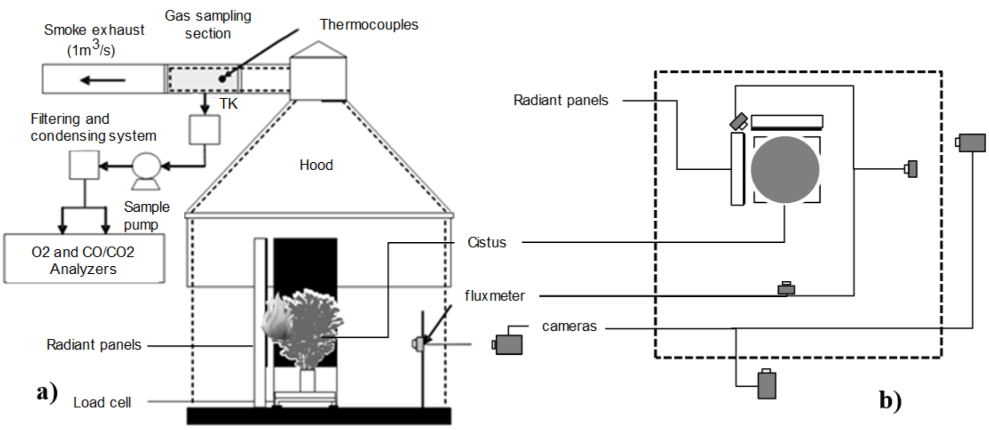

Figure 2 - Layout of the experimental set-up, a) side view b) top view

3. Results and discussion

3.1. Vegetation characterisation

A particular attention was paid to the proportion of thin particles (leaves and twigs with diameter between 0-2 mm) composing the shrub. As a first step, the mass proportion of the different classes of particles was estimated. It was defined for a class k as:

$$\Gamma_k = \frac{m_{kd}}{m_d} \quad (1)$$

where m_{kd} represents the dry mass of the k class and $m_d = \sum_k m_{kd}$ is the total dry mass of vegetation sampled. Experimental results show a similar distribution of particles for the three shrubs of rockroses characterized. It can be considered that a shrub of rockrose is composed of 22.1 ± 0.8 % of leaves, 26.1 ± 2.1 % of twigs with a diameter between 0 and 2 mm and 51.8 ± 2.0 % of twigs with a diameter greater than 2 mm.

In addition, during the burning experiments, the crown was the main part of the shrub that was consumed. Its composition was thus methodically measured in order to estimate the consumption of each class of particles. The crown represents 35.0 ± 0.4 % of the mass of the shrub of rockrose. It contains 83 % of the total mass of leaves and 41 % of the total mass of 0-2 mm diameter twigs. In addition, it should be highlighted that 72.0 ± 8.0 % of the total mass of particles thinner than 2 mm (participating actively in the combustion) is located in the crown. These results were used to assess the consumption ratio.

A second characterization was carried out on shrub of rockroses sampled in summer. A change in the mass proportion of leaves was observed with a decrease of the leaves mass (2/3 less). Furthermore, flowers containing seeds, have grown during this season. Their mass was almost equal to that of fallen leaves.

3.2. Ignitability

Ignitability was defined as the time needed to ignite a shrub submitted to the heat flux emitted by the radiant panels. When the vegetation is exposed to a heat flux from an external source (radiant panels in this study), its temperature increases and the thermal degradation begins. For the experimental setup used in the present study, the ignition occurred at the edge of the shrubs, where the concentration of combustible gases near an incandescent particle is rich enough. Then, the fire spreads mainly horizontally across the crown. The leaves firstly ignited. The flame then engulfed the other classes of particles. Therefore, relationship between the leaves MC (MC_l) and time to ignition was investigated. Figure 3 shows the time to ignition as a function of MC_l for different seasons.

Three tends were observed. For shrubs of rockroses sampled in autumn and summer, t_{ign} increases with increasing MC_l. However, the quantity of leaves is lower in the crown during summer, which causes a decrease in the mass of pyrolysis products. Thus, an increase of MC_l during summer led to a more significant increase in time to ignition than in autumn. Finally, very long ignition times are obtained for shrubs of rockroses sampled in spring for which MC_l was the lowest. In this case, juvenile leaves (absent in summer and winter) seem to have a flame retardant effect (probably related to their composition), significantly delaying the inflammation of the sample.

