Appraising fuel and fire behaviour for prescribed burning application in heathlands of Northwest Italy

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Abstract

Calluna-heathlands are one of the most fire-prone vegetation types in NW Italy. Fire risk at the wildland urban interface is increasing. Moreover, frequent and large wildfires threat the *Calluna*-heathland, a Priority Habitat in Europe. Prescribed burning for fire hazard reduction could be a suitable tool to create fuel discontinuities in strategic areas so as to facilitate fire suppression. Nevertheless, its effectiveness has to be assessed and burn prescriptions need to be developed. The objective of the present work is to study the links between burning conditions, fire behaviour and fire effects on heathlands fuels of NW Italy. We carried out 25 experimental burns during the legal burning season in winter, both in unburnt (UB) heathlands stands of different ages (4-14 years) and recently burnt (BU) stands (1-3 yrs). The fuel complex load and structure was characterized before and after burning. Short-medium term post-treatment fuel dynamics were studied. The seasonal variation of fine fuels moisture was analysed. A linear regression model was developed to predict the dead fine fuel moisture as a function of weather variables. Fire behaviour was studied with a microplot scale approach. Rate of fire spread and fireline intensity were quantified for backfire (A), headfire in the acceleration phase (B), and headfire in the quasi steady state (C). Generalized linear models with Tukey's comparison were used to investigate differences in fuel load and structure vs. time since fire, and fire behaviour descriptors in BU vs. UB burns. Results evidenced that prescribed burning treatments significantly mitigated potential fire behaviour. In BU, observed fireline intensity in A, B, C behaviours was respectively the 26%, 38% and 20% of the UB values. Finally, operational windows (i.e. optimum moisture scenario; available days for burning) and technical recommendations (i.e. ignition techniques) to assist prescribed burning for fire hazard reduction in heath fuels of NW Italy were set out.

Keywords: Prescribed burning, fuel management, fire behaviour, fuel dynamics, heathland

1. Introduction

Heathlands dominated by *Calluna vulgaris* Hull. are one of the most fire-prone vegetation types in Northwest Italy (Regione Piemonte, 2007; Borghesio, 2009).

Uncontrolled surface fires of moderate intensity (500–6000 kW m^{-1}), which spread in late winter over relatively large areas (up to 400 ha), every 1–5 years, characterize the fire regime of these heathlands. Ignition causes are human activities, such as the irrational use of fire by shepherds, and the people negligence (Ascoli and Bovio, in press).

The heathland fire proneness in late winter is mainly due to fuel characteristics and their interactions with seasonal weather patterns. In winter, the fuel complex is mainly constituted by a tangle of live crowns of *Calluna*, which presents a reduced physiological activity, and cured grasses, such as *Molinia arundinacea* Shrank; both species present high values in surface area to volume ratio: 9650 m^2 m^{-3} for *Calluna* foliage and shoots (Fernandes and Rego, 1998), and 8000 m^2 m^{-3} for *Molinia* cured leaves. Winter in NW Italy presents a dry period of scarce precipitation (Mercalli et al., 2008) which is responsible of low moisture contents of dead fine fuels (Cesti, 2005). Consequently, in correspondence of the föhn wind, which blows more frequently in late winter with a speed up to 70-80 km h^{-1} (Cesti, 1990), fire can spreads rapidly over extensive heathland areas characterized by homogenous and continuous fuels. In these conditions, fire-fighting is difficult because the distribution of the resources along the perimeter is slower than the growth of the wildfire perimeter. Moreover, these wildfires present some critical aspects. As a consequence of the urban growth, heathlands have been included within urban areas, thus the fire risk (*sensu* Blanchi et al., 2003) at the wildland urban interface is increased. Finally, frequent fires are responsible of the replacement of *Calluna*-heathlands, a Priority Habitat within the European Union (EU 92/43/CEE), by grasslands or woodlands (Ascoli et al., 2009; Borghesio, 2009; Ascoli and Bovio, in press).

For the above mentioned reasons, the reduction of wildfires extension and frequency in heathlands of NW Italy is a management issue to be addressed.

