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PRESCRIBED FIRE BEHAVIOR AND FUEL CONSUMPTION IN NORTHERN PORTUGAL AND GALIZA MARITIME PINE STANDS

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Summary

The available data from several experimental prescribed fires in maritime pine stands of Northern Portugal and Spain were gathered, covering a wide range of fuel moisture, weather and fuel accumulations. A broad variation in fire behavior and fuel consumption is possible between prescribed fires. Rate of spread and flame length varied 9-fold and 10-fold, respectively, and total fine fuels reduction averaged 53 % of the preburn load, ranging from 21 % to 95 %. The largest differences in reduction were showed by the duff component.

Equations relating preburn descriptors to fire behavior and fine fuel consumption were developed, showing that preburn fuel loadings, fuel moisture content and burning technique are the main factors that govern fire behavior and fuel reduction. However, fireline intensity seems to be indifferent to preburn fuel quantities, being a function of 1hr fuel moisture content and ignition pattern.

Introduction

Wildfires are a serious threat to forests in Portugal, specially those of maritime pine (*Pinus pinaster* Aiton). The average burned area per year in the last decade exceeded 10^4 hectares (Silva, 1993), about 3 % of the Portuguese forested land. This situation evolved from a dramatic decrease in land use in the 60's, and a simultaneous fire exclusion policy, which led to large fuel accumulations that are regulated by intense wildfires (Rego, 1991).

Prescribed burning has been introduced recently in Portugal, and in many cases it is the only practical way to achieve forest floor and vegetation fuels reduction (de Ronde *et al.*, 1990). Its future importance as a management tool to decrease fire hazard and improve shrubs quality for grazing is promising. Large experience is already available concerning the use of prescribed fire as a fuel management tool in maritime pine ecosystems, and past research has fairly established prescribed fire effects upon soil (Rego *et al.*, 1987a), water regimes (Rego & Botelho, 1992), understory vegetation (Rego *et al.*, 1991), and trees (Ryan *et al.*, 1993). However, if prescribed fire is to be of general application, more information about fire behavior, particularly intensity, and fuel consumption rates are necessary, which is specially important for the accurate assessment of prescribed burning costs and benefits (Kauffman & Martin, 1989).

In prescribed fire the correct balance between forest floor consumption and retention must be respected to reduce fire hazard but prevent site damage (Brown *et al.*, 1985 and 1991; Harrington, 1987). Predicting forest floor reduction is considered essential for the skillful planning of prescribed fires (Brown *et al.*, 1985 and 1991; Sandberg, 1980).

This study objectives were to document the patterns and ranges in fire behavior and fuel consumption from the assemblage of available data on previous prescribed fires, including the establishment of empirical numerical relationships of preburn variables with fuel consumption and fire behavior.

Methods

The burns were carried in pure and regular stands of maritime pine in five locations: TOM in Galiza (Spain), VNC, SEV and PENS in Northern Portugal and LOU in Central Portugal.

Establishment of stand characteristics was done by measuring all the trees in the plots. Table 1 exhibits the range of site and stand characteristics for the plots within each location.

Table 1. Range of site and stand characteristics of prescribed fire units

	TOM	VNC	SEV	PENS	LOU
Location	Pontevedra	Alto Minho	Trás-os-Montes	Trás-os-Montes	Beira Litoral
Elevation, m	340-360	510	970	650	420
Slope, %	0-26	15	11-18	2-20	12
Aspect	NO, E	N	SW	E, W	SW
Plot size, ha	0.09	0.02	0.02	0.09	0.05
t, yrs.	37-41	10	16	30-33	18
hdom, m	13.8-18.5	6.2-6.7	2.7-4.6	13.1-16.9	8.4-10.1
kr h, m	-	2.5	0.8-2.5	6.4-10.2	3.8-4.6
dbh, cm	20.6-26.8	9.7-10.3	2.9-6.4	14.6-19.2	10.4-12.3
G, m^2 ha^{-1}	20.0-54.1	18.8-23.7	3.2-10.3	30.6-38.6	22.3-31.0
N, tree ha^{-1}	577-967	2550-2850	3050-4900	1189-1989	2380-2740

t - stand age; hdom - dominant heigth; kr h - crown distance to ground; dbh - diameter at breast heigth; N - density; G - basal area.

Fuel sampling occurred before the burns and immediately after. Fuel loads were destructively sampled by 18 (TOM, PENS) or 6 (VNC, SEV, LOU) randomly placed 0.5 m^2 quadrates. All fuels within the quadrates were harvested, with field pre-separation in duff, litter, shrubs and herbs. The material was subsequently sorted into 7 different classes: needles, downed dead woody fuels (1hr, 10hr and 100hr time lag classes), shrubs (leaves and twigs or branches less than 6 mm in diameter, branches thicker than 6 mm) and herbs. These fractions were dried in a convection oven for 48 hours at 65° C to obtain dry weights.

