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Heat Transfer in the Soil During Very Low-intensity Experimental Fires: the Role of Duff and Soil Moisture Content

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Abstract. The aim of this study was to analyse the effects of duff thickness and moisture content, and of soil moisture content on the transfer of heat in the soil. The experimental design used intact soil blocks with their duff layer, subjected to controlled fires of variable very low intensities of up to 100 kW m^{-1}. The fuel on the surface was composed of needles and twigs of *Pinus pinaster*. The maximum temperatures measured within the fuel were of the order of 650°C and were independent of the fireline intensities. For fires with fireline intensity of the order of 30 kW m^{-1}, the presence of the duff layer reduced from 330°C the temperature rise at the soil surface. Duff thickness played only a secondary role, but increasing moisture content reinforced its insulating effect, so that the temperature rise was 2.5 times less at 1 cm depth in the duff when the moisture content exceeded 70% dry weight, than when the moisture content was less than 30%.

For more intense fires (> 50 kW m^{-1}) that produced longer-lasting surface heating, duff thickness and moisture content played an important role in significantly reducing the temperature rise at the soil surface (range 140°C to 28°C). Because of low soil thermal conductivity, temperature attenuation with increasing depth was noticed. In the case of low intensity fires (< 30 kW m^{-1}) in the absence of a duff layer, the maximum temperatures were reduced from 350°C at the surface to 7°C at 3.5 cm. The temperature rise in the soil decreased with depth according to a negative exponential relation. The rate constant of this relation was greater when the initial surface temperature and the soil moisture content were higher. For the soil studied, and under the moisture conditions encountered (between 7 and 19% of dry weight), the rate constant could be predicted with acceptable precision ($r^2 = 0.67$), if the surface soil temperature rise and the soil moisture content were known.

In these experimental fires, which were carried out when the air temperature did not exceed 20°C, lethal temperatures (> 60°C) were measured in the upper few centimetres of the duff layer in very low-intensity fires, and in the upper few centimetres of the soil (where nutrients are most concentrated and biological activity most intense) in the slightly more intense fires. The fire intensities were always very moderate, and of the order of magnitude of those encountered in the prescribed burns conducted on fuel-breaks of the french Mediterranean area. Their impact on the surface of the forest soil, in terms of lethal temperatures transmitted to the horizon rich in organic matter, are not negligible. In contrast, below 3 to 5 cm depth, prescribed burns, conducted under the conditions of the experiments, would not lead to significant change to nutrients or microfaunal or microfloral activity; in particular, root tips would not be subjected to heat stress sufficient to kill them.

Keywords: Heat transfer; Soil; Prescribed burning; *Pinus pinaster*; temperature; Duff.

Résumé. L'objectif était d'analyser les effets de l'épaisseur et de l'humidité de la couche d'humus, et ceux de l'humidité du sol sur les transferts thermiques dans le sol à l'aide d'un dispositif expérimental utilisant des blocs de sol intacts avec la couche d'humus, soumis à des feux de faibles puissances ne dépassant pas 100 kW m^{-1}. Le combustible en surface, était composé d'aiguilles et/ou de brindilles de *Pinus pinaster*. Les températures maximales mesurées au sein du combustible ont été de l'ordre de 650°C et indépendantes de la puissance du front de feu. Pour des feux dont la puissance était de l'ordre de 30 kW m^{-1}, la présence de la couche d'humus a réduit de 330°C l'élévation de température à la surface du sol. Son épaisseur ne joue qu'un rôle secondaire, mais son humidité renforce son effet isolant. Lorsque la teneur en eau de l'humus est de 70% du poids anhydre, l'élévation de température est 2,5 fois moins importante à 1 cm de profondeur que lorsque cette teneur en eau est inférieure à 30%. Pour des feux plus intenses (> 50 kW m^{-1}) qui provoquent un échauffement plus durable en surface, l'épaisseur de la couche d'humus et sa teneur en eau jouent un rôle important en réduisant significativement l'augmentation de température à la surface du sol (de 140°C et 28°C). Le sol, par sa faible conductivité thermique, amortit également les températures en profondeur. Dans le cas de feux de faible puissance (< 30 kW m^{-1}), et en absence de la couche d'humus, les températures maximums ont été réduites, de 350°C en surface à 7°C à 3,5 cm de profondeur. L'élévation de la température dans le sol décroît avec la profondeur selon une fonction exponentielle négative. La pente de cette fonction est d'autant plus forte que la température initiale en surface est élevée et que le sol est plus humide. Pour le sol étudié, et les teneurs en eau rencontrées (entre 7 et 19% du poids anhydre), cette pente peut être prédite avec une précision acceptable (r^2 = 0,67), si l'élévation de température à la surface du sol et sa teneur en eau sont connues. Pour ces essais de brûlages qui ont été réalisés alors que la température de l'air ne dépassait pas 20°C, des températures létales (> 60°C) ont été mesurées dans les premiers centimètres de la couche d'humus, au cours de feux de très faible puissance, et dans les premiers centimètres du sol, là où les nutriments sont les plus concentrés et les activités biologiques les plus intenses, au cours de feux un peu plus puissants. La puissance des feux a toujours été très modérée, de l'ordre de grandeur de celles rencontrées au cours des brûlages dirigés réalisés sur les pare-feux de la façade méditerranéenne française. Leurs impacts au niveau de la surface du sol forestier, en termes de températures létales transmises dans les horizons riches en matière organique, sont non négligeables. En revanche, au-delà de 3 à 5 cm de profondeur, les brûlages dirigés, conduits dans les conditions qui furent celles des essais, ne modifient pas significativement le statut des nutriments et les activités biologiques de la microfaune et de la microflore; en particulier, les coiffes racinaires n'ont pas subi un choc thermique suffisant pour être détruites.