Prescribed burning for fire hazard reduction could be a suitable tool to create fuel discontinuities in strategic areas so as to facilitate fire suppression (Rigolot et al., 2009). Strategic fuel management by prescribed burning has been thoroughly studied in European shrublands dominated by broadleaf or heath species (Vega et al., 2001; Baeza et al., 2002; Fernandes et al., 2002; Fernandes and Botelho, 2003; Davies et al., 2008), and is currently applied in several European countries (Lázaro and Montiel, 2010). Nevertheless, its effectiveness in reducing fire hazard in new areas has to be assessed (Rego et al., 2010), above all in those countries where forest managers are interested in implementing prescribed burning, but scientific and operational experiences are scarce, such as Italy (Leone et al., 1999; Ascoli et al., 2009; Lázaro and Montiel, 2010). Burn prescriptions, to translates burning conditions into fire behaviour, and fire behaviour into desired fire effects on fuel load and structure (Fernandes and Botelho, 2003), need to be developed.

The objective of the present work is to assess prescribed burning effectiveness for fire hazard reduction in heathlands of NW Italy. The links between burning conditions, fire behaviour and fire effects on fuels were studied. In particular we analysed: i) the fuel complex load and structure; ii) dead and live fine fuels moisture seasonal patterns; iii) fire behaviour variability in relation to fuel loading, moisture scenarios and ignition techniques; iv) short-medium term post-treatment fuel dynamics. Finally, operational windows and technical recommendations to assist prescribed burning implementation were set out.

2. Methods

Study site

The study was carried out within the Managed Nature Reserve of Vauda (Figure 1) which include one of the most valuable heathlands of NW Italy (Mugion, 1996; Borghesio, 2009; Lonati et al., 2009; Ascoli and Bovio, in press). The Reserve is located 20 km NE of Torino (7°41’17’’E, 45°13’13’’N), covers an area of 2635 ha on a stream terrace plateau at an altitude ranging from 240 to 480 m. The soils are acidic, rich in silt and clay, with limited water flow and plant root penetration. The climate is continental, with roughly 81% of the mean annual rainfall (1000-1100 mm) falling between April and November. The driest month is March with, on average, 35 mm of rain and 0.3 days of snow. The mean annual temperature is 11.8°C, with monthly means ranging from 1.6°C in January to 21.9°C in August (Ascoli et al., 2009).

The fire regime of the study area was determined for the last two decades. The wildfire statistics of the Corpo Forestale dello Stato (1986–2009 period) were analysed. The geo-referenced wildfire perimeters provided both by the Regione Piemonte and by the Land Managers of the MNR of Vauda for the period 1996–2009 are reported in Figure 1.

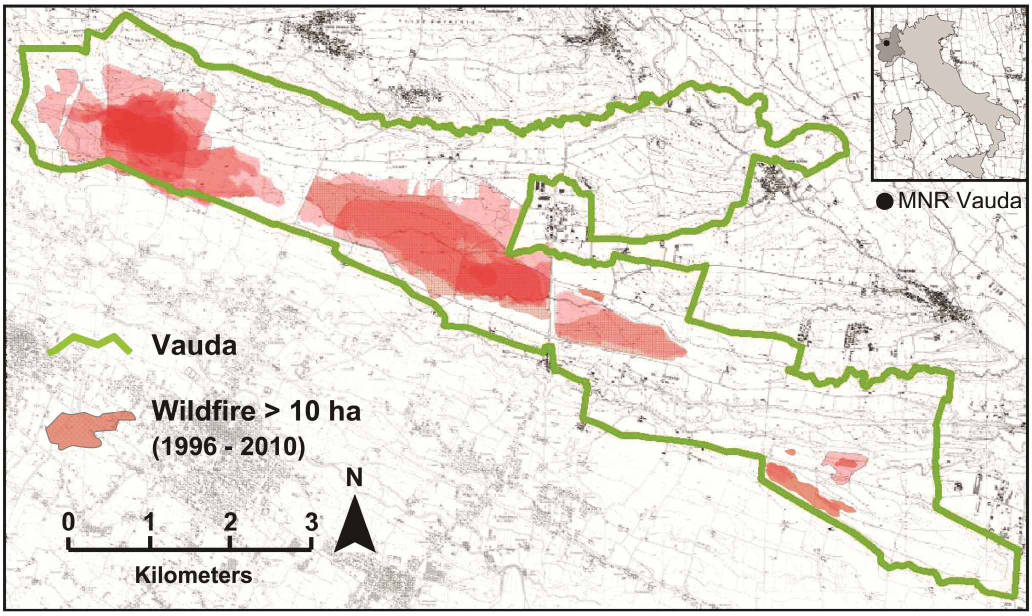

Figure 1 Map of the Managed Nature Reserve of Vauda showing the Reserve boundaries (green line) and the areas burnt within 1996 and 2009 (red area) (Data source: Regione Piemonte).