Prescribed burns were carried out during Winter or Spring, and conducted as head fires, strip fires or back fires. To avoid edge effects fires were ignited outside the plots. Registrations at breast height of temperature, relative humidity, windspeed and wind direction were made during the burns. Fuel samples were collected immediately before the burns throughout the plots for moisture content evaluation by oven drying. Observers placed in the plots lateral borders evaluated rate of spread, flame height (F_h, m) and flame angle. Rate of spread was calculated by timing the fire front advance between reference poles located at known intervals. Flame height was estimated by comparison of its average height with stakes height. Slope angle and flame angle allowed the determination of flame length, L (Finney & Martin, 1992):

$$L = F_h(\sin(90-\beta))/\sin(\alpha-\beta)$$

where α is the angle between flame axis and horizontal and β the slope angle from horizontal.

Fireline intensity (I_h) defined by Byram (1959) as the upward rate of heat release per unit length of a flaming front (kW m^{-1}), is normally viewed as the most important fire behavior parameter, largely responsible for aboveground fire effects (Alexander, 1982; Finney & Martin, 1992; Weber *et al.*, 1987). Fireline intensity is a product of three factors (Byram 1959):

$$I_h=HWR$$

H is the heat yield per unit mass of fuel (J g^{-1}), W is the weight of fuel consumed per unit area (kg m^{-2}) and R is the fire rate of spread (m s^{-1}). Only fuels that are consumed in the flaming zone should be used in the equation, otherwise fireline intensity calculation will be inflated (Alexander, 1982). The difference between preburn and postburn fine fuels load was applied for this purpose. H is the low heat of combustion, that varies little from fuel to fuel. An H value of 18700 J g^{-1} was assumed according to Albini (1976).

Fireline intensity was also computed following the empirical equation of Byram (Alexander, 1982):

$$I = 259.83L^{2.174}$$

The multiplication of H by W was used as an estimate of heat per unit of area (H_A, kJ m^{-2}).

The calculation of flame depth (D, m) from flame length, flame height and flame angle allowed the determination of two more fire behavior parameters, reaction intensity (I_R, kW m^{-2}) and residence time (t_R, s) (Alexander, 1982):

$$I_R = \frac{I_h}{D} \quad \text{and} \quad t_R = \frac{D}{R}$$

Prediction equations for fuel consumption and fire behavior were developed using multiple linear regression. Stepwise procedures selected the independent variables from site and stand characteristics and burning time fuel moisture and weather. Dummy variables were also included to examine the influence of burning technique and fuel complex type. Dependent and independent variables are in Table 2.

Table 2. Variables used in regression analysis

Variable	Abbreviation
Dependent	
Litter fine fuels reduction, kg m^{-2}	LFR
Shrubs fine fuels reduction, kg m^{-2}	SRFR
Duff reduction, kg m^{-2}	DR
Rate of spread, m s^{-1}	R
Flame length, m	L
Fireline intensity, kW m^{-1}	I_h
Heat per unit of area, kJ m^{-2}	H_a
Independent*	
Preburn litter fine fuels load, kg m^{-2}	PLF
Preburn shrubs fine fuels load, kg m^{-2}	PSRF
Preburn surface fine fuels load, kg m^{-2}	PSF
Preburn duff load, kg m^{-2}	PD
1hr fuels moisture content, %	FMC
Duff moisture content, %	DMC
Windspeed, m s^{-1}	U
Air temperature, ^{o}C	T
Slope, %	SL
Burning technique (backfires=-1, strip fires=0, head fires=1)	BT
Fuel type (litter=-1, litter and shrubs=0, shrubs=1)	FT

* Selected to be in the models by stepwise procedures

Burn conditions and fire behavior

Table 3 displays the range of weather, fuel moisture contents and fire behavior during the prescribed fires. Temperature and relative humidity values generally remained within the adequate limits defined by Rego *et al.* (1987b), that allow prescribed fire execution to accomplish fire hazard reduction objectives without damages. Relative humidity exceeded the upper limit (80 %) in one burn, but temperature exceeded it (15^{o} C) in 6 burns, which were carried in Spring.