Mots-clés: Transferts thermiques, sol, brûlage dirigé, *Pinus pinaster*, température, humus

Introduction

The duff layer, defined as the layer of decomposing organic matter situated below the fresh litter layer (OL) and above the mineral soil, plays an essential role in forest ecosystems in protecting soils from erosion, retaining moisture and by releasing nutrients. During forest fires, many authors have noted that this layer, if it is not burnt, protects the soil from the high temperature levels recorded at the surface (Van Wagner 1970; Raison et al. 1986), the soil itself being a poor conductor of heat (Beadle 1940; Packham 1971; Aston and Gill 1976; Raison et al. 1986; Dimitrakopoulos and Martin 1990).

Many studies have aimed at quantifying and modelling duff combustion during prescribed fires (Sweeney and Biswell 1961; Van Wagner 1972; Shearer 1975; Norum 1977; Sandberg 1980; Brown et al. 1991; Frandsen 1987). One of the aims of prescribed burning can be to reduce the thickness of this layer, which can inhibit natural regeneration of vegetation if it is too thick. On the other hand, prescribed burning can also be conducted in a manner that protects the duff so as to minimize nutrient loss and avoid exposing the mineral soil to erosion. Previous studies have generally shown that the extent of duff burning depends on its moisture content, the surface fire duration and the heat load. Recently, Blackwell et al. (1992) observed that the consumption of forest floor during broadcast burns depended mainly on the forest floor fuel mass and its moisture content with the surface fire duration and the slash load being less important.

Bradstock et al. (1992) clearly demonstrated the influence of fuel mass and fuel thickness on maximum temperatures recorded in the soil. However, few studies have attempted to quantify the insulating role of the duff in limiting heat transfer into the soil. Only Frandsen and Ryan (1986) have measured the decrease in heat transfer across a thin layer (-2 cm) of dry or moist peat moss, simulating the role of the duff in a mineral soil composed of either dry or moist sand, by experimentally reconstituting a burning fuel pile. It appeared that the reduction in temperature could reach 500°C, on condition that the peat moss and sand were moist. It appeared also that the heat load transmitted into moist sand could be a fifth of that transmitted into dry sand. This led the authors to recommend forest managers to conduct prescribed burning when the mineral soil is close to saturation to avoid major impacts by fire on the soil.

If prescribed burning is to be used effectively as a management tool to lower fuel amounts, to reduce the risks of wildfires or to improve seedling regeneration, the insulating role of the duff and on the effects of fire on the soil need to be known so that prescriptions can be set to minimize excessive consumption of organic matter or soil sterilization (Sweeney and Biswell 1961; Raison 1979; Rundel 1981).