Fuel characterization

The experiment design adopted to characterize fuel loading and structure consisted in selecting 12 heathland stands which differed in time passed since the last fire. The map of burnt areas (Figure 1) was used to choose stands locations. The stand age was determined by counting rings of basal sections of 10 *Calluna* stems selected among the largest stems found in each stand. The average stand fuel load was estimated by destructive samplings in a 1-m^2 square (n=8 per stand). Dead and live fine fuels (<0.6 cm) were separated, and oven-dried at 60°C for 24 hours to estimate the fuel load. The fuel structure was assessed in linear transects, 10 m in length (n=4 per stand). Along each transect, every 50 cm, the height of *Calluna* and *Molinia* was collected. The average species height was then calculated for each stand. The species cover was assessed along each transect measuring the specific contribution according to Daget and Poissonet (1971). All samples were randomly located. Field work was carried out in winter in 2008.

Fuel moisture was assessed along the winter season in 2009. A total of 30 days of field sampling were carried out from November to March. Fuels were collected between 10.00 am and 14.00 pm. Each date, samples of ~50 g of fine dead fuels (*Molinia* cured leaves) and live fuels (*Calluna* crowns) were collected (n=6); the fresh weight was determined *in situ* using a field balance. Samples were oven-dried at 60°C for 24 hrs. The moisture content was calculated as follow: M=(Wi-Wf)/Wi (where: Wi: initial weight; Wf: final weight).

Fire behaviour characterization

Experimental burns (n=25) were carried out from winter 2005 to winter 2010, both in unburnt heathland stands (UB; n=9), whose age ranged between 6 to 14 years, and in recently burnt stands (BU; n=16), whose time since fire ranged between 1 to 3 years. Plots dimensions range was 1250-4000 m^{-2}. Slope was <5%. Ignition techniques were backfires, headfires with linear ignition (25-50 m), and strip head fires with strips at a distance of 15 m.

For each burn, fuel samples in a 1-m^2 square (n=6 per experiment) were collected before and after the fire treatment to estimate fuel load before burning and fuel consumption on a dry weight basis. On the burn dates, ~50 g of fine dead fuels (*Molinia* cured leaves) and live fuels (*Calluna* crowns) were sampled (n=5) to measure fuel moisture.

Rate of spread (ROS; m min^{-1}) was estimated with a microplot scale approach (Smith et al., 1993; Fernandes et al., 2000) by timing the arrival of the fire front to 2 m high aluminium rods placed within the fuel bed at the vertexes of a regular grid. This method allows to distinguish, within the same burn, a backfire phase, headfire in the acceleration phase (i.e. fire growth within 15 m from the ignition line) and headfire in the quasi steady state (Cheney and Gould, 1995). Ascoli (2008) describes in detail the methodology used. As the rods had height increment markers visual estimation of flame height was possible. Fireline intensity (I*;* kW m^{-1}), was calculated according to Byram (1959). High heat of combustion of *Calluna vulgaris* was determined by Gillon et al. (1997) as 22940 kJ kg^{-1}; a value of 18000 kJ kg^{-1} was used for grass fuels. Relative humidity, air temperature and wind speed at 2 m above the ground were recorded every 30 seconds during each burning using 2 mobile weather stations positioned upwind.

Data analysis

A generalized linear model with Tukey’s comparison was used to investigate differences in fuel load between heathland class ages (fixed factor). Means were square root transformed. Significant differences were tested at the 5% level. Data were examined for homogeneity of variance (Levene test), and normality (K-S test). Correlation analysis was used to test the relationships among dead and live fine fuels moisture and weather variables taken from Front Malone (Arpa Piemonte), 4 km North from the study site. Regression modelling was used to develop equations to predict the fuel moisture of dead fine fuels as a function of weather variables. The best model fitted was used to plot the daily trend of dead fine fuel moisture in winter for the period 1996-2008, entering weather data from F. Malone.