Table 3. Ranges of prescribed fires characteristics

	TOM	VNC	SEV	PENS	LOU
Air temperature, ^{o}C	10.0-19.1	6.5-16.5	7.0-13.5	3.8-6.5	15.5-17.7
Relative humidity, %	56-76	51-60	66-85	61-69	68-70
Windspeed, m s^{-1}	0.3-1.6	2.0-3.0	0.5-1.8	0.6-1.2	0.5-1.0
1hr moisture content, %	14.5-23.6	18.4-21.7	16.6-28.9	26.2-30.1	18.2-18.6
Duff moisture content, %	60.8-143.5	98.5-152.9	57.5-86.3	130.0-142.3	61.8-68.3
Type of burn	strip head	back fire	strip head, head fire	strip head, back fire	back fire
Nº of burns	6	2	7	6	3
Rate of spread, m s^{-1}	0.012-0.020	0.006-0.008	0.005-0.046	0.008-0.017	0.008-0.017
Flame length, m	0.25-0.75	0.80-1.61	1.35-2.50	0.28-0.81	1.21-1.54
Flame depth, m	0.23-0.57	0.51-0.66	0.14-1.71	0.17-0.43	0.10-0.66
Residence time, s	12-32	62-104	20-247	14-36	12-49
Heat p/unit area, kJ m^{-2}	6265-14306	4675-11613	12389-20157	4432-8989	5647-12207
Reaction intens., kW m^{-2}	301-1124	76-111	78-740	188-470	250-458
Fireline intensity					
I_h, kW m^{-1}	91-272	39-73	87-812	64-121	47-195
I_L, kW m^{-1}	13-139	161-733	498-1904	16-165	392-663

Fine dead fuels moisture content values surpassed 25% in 8 burns, reflecting marginal conditions for sustained propagation but that often occur during the prescribed fire season. Maritime pine needles moisture of extinction was not yet determined, but Gillon *et al.* (1993) report that in experimental laboratory fires, rate of spread and intensity are reduced 4 times when moisture content increases from 6 to 30 %.

Wind velocity and direction were fairly constant during the burns, which helped in their execution.

Rate of spread values were low and ranged from 0.005 to 0.020 m s^{-1}, except one SEV headfire that attained 0.046 m s^{-1}. Overall variation between fires was 9-fold and the average rate of spread was 0.013 m s^{-1}. Similarly to rate of spread, flame length varied 10-fold (from 0.25 to 2.50 m), the highest value corresponding to the same SEV burn mentioned before. Mean flame length was 1.10 m. Residence time varied between 12 s and 247 s, with an average of 51 s.

Fireline intensities computed with both methods did not agreed and were poorly correlated (R=0.47), which is not surprising according to other authors (Armour *et al.*, 1984; Smith *et al.*, 1993). I_h averaged 148 kW m^{-1} and ranged from 39 to 812 kW m^{-1}, while I_L showed a wider variation (13 - 1905 kW m^{-1}), averaging 444 kW m^{-1}. I_L generally exceeded I_h by a factor between 1.6 and 10.0. However I_h estimates were greater (by a factor varying from 1.6 to 9.1) than I_L estimates in the majority of the burns with flame lengths lesser than 0.8 m. In the burns accomplished with a single ignition line the following relationship between I_h and L was found:

$$I_h = 83.879L^{1.574} \qquad R = 0.84\ (n=9)$$

This equation has an exponent similar to the empirical equations derived by Nelson (1980) and by Thomas (1963) cit. Finney & Martin (1992). Since it is difficult to estimate consistently fireline intensity, both methods should be used independently at the same burn (Johnson, 1982).

Preburn fuel loads and fuel consumption

Three fuel complex types could be distinguished: shrubs with non continuous litter (SEV), litter (half of TOM and PENS plots) and a mix of litter and shrubs in the rest of the plots. *Chamaespartium tridentatum* and ericaceous species appeared in all locations, but *Ulex* spp. and *Pteridium aquilinum* existed only in the less xeric sites (VNC and LOU). Fuel loading results are presented on Table 4, where surface fuel refers to non duff (litter and understory vegetation) fine fuels, while total includes all the fine fuels.

Preburn fuel quantities covered a wide range, as a result of stand age and site quality differences. Duff (F and H layers) quantities exhibited large variations between plots, from 0.07 kg m^{-2} to 1.43 kg m^{-2}. Litter (needles and 1hr downed woody fuels) averaged 0.44 kg m^{-2} and ranged from 0.12 to 0.74 kg m^{-2}. The litter and duff component accounted for 28-100% of the total fuel load. Shrubs fine fuels varied from 0 to 0.89 kg m^{-2}, with an average of 0.34 kg m^{-2}.