This study analysed the insulating role of the duff and the effects of soil moisture content on temperature rise in the soil during very low intensity prescribed fires. Experimental fires under as stable as possible conditions, so as to provide replicates, and soil and duff samples were disturbed as little as possible to provide conditions comparable with those found in the field.

The assessment of the influence of duff and soil properties on the transmission of heat into the soil during experimental fires was mainly based on measuring maximum temperatures or temperature increases at different soil depths. According to Raison (1979) and Raison et al. (1986), measurement of the temperature profile is probably the best method for describing fires in terms of their ecological impact, since critical temperature thresholds for biological, physical and chemical changes in the soil are well known (See review of Walker et al. 1983).

Material and Methods

Experimental design

The fires were conducted in the laboratory on a 1m^2 (1.7 x 0.6 m) test bench 0.3 m deep, filled with silica sand, in the centre of which was placed a soil block (Figure 1). All the soil blocks came from the Amarine site, a plantation of maritime pine (*Pinus pinaster* Ait.), aged 45 years, located near Nîmes (Southern France). Each 20 x 20 x 20 cm soil block, including its upper duff horizon (horizon OF), a thin humified layer (horizon OH) and the mineral soil (horizon A), was collected after removal of the lightly decomposed litter layer (horizon OL). Each sample was placed on a tray, covered with a plastic bag and taken to the laboratory,

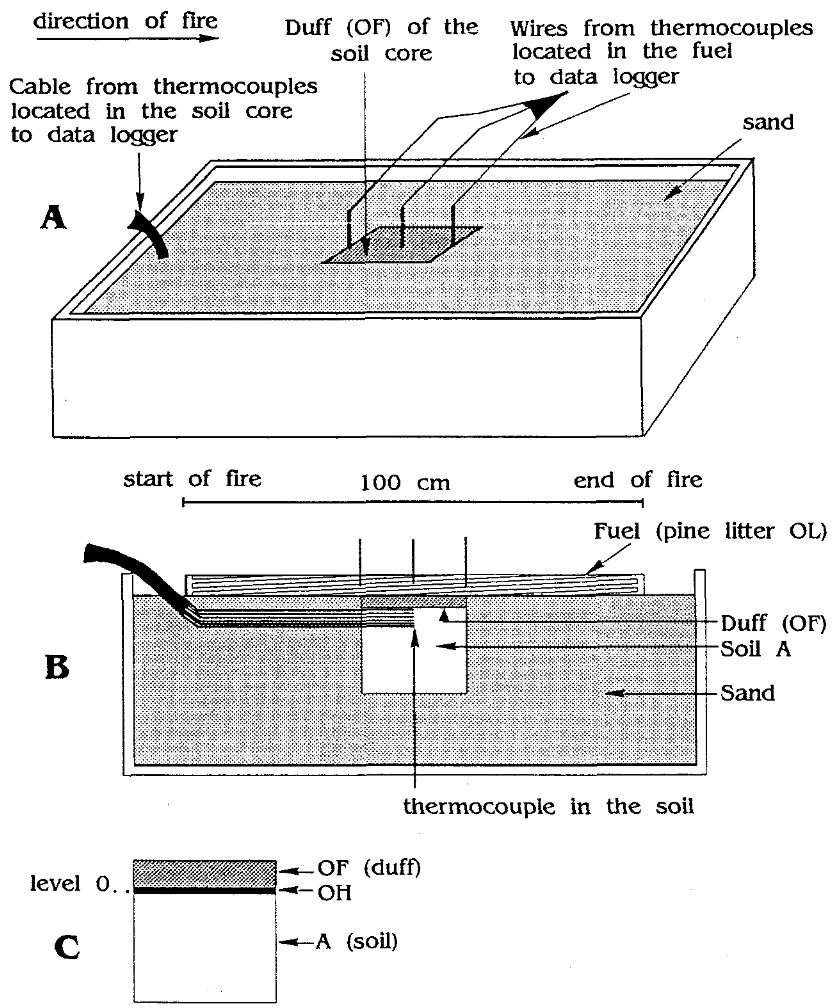

Figure 1. Experimental design. (A): view from above before fuel laying; (B): section after fuel laying; (C): section of soil block.

care being taken to ensure the structure was kept intact. The soil was a calcareous calcisol (or brown calcareous soil) (organic matter 2%, pH = 8.3, C/N = 13.3) with a silty-sandy-clayey texture, an apparent density varying from 1.1 to 1.4 g cm^{-3} and a structural porosity of between 25.6 and 17.8% (see Figure 2).