The microplot scale analysis allowed to have a consistent number of observations to compare fire behaviour descriptors (ROS; I) between backfire (n=62), headfire in the acceleration phase (n=57), and headfire in the quasi steady state (n=67), both in UB and BU plots. The subset of data relative to the headfire behaviour was studied as a function of the fine dead fuel moisture. Fuel moisture threshold values, respectively the moisture of extinction above which fire sustainability is not guaranteed, and the moisture below which fire control becomes difficult (I>500 kW m^{-1}) (Andrews and Rothermel, 1982), were determined. These threshold values were superimposed to the daily average fine dead fuel moisture in winter, as estimated by the moisture model, to identify operational windows. Finally, the number of available operative days to apply prescribed burning efficiently and safely was determined.

All analyses were performed using the SPSS v.16.0 statistical package (SPSS 2007).

3. Results and discussion

Fuel characteristics and dynamics

Stand age ranged from 1 to 15 years, that corresponds to the time passed since the last fire. According to the *Calluna* developmental phases (Gimingham, 1988), the studied stands were in the pioneer, building and late building phases. Stands were grouped in 5 age classes (I: 1-3; II: 4-6; III: 7-9; IV: 10-12; V: 13-15 years).

The average total fine fuel load ranged from 3.4 ± 0.2 t ha^{-1} to 12.6 ± 0.8 t ha^{-1} in the I and V age classes respectively. Significant increases in live fine fuel loads vs. age classes were observed (Figure 2). Diversely, no significant differences were found in dead fine fuel load. In the pioneer phase, 1-6 years after fire, *Calluna* slowly reconstitutes the cover (Lonati et al., 2009), while *Molinia* dominates the short-term post-fire succession (Ascoli and Bovio, in press). Consequently, the fine dead fuel component in heathland stands up to 6 years, constitutes most of the fuel complex load (89% and 55%, in the I and II age classes respectively). As *Calluna* ages, its average height and cover increase (Figure 3), up to 27 ± 2.7 cm in height and 50% of the total cover in class V, thus becoming more competitive. As *Molinia* is gradually dominated by *Calluna*, its biomass does not step up, thus the rate of accumulation of the dead fuel component is balanced by degradation, and its load seems even to slightly decrease, despite no significant differences were found between age classes (Figure 2).

These results evidence that as time pass since fire there are significant increases in fuel load (up to 17.3 t ha^{-1}) and fuel continuity (up to 100% in cover): thus, the fuel complex becomes more flammable; in fact, as demonstrated in previous studies in similar fuel complexes (Ascoli, 2008; Davies et al., 2009), and in others shrubland fuel types (among others: Fernandes et al., 2000; Fernandes, 2001; Baeza et al., 2002), increases in fuel load, height and continuity are in part responsible of the rise in rate of fire spread and fire intensity.