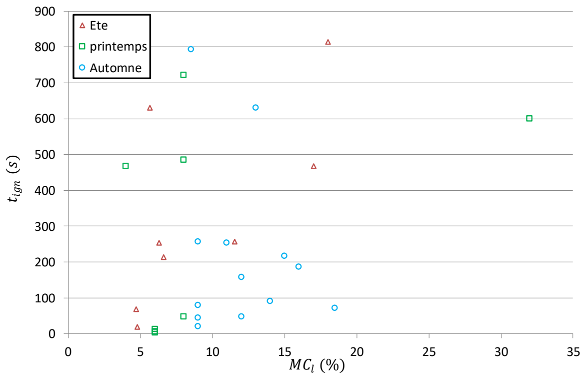

Figure 3 - Time to ignition in function of the leaves moisture content

3.3. Combustibility

Combustibility was defined as the intensity of the combustion. The combustion dynamic was analyzed with the following two characteristics of the HRR curves over time: the growth rate just after ignition and the established burning phase. It should be pointed out that summer rockroses were not considered in this section. Indeed, the presence of flowers end seeds alters the combustion dynamics and cannot be studied using this method.

Growth phase

To study the growth phase (HRR >10kW), the HRR was fitted to the following relationship over time (NFPA 72 [22]):

$$HRR = \alpha\, t^2 \qquad (2)$$

where α is the growth factor of the combustion.

The analysis of the data allowed to distinguish three combustibility types according to the value of α (Figure 4). For low values of α (α <0.2), the combustion regime was slow and the fire propagated step by step across the crown. An intermediate combustion regime could be observed for medium values of α ($0.2 < \alpha < 0.4$). The fire spread was horizontal from the ignition zone towards the opposite edge of the crown. Finally, for high values of α ($\alpha > 0.4$), the fire spread horizontally at a fast rate throughout the entire fine particles of the crown. The fire then spread vertically downward consuming larger diameter particles. The behavior of summer shrubs of rockrose is not presented here because their phenological characteristics lead to a very different combustion dynamic that will be presented hereafter.

Figure 4 - Regimes of combustion 30s after the ignition for a) α <0.2; b) 0.2 <α <0.4; c) 0.4 <α

Established burning phase

Two parameters were used to characterize the established burning phase: the peak HRR (obtained from the HRR over time) and the duration of the flaming combustion (obtained from observation).

Different combustion regimes and peaks of HRR were observed as a function of the growth factor (Figure 5). The slow combustion rate ($\alpha < 0.2$) was obtained for 19% of the experiments. This combustion regime was characterized by a low value of the average peak HRR of 100 ± 5 kW and long times of combustion of 100 ± 14 s. The intermediate combustion regime ($0.2 < \alpha < 0.4$), corresponding to 38% of the tests, showed a medium value of the peak HRR of 188 ± 27 kW and combustion times of the order of 77 ± 10 s. Finally, the fast combustion was obtained for 43% of the experiments and it exhibited

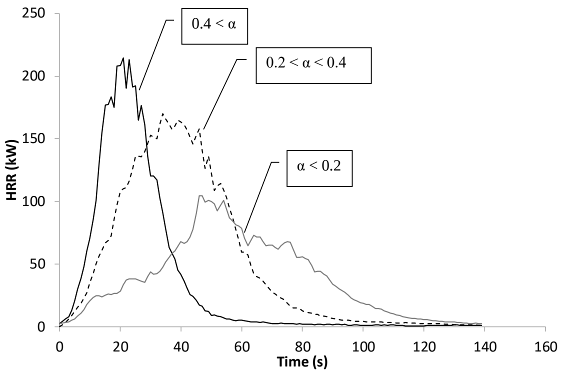

Figure 5 - Typical curve of HRR as function of time for the three regimes of combustion

HRR peaks of the order of 257 ± 63 kW and short combustion times of 60 ± 19 s. In order to understand the cause of the different combustion regimes, a particular attention was paid to the ignition zone. We found that the growth coefficient strongly depends on the amount of fuel present above the ignition zone. When ignition occurred in the upper layer of the crown, without fuel above, a low growth coefficient and a slow combustibility was observed. When ignition occurred in between the middle and the top of the crown, with a significant presence of fuel, a more intense flaming was observed at ignition time and a moderate combustibility ensued. The greater the amount of fuel, the greater the growth coefficient. Finally, when ignition occurred in between the bottom and the middle of the crown, the convective heat transfers, by contact of the flame with the crown, caused a high growth coefficient, leading to the fast combustion regime. The different ignition zones are shown in Figure 6. In the following, an ignition that occurred in between the bottom and the middle of the crown will be called a favorable ignition whereas an ignition located above this last zone will be called as unfavorable.