The fuel was composed of *Pinus pinaster* needles alone or with twigs, coming from the litter layer (horizon OL) collected at the same site. Before each experiment, a precise quantity of litter, of known moisture content, was weighed, then spread out on the surface of the sand and the soil block as uniformly as possible. The fires were ignited at one end of the bench using 5 ml of alcohol spread in a transverse line with a pipette.

Three thermocouples recorded the temperature within the fuel (Figure 1). These thermocouples, of the sheathed K type, 0.6mm in diameter, were connected

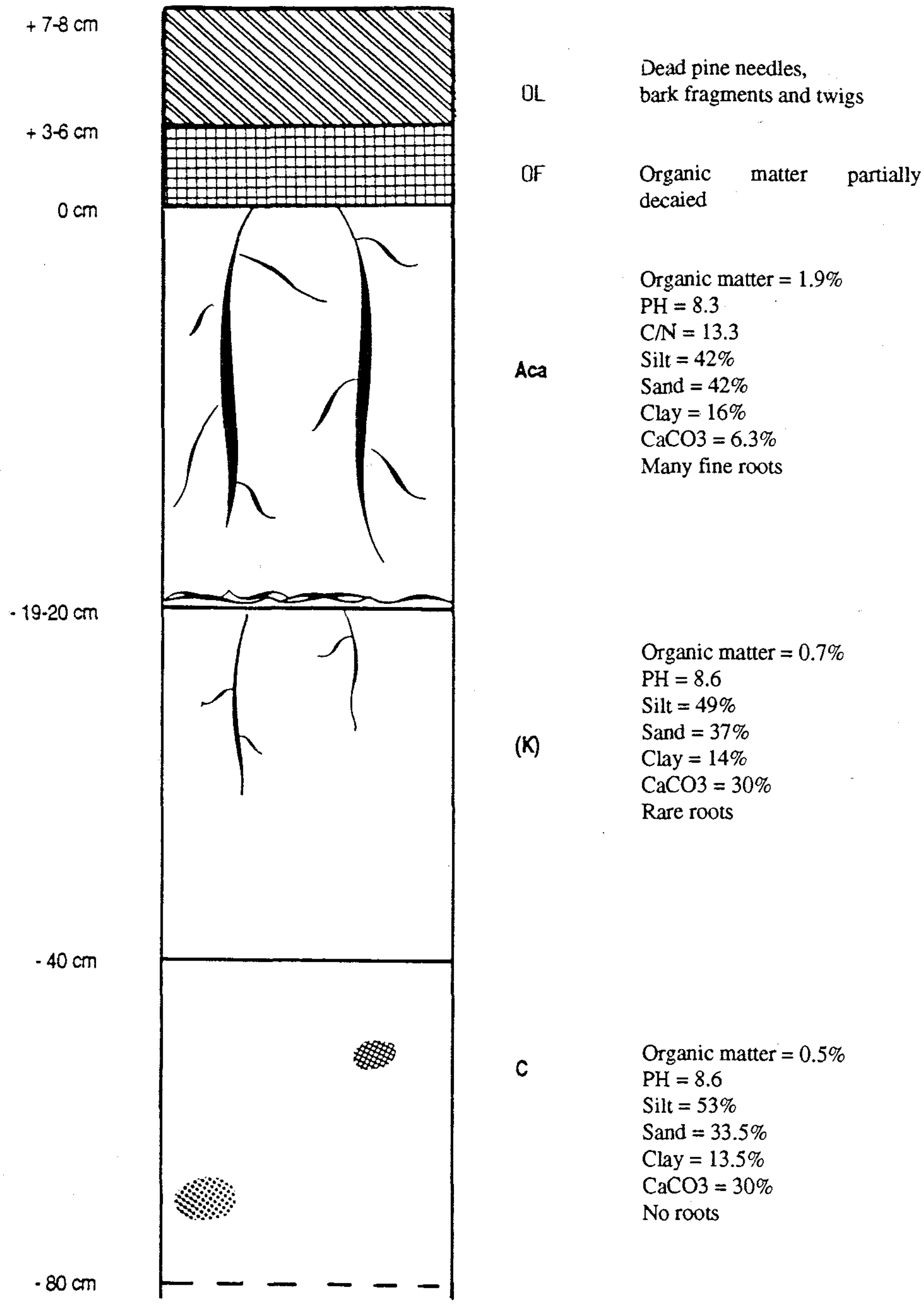

Figure 2. Soil structure of the experiment site (Amarine, Gard)