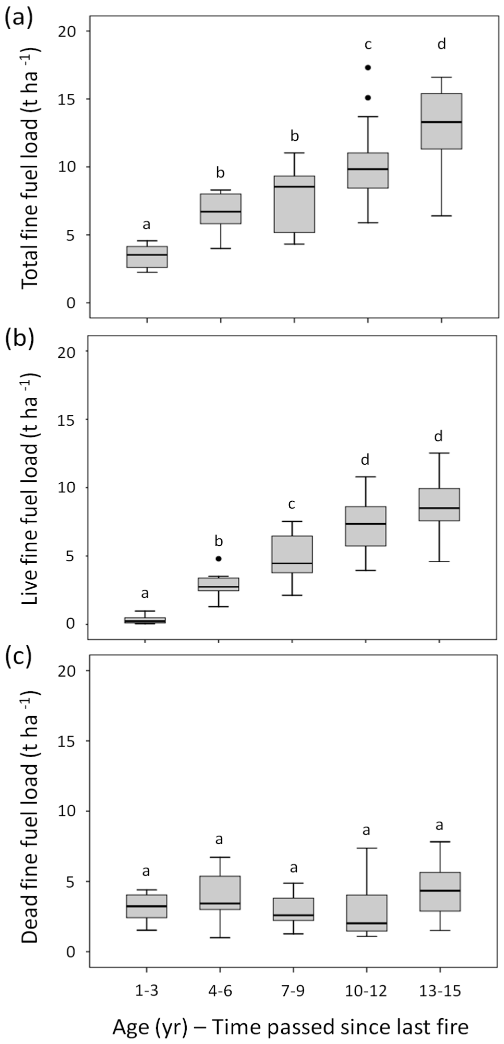

Figure 2 Variation in fuel load vs. age classes. (a) Total (live +dead) (b) live (*Calluna*) (c) dead (*Molinia*) fuel load (t ha^{-1}). Boxes show the 1st and 3rd quartiles; the black line is the median. Whiskers show the general range of the data with outliers shown as a dot. Significant differences are evidenced by different letters.

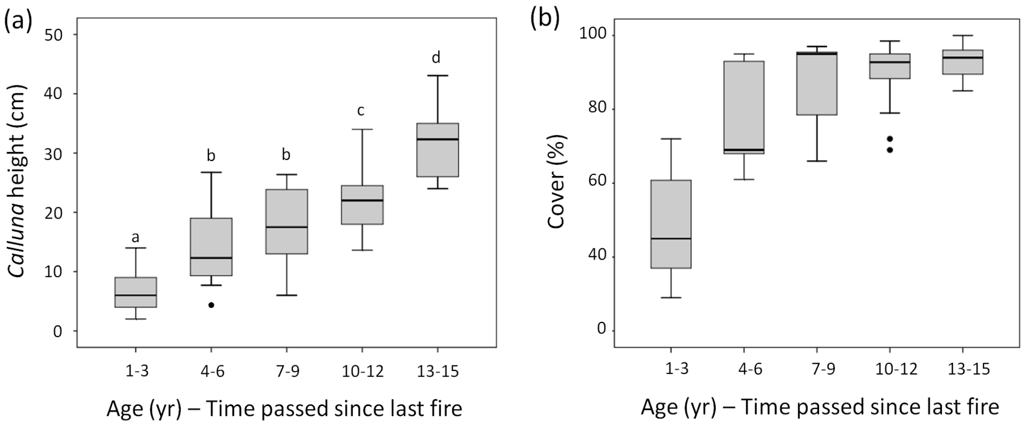

Figure 3 Variation in the fuel structure for five age classes. (a) *Calluna* height (cm), (b) Vegetation (*Calluna* + *Molinia*) cover (%). Significant differences are evidenced by different letters.

In winter 2009 the moisture content of live fuels (i.e. *Calluna* crowns) and dead fuels (i.e. *Molinia* cured leaves) resulted significantly correlated (0.679; $P < 0.01$): ranges were 37%-58% and 8%-54%, respectively (Figure 4). As dead fuels are present in all age classes (Figure 2), and present a higher range of variation in the moisture content (Figure 4), they play an important role in determining the fire behaviour of heathland fuels (i.e. fire sustainability, or difficulties in fire control) (Ascoli, 2008). Consequently, to define suitable burning conditions we deepened moisture dynamics of the fine dead fuel component.

The moisture of dead fine fuels (Mf) resulted significantly correlated to the average air relative humidity (0.722; $P < 0.01$) and to the cumulative precipitation within the last 15 days (0.526; $P < 0.01$); diversely, no correlation was found with the air temperature (-0.37; $P = 0.845$), and the dew point temperature (0.168; $P = 0.325$), probably as a consequence of the low range of temperatures in winter. The first two variables were chosen as regression predictors. Relative humidity (RH) is a commonly used variable in fuel moisture models (Marsden-Smedley and Catchpole, 2001). It was assumed that the cumulative precipitation (P15) plays also an important role in determining Mf: in heathlands of NW Italy soils are rich in clay, consequently the cumulation of precipitation determines water stagnation, which can last for several days after precipitation, affecting trough evaporation the Mf of fuels close to the soil. The best model fitted was a linear regression:

$$\mathrm{Mf} = 3.179 + 0.206 * \mathrm{RH} + 0.207 * \mathrm{P15} \qquad \text{[Equation 1]}$$

Mf: fine dead fuel moisture;