22 to 100% of the preburn litter fuels were reduced in the burns, with an average of 63%; these percentages correspond to a 0.04-0.53 kg m^{-2} interval and a 0.29 kg m^{-2} average. The

extent of duff reduction was smaller; it exceeded 0.2 kg m^{-2} only in 6 burns, with a maximum of 0.56 kg m^{-2} (equivalent to 39% of preburn load), and in 5 fires didn't happened at all. In the plots with shrubs, its consumption averaged 0.34 kg m^{-2} (83% of the initial load) and peaked at 0.86 kg m^{-2} (97%). Shrubs reduction was always above 90% of the preburn load in SEV burns, probably due to the continuity of the understory layer.

10hr and 100hr downed woody fuels as well shrub fuels larger than 6 mm did not suffer a significant reduction ($P<0.05$) in the majority of the fires and they were excluded from the analysis. The high fuel moisture contents verified can be partially accounted for this result, but the primary reason must be searched in fuel sampling insufficiency.

Surface fine fuels reduction averaged 0.58 kg m^{-2} (66%) and ranged from 0.24 to 1.01 kg m^{-2} (36-98%), while the average total fine fuels consumption was 0.68 kg m^{-2} (53%), in an interval from 0.24 to 1.08 kg m^{-2} (21-95%).

Table 4. Ranges of preburn fuel loadings and fuel consumptions

	TOM	VNC	SEV	PENS	LOU
Preburn fine fuel loadings, kg m^{-2}					
Litter	0.63-0.74	0.52	0.12-0.41	0.24-0.63	0.38-0.46
Shrubs	0.00-0.37	0.18	0.67-0.89	0.00-0.36	0.10-0.29
Surface	0.66-1.02	0.70	1.06-1.93	0.49-0.67	0.57-0.68
Total	1.88-2.10	0.91	1.12-1.95	0.93-1.25	0.98-1.05
Fine fuel consumption, kg m^{-2}					
Litter	0.33-0.53	0.14-0.45	0.09-0.18	0.18-0.37	0.38-0.43
Shrubs	0.00-0.24	0.11-0.17	0.62-0.86	0.00-0.25	0.07-0.24
Surface	0.33-0.76	0.25-0.62	0.66-1.01	0.24-0.48	0.30-0.65
Total	0.56-1.00	0.29-0.87	0.66-1.08	0.24-0.50	0.54-0.98

Fuel consumption and fire behavior predictive equations

Of all the independent variables available for correlation with fuel consumption and fire behaviour, stepwise multiple regression selected primarily preburn fuel quantities, fuel moisture content and ignition technique. Besides slope, none of the stand and site characteristics arises in the equations (Table 5).

Preburn fuel loads (PLF, PD and PSRF) and burning technique (BT) appear in the three fuel reduction equations. Preburn loads are the most important independent variables for predicting litter (LFR) and shrubs (SRFR) consumption. For duff reduction (DR), however, moisture content played the major role, which is of general agreement (Armour *et al.*, 1984; Brown *et* *al.*, 1985 and 1991; Harrington, 1987; Martin *et al.*, 1979; Sandberg, 1980), though other factors can also be pertinent, like woody fuels consumption and preburn duff depth (Brown *et al.*, 1985 and 1991; Harrington 1987).

Burning technique influence is different according to fuel type. The negative signal of BT coefficient for LFR and duff (DR) fine fuels consumption shows that backfires favor forest floor reduction, while shrubs are more consumed in headfires.

Moisture content of 1hr timelag fuels (FMC) was not choosed for the LFR model, but air temperature (T) did. In fact FMC and T are correlated (R=0.74).

Relationships between the independent descriptors and fire behavior are weaker. The higher rates of spread (R), according to our model, are achieved with the lighter surface fuel loads (PSF) in headfires, BT being the predominant explicative variable. Flame length correlates only with fuel complex type (FT), meaning longer flames in the higher shrub fuels. The uncertainties and bias inherent to field measuring of flame heights and angles probably determined this unusable result; video and still photography of flame characteristics and passive sensors, as described by Finney & Martin (1992), can estimate more accurately flame length.