to an insulated box whose internal temperature was measured using a platinum sensor of 100 Ohms resistance at 0°C. A further eight thermocouples of the same type were inserted horizontally into the soil block and provided measurements of temperature changes with time along a vertical axis at varying soil depth. Their theoretical depths of burial were: in the centre of the duff, at the OF/mineral soil interface (level 0), then at -0.5, -1, -1.5, -2, -3 and -5 cm depth in the mineral soil. After each experiment, the true depth of each thermocouple was measured at the time it was removed. All the thermocouples were connected to a data logger. Temperature measurements were made every second during the fire, then at ten seconds intervals for one hour after the fire. The initial temperature of each thermocouple was measured to be able to calculate the temperature rise in the soil profile.

Forty six experiments were carried out with a fuel load of 800 g m^{-2} (8 t ha^{-1}) composed of needles (fire intensity 1 of the order of 30 kW m^{-1} according to Byram's formula, see below), which is equivalent to the mean mass of litter measured on the forest floor at the Amarine site. Nine experiments were carried out with a fuel load of 1600 g m^{-2} (16 t ha^{-1}) composed of half-and-half needles and twigs (fire intensity 2 of the order of 60 kW m^{-1}), and three experiments with 2400 g m^{-2} (24 t ha^{-1}) composed of 2/3 twigs and 1/3 needles (fire intensity 3 of the order of 80 kW m^{-1}). These three different conditions were representative of the spatial variability encountered on the forest floor. They enabled the duration of surface heating and the dynamics of heat transfer into the soil to be varied. Two types of experiment were conducted with fires of intensity 1: (i) thirty four fires were carried out with complete soil blocks, including their duff layer, and (ii) twelve fires were carried out with soil blocks on which the duff layer had been removed, acting as a control against which to compare the effect of the duff layer. A total of fifty eight experiments were therefore conducted. Not all data were obtained for each fire however. Some thermocouples did not function during some fires or thermocouples were situated at the same depth, despite the care taken in inserting them.

Before and after each experiment, triplicate samples were taken from the soil block, from the duff layer (OF), the superficial humified soil layer (OH) and at 5 cm depth in the mineral soil (A), in order to measure the moisture content. The exact thickness of the duff layer was measured before each fire. For the entire series of experiments, the thickness of the duff layer varied from 1.5 to 6 cm, its moisture content from 7 to 127% and the soil moisture content from 7 to 19%. Experiments were conducted from February to April 1992 in an unheated laboratory, the air temperature varying between 2°C and 18°C and its relative humidity from 35% to 88%. Initial temperatures of the fuel, duff and soil before the fires therefore differed from one experiment to another. The proportion of the fuel burnt was always about 95%. During the experiments, the duff layer was never subjected to flaming combustion; the proportion and thickness of duff that disappeared could not be assessed precisely. The only trace of fire passage even in the highest intensity fires was a blackened layer at the surface.

During each experiment, measurements were taken to determine the fire intensity. One observer timed the passage of the flame front perpendicular to each thermocouple in order to calculate the fire rate of spread above the soil block. The fire intensity index (I) of Byram (1959) could thus be calculated : $I = H \times W \times R$, expressed in kW m^{-1}, where H is the high calorific value of the fuel in kJ kg^{-1} (in this case 21000 kJ kg^{-1} for maritime pine litter (Doat and Valette, 1981)), W is the weight of fuel consumed in kg m^{-2}, and R is the rate of spread of the flame front in m s^{-1}. The percent fuel consumption was obtained by weighing dried ashes derived from a known fuel mass and collected on a rectangular ceramic tile (20 x 25 cm), placed at about 70 cm from the fire starting line. The fire residence time in each experiment was defined as the time during which the temperature in the fuel bed remained above a determined level; this was set at 60°C in this study, since this is the temperature at which heat-induced biochemical changes start to occur to organic matter.