RH: average air relative humidity;

P15: cumulative precipitation in the last 15 days;

The model had a $R^2_{adj} = 0.86$. Best predictions were between 5%-30% (Figure 4) which is of interest for prescribed burning application. A brief consideration must be done as RH and P15 were correlated (0.530; $P < 0.01$); consequently the use of these variables could result in problems of multi-collinearity. Nevertheless, the risk of multi-collinearity is low because the predictor variables are not highly correlated, and the standard errors of RH and PG15 are low: 0.049 and 0.023 respectively (Quinn and Keough, 2002). Moreover, the nearby weather station of Front Malone is placed in an area with no heathlands, consequently RH should be marginally affected by the evaporation from heathlands soils.

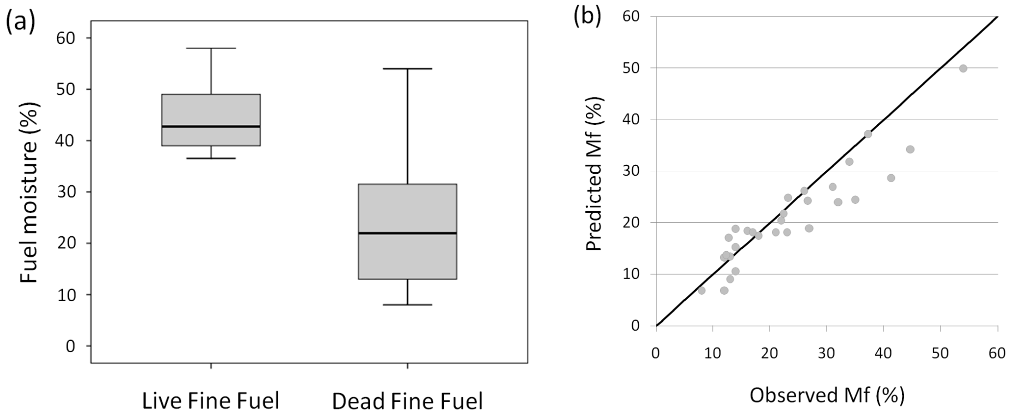

Figure 4 Moisture dynamics: (a) Variability in moisture content of live and dead fine fuels measured in winter 2009; (b) Predicted versus observed dead fuel moisture from Equations 1.

Fire behaviour analysis

All experimental burns were carried out in collaboration with the Corpo Volontari Antincendi Boschivi of the Piemonte Region, under the responsibility of the State Forestry Corp, as regulated by the Regional Law 16/94. Two burns failed (n. 13 and n. 25) because fire sustainability was not guaranteed. All others burns achieved the burn objective: total fine fuel load reduction higher than 80%. Wind speed ranged from 2 to 9 km h^{-1} in all burns.

Significant differences in ROS [F (2, 126) = 0.865; P = 0.001)] were observed in UB burns between behaviour types: backfire (A), headfire during the acceleration phase (B), and the headfire of the quasi steady state (C) (Figure 5). The type of fire behaviour (A, B, C) explained the 59% of the observed variability in ROS. All others factors which affect fire behaviour, such as wind speed, dead fine fuel moisture and total fuel load (Fernandes, 2001; Davies et al., 2009), were not significantly different between A, B and C groups. Remarkable differences were also observed in fireline intensity, but it was not possible to test significant differences, despite transformations, because the homoscedasticity was not satisfied.