Table 5. Best fitting equations for predicting fuel consumption and fire behavior

Equation	R^2	Se*	P
Fuel consumption			
LFR = -0.041 + 0.654 PLF - 0.066 BT - 0.66 U + 0.009 T	0.89	0.055	< 0.0001
DR = 0.165 + 0.155 PD - 0.003 DMC - 0.119 BT + 0.008 SL	0.78	0.077	< 0.0001
SRFR = - 0.019 + 0.954 PSRF + 0.027 BT	0.98	0.045	< 0.0001
Fire behavior			
R = 0.025 - 0.010 PSF + 0.011 BT	0.45	0.006	< 0.0020
L = 1.059 + 0.697 FT	0.57	0.37	< 0.0001
I_h = 414.097 -10.032 FMC + 151.625 BT	0.65	122	0.0030
H_a = 7139.398 + 10224.953 PSF - 236.344 FMC	0.81	2087	< 0.0001

* Se is the standard error of estimate

Likely to LFR and SRFR, and since H_A depends of fuel consumption in the fire front, preburn surface fuel load (PSF) explains its main variation. I_h is the product between H_A, positively correlated with preburn fuel load, and R, negatively correlated with preburn fuel load. Due to that reason, preburn load disappears from I_h equation, where FMC and BT are the independent variables. This is an interesting result for prescribed fire planning, since the burning technique can be selected according to 1hr fuel moisture contents, in order to achieve a fireline intensity within the appropriate limits. 350 kW m^{-1} is defined as the upper limit, because above it the fires are too intense for direct attack on the head by persons with handtools, and a hand line cannot be relied on to hold fire (Andrews & Rothermel, 1982). The lower limit considered was 40 kW m^{-1}, reflecting the more unfavorable conditions verified in this study data, but for which prescribed fire remains an efficient tool. The results (Fig. 1) show that strip fires can be performed over the whole range of the observed 1hr fuel moisture contents (14-30 %), but the effectiveness of back fires lies below 23 %, while head fires execution is safe only above 22 %.

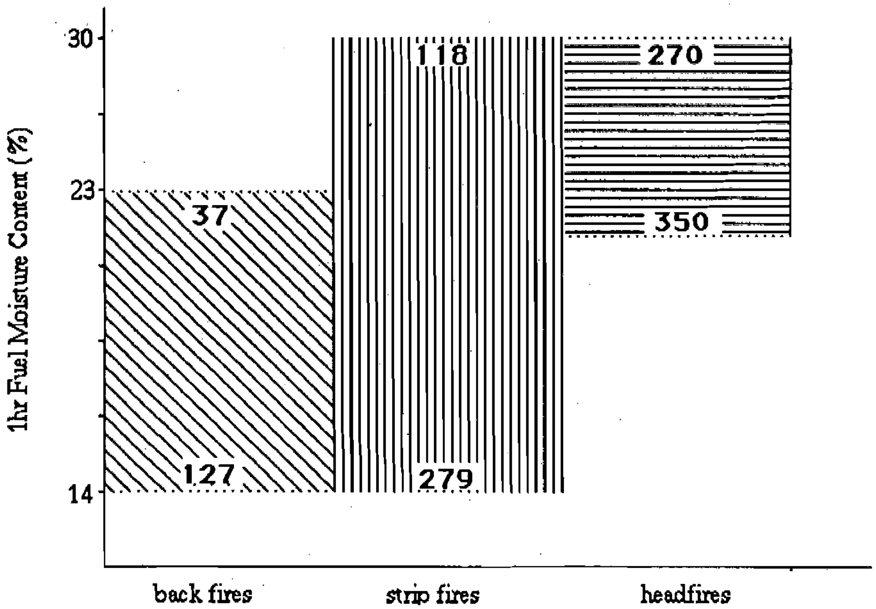

Fig. 1 - Prescribed fires Fireline Intensity (Kw.m^{-1}) according to Fine Fuel Moisture Content (%) ranges for different techniques

Conclusions

The reported results on fuel reductions and fire behavior cover a wide range, outcoming from various combinations of fuel moisture, weather and fuel accumulations commonly experienced in maritime pine stands, and are markedly influenced by the burns ignition pattern. The broad variations in fuel consumption that can occur between fires (specially in duff consumption), certainly affect the overall fire impact upon the ecosystem.

Fire severity, which involves the effects of upward and downward heat flux, is a qualitative measurement of the fire effects on the ecosystem (Brown & DeByle, 1989) and can be rated by ground fuels consumption and crown scorch (Merrill & Alexander, 1987 cit. Hartford & Frandsen, 1992). In the majority of these experimental burns fire severity was low, since duff consumption was insubstantial and crown scorch happened only in the young stands.

The diversity of burn conditions can reduce the models predictive value, but, at the same time, it ensures its extensiveness. Following this first attempt, to ameliorate prescribed fire planning and efficiency and contribute to a wider application, experiments should be designed exclusively to study the relationships between preburn descriptors and fire behavior. Special care should be given to the accuracy of fuel sampling and fire behavior parameters measurement. The predictive equations must include a minimum of independent variables readily obtained by practitioners (like forest floor depths, instead of loads).

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