All these tests have been conducted without any wind.

Data analysis

The characteristics of fires conducted with the same quantity of fuel were compared by analysis of variance of three variables: the maximum temperature reached in the fuel bed, the intensity index and the duration of temperatures > 60°C in the fuel bed.

The maximum temperature and temperature rises were analysed at 1 cm within the duff layer and at four different levels in the soil: at the soil surface or level 0 (between 0.5 and -0.5 cm) (duff/soil interface); at -1 (-0.5 to -1.5 cm); at -2 (-1.5 to -2.5 cm) and between -3.5 and -6 cm.

The duff moisture content and thickness, and the soil moisture content varied independently of one another from experiment to experiment. To study the influence of these factors on the temperatures transmitted to the soil, their values were grouped into classes. Two duff thickness classes were thus defined: thin (up to 2 cm) and thick (greater than 2 cm). The thinnest duff layer recorded at the Amarine site was 1.5 cm.

Three duff moisture classes were defined: dry (less than 30% moisture content), moderately wet (from 30% to 70%) and wet (greater than 70%). The critical value of 30% moisture content was chosen to distinguish between dry and moderately wet duff, because of the general agreement that below this level duff burns independently of surface fuel (Shearer 1975; Norum 1977; Artley et al. 1978; Sandberg 1980). The soil moisture content varied between 6 and 19% in the experiments, which is equivalent to the minimum and maximum soil moisture contents found at the Amarine site in winter. Two moisture content classes were adopted: dry, between 6 and 12% and wet, between 12 and 19%. The temperature paterns were then compared by one- or two-way analysis of variance. For the comparison of maximum temperatures, the initial temperature of the thermocouple was taken as a covariate. For studying the temperatures reached at the various depths in the soil, the maximum temperature reached at the soil surface (level 0) was used as a covariate.

Results

Fire intensities

Table 1 shows that the three fuel loads used led to fires of different intensities, typified by their statisti-

Table 1. Fire characteristics. Standard errors are given in brackets; (n): number of replicates. Maximum temperatures and the duration of temperatures higher than 60°C were recorded in the fuel bed. See Table 2 for the duff depth and moisture content class ranges.

Fire types (fuel load)	Maximum Temperature (°C)	Fire intensity index ($kW\ m^{-1}$)	Duration of temperature > 60°C (min)	(n)
Intensity 1 (0.8 $kg\ m^{-2}$)				
Fire with duff thin and dry	656.3 (14.4)	34.5 (2.3)	2.2 (0.14)	8
thin and moderately wet	629.8 (20.2)	31.2 (4.3)	2.0 (0.12)	5
thin and wet	633.2 (21.6)	29.6 (3.2)	1.9 (0.33)	3
thick and dry	639.8 (18.0)	25.2 (5.9)	2.2 (0.32)	3
thick and moderately wet	656.9 (13.2)	28.2 (3.0)	2.0 (0.08)	11
thick and wet	651.5 (41.9)	25.7 (2.9)	1.6 (0.06)	4
Fire without duff	690.3 (10.3)	34.4 (2.1)	1.9 (0.09)	12
Result of ANOVA	$F = 1.6; p = 0.17$	$F = 1.3; p = 0.26$	$F = 1.8; p = 0.13$	
Intensity 2 (1.6 $kg\ m^{-2}$)				
duff thin and dry	645.8 (11.7)	58.6 (2.5)	5.2 (0.19)	3
duff thin and moderately wet	653.0 (-)	57.0 (-)	4.2 (-)	1
duff thick and dry	621.6 (35.3)	54.2 (5.7)	5.9 (1.42)	3
duff thick and moderately wet	672.6 (5.4)	58.8 (1.2)	4.9 (0.50)	2
Result of ANOVA	$F = 0.65; p = 0.62$	$F = 0.77; p = 0.56$	$F = 0.37; p = 0.78$	
Intensity 3 (2.4 $kg\ m^{-2}$)				
duff thin and dry	654.5 (19.7)	75.4 (6.7)	8.6 (1.13)	3
ALL FIRE TYPES				
Result of ANOVA	$F = 1.1; p = 0.4$	$F = 14.5; p<0.001$	$F = 31.9; p<0.001$	

cally different Byram indices and residence times. In contrast, the maximum temperatures reached within the fuel were not significantly different; they varied between 620°C and 670°C.