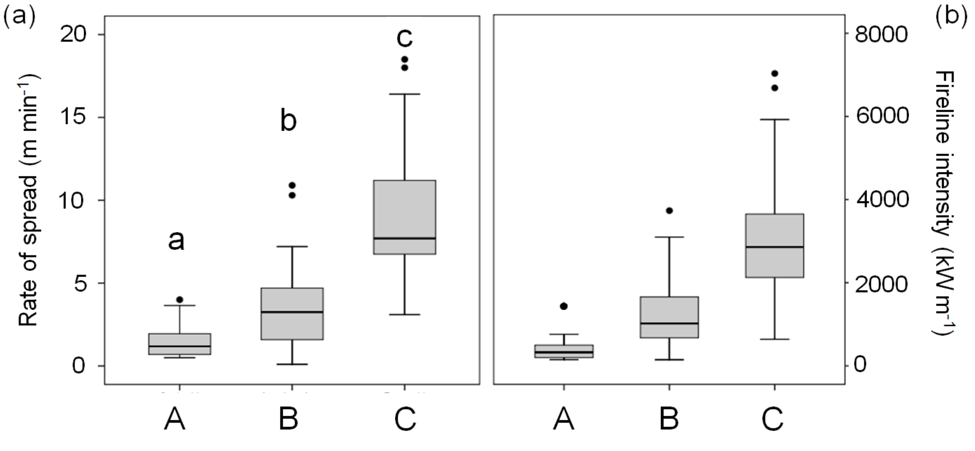

Figure 5 Variation in rate of spread (a), and fireline intensity (b), observed in UB experiment (n=9), for backfire (A), headfire in the acceleration phase (B), and headfire of the quasi steady state (C). Significant differneces are evidenced by different letters.

On the basis of these results, as observed also in previous studies (Cheney and Gould, 1995), it is possible to assert that the headfire during the acceleration phase presents a behaviour remarkably milder in comparison with the subsequent phases, and consequently can be controlled more easily. In fact, within 15 m from the line of ignition, 75% of the observed values of rate of spread and fireline intensity were respectively below 5 m min^{-1} and 1800 kW m^{-1}. The strip head fire ignition technique, with strips progressively distanced up to 15 m, should be suitable to implement prescribed burning to reduce heathland fuels, both because it enables to maintain fire behaviour under control, and allows to burn rapidly extensive areas in comparison with the backfire technique. Experimental burns on 1250 m^2 in 2008 (n=4), carried out adopting the strip head fire ignition technique, had an average (±SE) duration of 15 ± 2 minutes.

The average fireline intensity was significantly higher in UB vs. BU experimental burns both for backfire, 381 kW m^{-1} and 100 kW m^{-1} [F (1, 62) = 7.6; P = 0.008)], headfire in the acceleration phase, 1205 kW m^{-1} and 463 kW m^{-1} [F (1, 58) = 10.5; P = 0.002)], and headfire in the quasi steady state, 3072 kW m^{-1} and 619 kW m^{-1} [F (1, 67) = 122.8; P = 0.001)], respectively.

These results evidence that fireline intensity can be remarkably mitigated in recently burnt areas (1-3 years since fire) were the fuel load has been reduced by prescribed burning. In fact, even the headfire behaviour in the quasi steady state showed a fireline intensity close to the value of 500 kW m^{-1}, which is commonly considered the upper limit for the direct attack in fire control interventions on flat terrains (Andrews and Rothermel, 1982).

The fuel moisture effect on fire behaviour was tested for the subset of observations relative to headfires (both in the acceleration and quasi steady state) grouping together BU and UB datasets. Significant differences in ROS were found [F (2, 124) = 3.226; P = 0.043)] between moisture contents of dead fine fuels below 15% and higher than 25% (Figure 6). The average ROS for moisture contents <15% was 7.6 ± 0.6 m min^{-1} and values beyond the direct attack capability (up to 20 m min^{-1}) were observed. On the other side, the 50% of observed values of ROS for moisture content >25% was below 2.2 m min^{-1}, which implicates a time-consuming job.

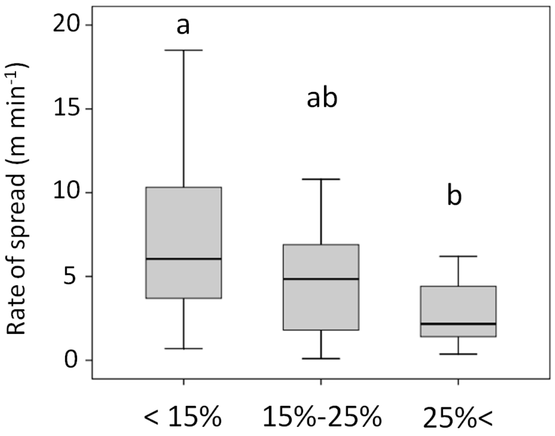

Figure 6 Variation in rate of spread (m min^{-1}) for moisture classes of dead fine fuels, Significant differneces are evidenced by different letters.