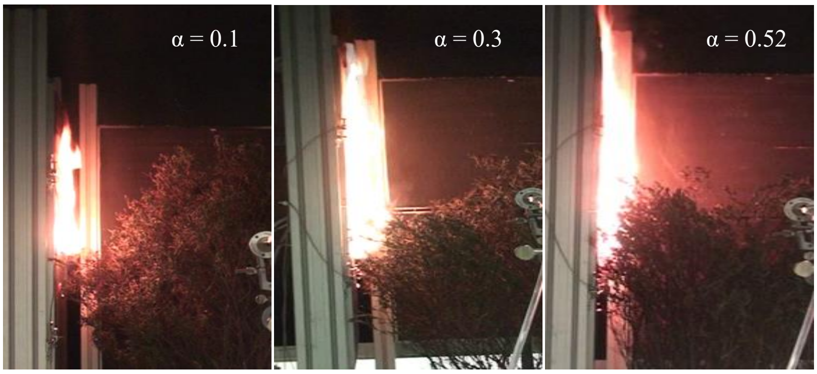

Figure 6 - Position of the ignition point in the shrub a) top of the crown, b) in the crown, c) at the bottom of the crown

3.4. Sustainability

Sustainability was defined by how well a fire will continue to burn once ignited. The main parameter used to characterize this criterion was the flame duration, t_{fl}. The results presented in the previous section suggested the existence of a relationship between the flame duration and the peak HRR. Flame durations greater than 80 s and up to 120 s were obtained for low peaks of HRR (≤ 150 kW), while the shortest durations (around 40 s) were obtained for high peaks of HRR (≥ 210 kW). Figure 7 shows that the flame duration decreases with increasing peak HRR. These results can be explained by analyzing the fire spread within the crown for the different positions of ignition. When ignition occurred in the lower part of the crown, the heat transferred by convection and radiation from the ignition zone to the vegetation above involved the entire height of the crow. The fire quickly engulfed the crown of the shrub leading to a short duration of flame and a high HRR ensued. An ignition at the edge and middle of the crown height led to a flame that impacted a fewer amount of fuel located above. It resulted in a lower rate of spread, a longer residence time of flame and a weaker HRR. Finally, when the ignition occurred in the upper part of the crown, the fire spread mainly dominated by radiation. The fire was stopped when it encountered a small fuel discontinuity. The propagation was slow and combustion times were long. Thus, the sustainability is linked to the HRR and subsequently to the combustibility.

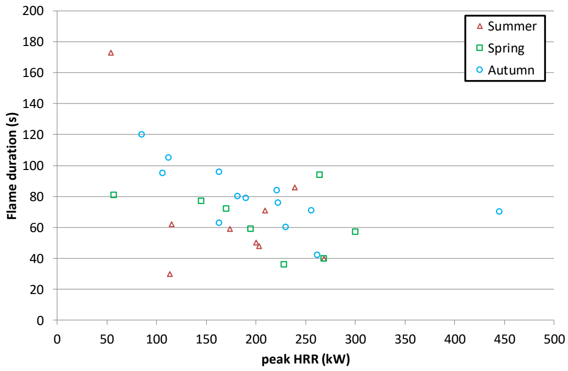

Figure 7 - Flame duration as function of the HRR peak for the different seasons

In addition, Figure 7 shows a shift in the trend of flame duration as function of peak HRR with the seasons. For a given peak HRR, the flame duration decreases when going from autumn to spring and then summer. This shift can be explained by the mass decrease of the finer classes of particles during spring and summer.

3.5. Consumability

Consumability was measured by the quantity of fuel consumed by the fire. From the characterization study, the amount of initial and remaining fuel of each particles class was estimated (taking into account the moisture content of the different classes). But for the sake of clarity only the whole burned mass fraction η, will be presented here. It defined as:

$$\eta = 1 - \frac{m_{rd}}{m_d} \tag{3}$$

where m_{rd} and m_d are the residual dry mass and initial mass on dry basis, respectively. The average mass lost for these specific experiments was 0.52 ± 0.2 kg which represents 25 ± 8 % of the mass of the shrub. The results displayed in Figure 8 suggest a decrease of the fuel consumed with increasing MC of the leaves for shrub rockroses sampled during autumn. The results concerning the shrub of rockroses collected in summer do not follow this trend because of the presence of seeds that alter the combustion dynamics (see section combustibility).