In fires conducted with 800 g m^{-2} (intensity 1), the Byram indices varied from 27 to 36 kW m^{-1} and the duration of temperatures > 60°C varied from 1.6 to 2.2 min. In fires conducted with 1600 g m^{-2} (intensity 2), the Byram indices were of the order of 60 kW m^{-1} and the duration of temperatures > 60°C ranged from 4.2 to 5.9 min. In fires conducted with 2400 g m^{-2} (intensity 3), the Byram indices were of the order of 80 kW m^{-1} and the duration of temperatures > 60°C averaged 8.6 min.

Experiments conducted with the same quantity of fuel were statistically identical in terms of fire intensity, maximum temperature reached within the fuel and the duration of temperatures > 60°C. It is therefore valid to compare the temperatures reached within the soil or temperature rises, in relation to the presence or absence of duff and to duff characteristics, for experiments carried out with the same fuel load (Table 1).

Effect of the presence of the duff layer on the transmission of heat to the soil

The determinant role of the duff in the transmission of heat to the soil is clearly demonstrated by comparing the maximum temperatures reached at the surface of the mineral soil (level 0), in experiments conducted with or without the duff layer with fires of intensity 1. The maximum temperature rises varied between 3°C and 26°C under the duff layer, depending on its thickness and moisture content, whereas they reached a mean value of 362°C with bare soil (Table 2). The presence of a duff layer, irrespective of its thickness, led to a reduction in temperature rise at the surface of the mineral soil of at least 330°C. Even at 1 cm depth within the duff, the temperature rise did not exceed 40°C, whereas the maximum temperatures within the fuel were of the order of 650°C (Tables 1 and 3).

In fires of higher intensity, releasing a greater quantity of energy, the maximum temperature reached within the fuel was not however any higher than in fires of intensity 1, but the temperature rise lasted longer

Table2. Mean maximum temperatures and maximum temperature rises measured at the soil surface at level 0, in relation to duff characteristics.
Standard errors are given in brackets. n = number of replicates. Mean values of maximum temperature or temperature rises followed by the same letter in each category of fire are not statistically different from one another at a probability of 5%.

Fire types (fuel load)	Maximum temperature (°C)		Rise in temperature (°C)	
FIRE WITHOUT DUFF				
Intensity 1 (0.8 kg m^{-2})	372.3 (42.4) n = 12		361.6 (42.3) n = 12	
FIRE WITH DUFF	Thin [1.5-2 cm]	Thick [2-6 cm]	Thin [1.5-2 cm]	Thick [2-6 cm]
Intensity 1 (0.8 kg m^{-2})				
dry [6-30 %]	38.56 a (3.15) n = 9	39.25 ab (4.73) n = 4	21.44 a (3.06) n = 9	25.50 a (4.58) n = 4
moderately wet [30-70 %]	29.29 bc (3.57) n = 7	28.08 c (2.73) n = 12	19.57 ab (3.46) n = 7	18.50 ab (2.65) n = 12
wet [70-130 %]	23.78 c (3.15) n = 9	10.00 d (3.86) n = 6	13.33 b (3.06) n = 9	3.17 c (3.74) n = 6
Intensity 2 (1.6 kg m^{-2})				
dry [6-30 %]	153.3 a (18.3) n = 3	71.8 b (15.8) n = 4	141.0 a (19.6) n = 3	56.0 b (16.9) n = 4
moderately wet [30-70 %]	66.0 b (22.4) n = 2	41.5 b (15.8) n = 4	52.0 b (24.0) n = 2	28.0 b (16.9) n = 4
Intensity 3 (2.4 kg m^{-2})				
dry [6-30 %]	220.3 (65.0) n = 4		209.0 (64.8) n = 4	

Table 3. Mean maximum temperatures and maximum temperature rises measured at 1 cm depth in the duff layer, in relation to duff moisture content.
Standard errors are given in brackets. Mean values of maximum temperatures or temperature rises followed by the same letter in each category of fire are not statistically different from one another at a probability of 5%.