Additional information to set fine dead fuels moisture operational thresholds were provided by experiments n. 13 and 25. In fact, these two fire experiments failed because fire sustainability was not guaranteed as a consequence of the elevated dead fine fuel moisture content, which was 29% and 32% respectively. Consequently, the optimum moisture scenario appears to be the one whose values range between 15% and 25% (average ROS equal to 4.4 ± 0.5 m min^{-1}), because it guarantees a sustained fire behaviour on one side, but does not exceed operative limits on the other.

In order to identify the prescribed burning operational period in winter, the optimum burning windows of dead fine fuel moisture (15%-25%) were superimposed to the daily fine dead fuel moisture estimated by Equation 1 for years 1996-2008 (Data source: Front Malone weather station. Arpa Piemonte). The yearly variability of RH and P15 between 1996-2008 period was high. The difficulty to define the exact period in which is possible to apply prescribed burning is evidenced in Figure 7 where the daily moisture content of dead fine fuels is plotted for the year with minimum (2005) and maximum (2008) precipitation. Despite the seasonal trend is verified in both curves, they differ remarkably in the distribution of suitable periods to apply prescribed burning. Available days for burning within optimum moisture windows between October and early February ranged from 39 to 111 days (from middle February it starts the wildfire season and the use of prescribed burning is not authorized in the Piemonte Region – R.L. 16/94).

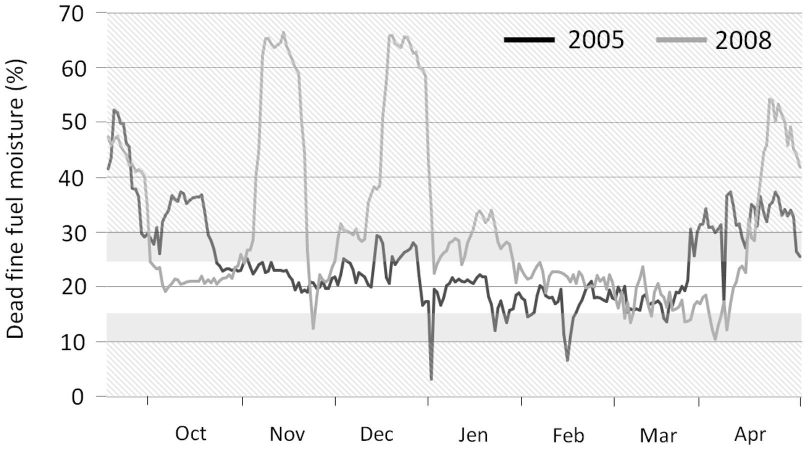

Figure 7 Dead fine fuel moisture content in winter 2005 (black line) and 2008 (grey line) as predicted by Equation 1. The white area represent the optimum of dead fine fuel moisture values (14%-26%) for prescribed burning application; grey areas the lower (14%-10%) and upper (26%-30%) marginal conditions; lined areas evidence moisture conditions (< 10%; > 30%) out of prescriptions.

4. Conclusions

The present study evidenced that prescribed burning can be an effective fuel management technique to reduce fire hazard at the stand level in heathlands of NW Italy. Prescribed burning treatments have to be implemented from October to the early February, before the wildfire season starts. Fuel treatments are going to be effective not only the year of the burn, where expected fuel reduction is higher than 80% of the total fine fuel load, but also up to 3 years after the burn, as the fuel load remains below 5 t ha^{-1}. The strip head fire ignition technique is suitable to implement prescribed burning because gathers fire control and efficiency. The optimum dead fine fuel moisture window is between 15% and 25%, as it guarantees a sustained fire behaviour which does not exceed operative limits. The seasonal distribution of available days for burning is extremely variable between years, consequently the maximum flexibility is required; the authorization process should thus consider this issue. Nevertheless, in Italy prescribed burning is still a controversial issues because of the lack of knowledge, experiences and expertises (Leone et al., 1999; Ascoli 2008), consequently the set of rules tends to protect itself from an unwise fire use. Muldisciplinary and long term experimental studies carried out in Italy (Ascoli, 2008; Delogu, 2009; Catalanotti et al., Proceedings of this Conference) can thus help to improve knowledge of forest managers and facilitate a more critical approach to prescribed burning.

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