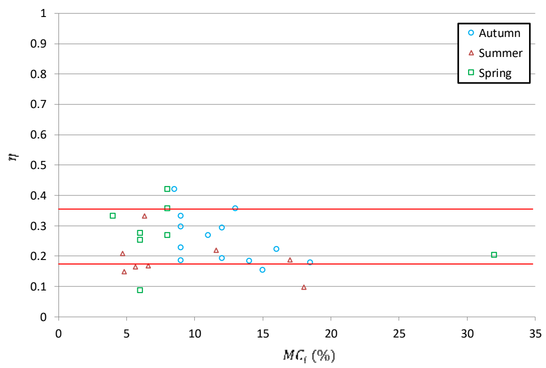

Figure 8 - Burnt mass fraction in function of the leaf moisture content for the different seasons

Experimental results showed that the mass lost was quasi exclusively located in the crown which is mainly composed of fine particles (leaves and 0-2 mm diameter twigs) representing 35% of the total dry mass of the shrub. We recall that the characterization study revealed that the leaves and the 0-2 mm diameter twigs in the crown represent 18% and 10% of the total mass of the rockrose, respectively. Therefore, a burned mass fraction below 18 % indicates that the leaves in the crown have not all been consumed and the fire did not spread across the whole crown. For a burned mass fraction between 18 and 35%, the measurements shown that all the leaves and part (or totality for 35%) of the 0-2 mm particles class in the crown were consumed. Finally, a burned mass fraction greater than 33% indicates a consumption of the crown and a part of the classes of particles in the range of 0-6mm (mainly 0-2 mm and 2-4 mm particles classes) within the intermediate part of the rockrose. The classes of particles larger than 4 mm were partly burned only when the peak of HRR was high enough (250 ± 10 kW). It should be noticed that the shrub of rockrose was burned wet and the initial dry mass was not measured. It was estimated from the wet mass, moisture content and distribution of each class of particles. Thus, the uncertainty related to the estimation of the dry mass affect directly the calculation of the burned mass fraction.

The current results allowed distinguishing three regimes for the consumability criterion: a low consumability regime for which only a part of the leaves inside the crown was consumed; a medium consumability regime for which the leaves and part of the 0-2 mm diameter twigs were consumed in the crown and a high consumability regime for which the crown was totally burned. Furthermore, for this last regime it should be noticed that some of the fine particles also burned under the crown of the shrub as well as some of the large diameter particles when HRR was high.

3.6. Flammability

Flammability was finally considered as the combination of the four criteria studied hereabove. In order to observe the impact of the different combustibility and consumability regimes on the flammability, a Principal Component Analysis (PCA) was performed. The parameters considered to study the criteria (ignition position, flame duration, HRR peak, growth coefficient and burnt mass fraction) were used as input parameters of the statistical analysis. It should be pointed out that the combustion dynamics of summer shrubs of rockroses was not considered in this statistical analysis between their reaction to fire was much more different that for the shrubs collected during the other seasons. The PCA provides information on the possible links and correlations between the input parameters. It allowed to cluster the experiments according to the parameter values in order to assess the flammability. Results extracted three main components that explain 87 % of the total variance. The main component (PC 1) explains 54% of the variance while the components PC 2 and PC 3 explain 19 % and 14 % of the variance, respectively. The projection of the combustion experiments on the factorial map in the plane (PC 1, PC 2) highlighted four types of flammability (Figure 9). The first group (circles) corresponds to the low flammability with $\alpha < 0.2$, a low HRR peak (83.9 ± 20 kW), a very long flame duration (100 ± 14 s) and a weak burnt mass fraction (18.9 ± 3.0%), mainly involving leaves and 0-2 mm twigs diameter. The second group (squares) corresponds to a medium flammability with a value of α between 0.2 and 0.4, a medium peak of HRR (188 ± 27 kW), a long flame duration (77 ± 10 s) and a moderate fuel consumption (23 ± 5%) including leaves and larger particles up to 2 mm in diameter. A high and fast flammability was associated to the third group (diamonds), characterized by α greater than 0.4, a high peak of HRR (228 ± 15 kW), a short flame duration (44 ± 9 s) and a moderate fuel consumption (25 ± 6%) involving the same classes of particles as the medium flammability. Finally, the last group (triangles) corresponds to the high and mass consuming flammability with α greater than 0.4, a very high HRR peak (384 ± 99 kW), a long flame duration (70 ± 14 s) and a high mass consumption (32 ± 4%). It should be noted that, for the fourth group, twigs with diameter greater than 4 mm were burned while for the other groups, only thinner particles were involved in combustion.

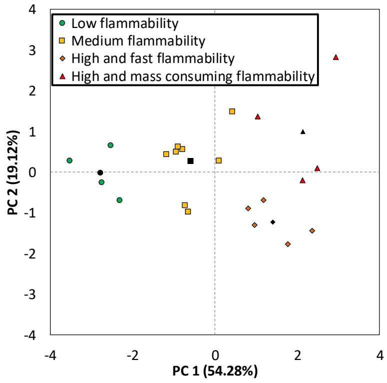

Figure 9 - Projection of the fire tests on the factorial plane (PC1 and PC2) of the PCA

The different flammability could be explained (Figure 10) by the ignition position, the time to ignition as well as the proportion of the thin particles within the crown. Favorable ignition (see combustibility section) results in a high flammability, while unfavorable ignition causes a low or medium flammability. In the case of high flammability, the difference between "high and fast" and "high and consuming" is caused by long time to ignition. For long time to ignition, the moisture content of the various particle classes is considerably reduced when ignition occurs, resulting in high mass consumption, including twigs classes with a diameter greater than 4 mm. For shorter ignition times (high and fast flammability), large diameter twigs (greater than 4 mm) do not receive enough heat to achieve desiccation and reach ignition. The differentiation of low and medium flammability is due to the structure of the vegetation. Indeed, among the 41 collected samples, some of them had a lower bulk density than the selected reference type of shrub. We noted a lower value of bulk density of leaves (0.9 ± 0.2 kg / m^3) for the low flammability regime in comparison to the medium flammability one (1.4 ± 0.3 kg / m^3). The low flammability was obtained for this type of shrubs. The reduction in the mass of thin particles (leaves and 0-2 mm) leads to the decrease of the heat released, which limits the spread of the fire in the shrub.

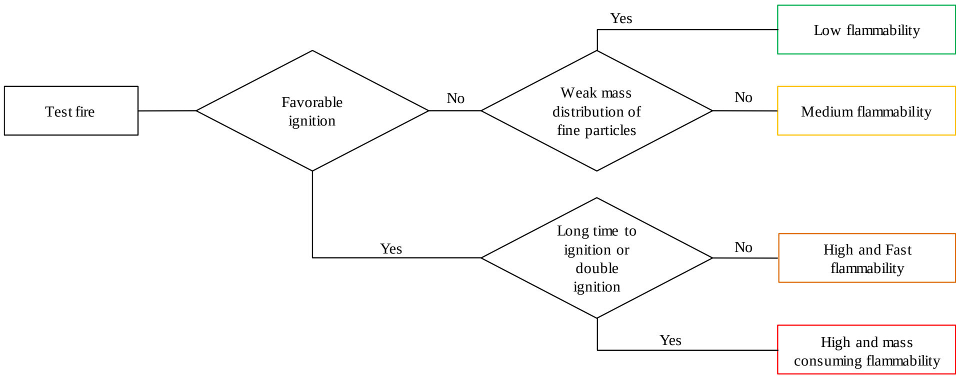

Figure 10 - Types of flammability

4. Conclusion

In this study, the structure and flammability of shrubs of rockrose were investigated. Theses shrubs were characterized in order to determine their structure and the mass proportion of the different particle classes. A particular attention was paid to the composition of the crown which is the main part of the shrubs to be consumed. The characterization highlighted a very close repartition of the particles for similar shrubs. A 1.5 m high shrub of rockrose is composed of 48.2 ± 2.9 % of thin particles mainly located in the crown.

The flammability of the shrub of rockrose was then analyzed using the ignitability, sustainability, combustibility and consumability criteria and the associated measurable parameters. The ignitability, linked to the time to ignition, decreases with the leave MC. Combustibility and sustainability, studied with the HRR during the combustion and the flame duration, are influenced by the ignition position. The lower the position of ignition in the crown, the higher the peak HRR and the shorter the flame duration. The consumption ratio, corresponding to the consumability, increases with the decrease of the leave MC. Finally, a statistical analysis was carried out on the studied parameters in order to observe the global flammability of the shrubs of rockroses. The PCA highlighted four types of flammability depending on the ignition zone, the ignition HRR and the burned mass of thin particles.

It should be noted that more experiments with summer shrubs of rockroses are needed to further assess their behavior for this season. Indeed, the presence of a non-negligible dead leaves litter was observed during plant sampling in the field resulting in a different mass distribution of the leaves. Due to the presence of falling firebrands generated by flaming seeds, the interactions between fire spreading across the shrub’s crown and bed of leaves need to be taken into account. Finally, a study of the combustion dynamics of simultaneously several burning shrubs will be necessary in order to get closer to real fire conditions.

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