Fire types (fuel load) Level of moisture content [%]	Maximum Temperature (°C)	Maximum temperature rise (°C)	n
Intensity 1 (0.8 kg m^{-2})			
Dry [6-30]	54.5 a (6.7)	36.8 a (6.9)	8
Moderately wet [30-70]	45.6 a (4.0)	37.9 a (3.9)	11
Wet [70-130]	25.3 b (2.1)	14.8 b (2.0)	12
Result of ANOVA	F = 13.3; p = 0.0001	F = 10.9; p = 0.0003	31
Intensity 2 (1.6 kg m^{-2})			
Dry [6-30]	228.7 a (57.9)	215.0 a (58.7)	7
Moderately wet [30-70]	81.5 a (3.5)	67.0 a (4.0)	2
Result of ANOVA	F = 1.7; p = 0.24	F = 1.7; p = 0.24	9
Intensity 3 (2.4 kg m^{-2})			
Dry [6-30]	273.5 a (50.0)	262.3 a (49.7)	6

(Table 1). These fires led to much greater temperature rises: maxima of 215°C and 262°C at 1 cm depth in the duff during fires of intensity 2 and 3, respectively (Table 3) and maxima of 141°C and 209°C at the soil surface, under the duff layer, with the same intensities (Table 2). But the buffering effect of the presence of the duff was nevertheless great, since the temperatures reached at the bare soil surface in the absence of a duff layer were of the order of 362°C during fires of lower intensity (intensity 1).

Effects of the thickness of the duff layer and of its moisture content

The duff was of variable thickness and moisture content from one experiment to another. The relative roles of thickness and duff moisture content on reducing the temperature reached at the soil surface were tested by two-way analysis of variance, calculated on the maximum temperatures and temperature rises recorded at level 0 during fires of intensities 1 and 2 (Table 4).

For low intensity fires (1), as shown above, the presence of a duff layer, on its own, was sufficient to appreciably reduce the temperatures at the soil surface. Its thickness only played a significant role when the moisture content was greater than 70% (Table 2). In contrast, the duff moisture content always had a significant effect in reducing temperatures, irrespective of the thickness, by reinforcing its insulating role (Tables 2 and 4). The impact of the higher heat conductivity of wet duff is lower than the fact that it requires more energy to remove moisture in wet duff than in dry one. Similarly, the moisture content contributed to moderating temperature rises at 1 cm depth within the duff: 37°C in dry duff compared to 15°C when the duff had a moisture content of more than 70% (Table 3).

For higher intensity fires (intensity 2), where surface heating lasted longer, the thickness and moisture of the duff both had a significant effect on the temperatures reached in the soil (Table 4). A thin layer of dry duff led to a temperature rise at the soil surface of 141°C, whereas either a thicker (more than 2 cm) or wetter layer (moisture content > 30%) was needed to reduce the temperature significantly to less than 50°C (Table 3). An increase in the moisture content from 30 to 70% reduced the mean temperatures at 1 cm depth within the duff by more than a third (215 to 67°C), but the difference was not statistically significant (Table 3). This reflects the great heterogeneity of temperatures recorded at this level, especially when it was dry, because very great heating sometimes caused part of the duff to burn slowly.

Table 4. Results of analysis of variance and covariance testing the effects of thickness and duff moisture content on maximum temperature and temperature rise at level 0 of the duff/soil interface.

The initial temperature (ti) has been used as a covariate (Cov) when comparing the maximum temperature reached.

Fire types (fuel load)	Thickness (T)	Moisture content (MC)	T x MC	Cov (ti)
Intensity 1 (0.8 kg m^{-2})				
Maximum temperature				
F	2.64	17.27	2.41	2.53
p	0.11	0.0001	0.10	0.12
Temperature rise				
F	0.71	9.71	2.01	
p	0.40	0.0004	0.15	
Intensity 2 (1.6 kg m^{-2})				
Maximum temperature				
F	10.53	28.00	0.66	14.35
p	0.012	0.0007	0.44	0.0053
Temperature rise				
F	7.76	8.94	2.43	
p	0.021	0.0152	0.15	

Soil temperature profiles

The distribution of temperature rises in relation to depth in the soil, usually followed a negative exponential function. Regressions of the following type were calculated for each experiment:

$$y = t_0 \times e^{-ax} \qquad (1)$$

where y is the maximum temperature rise (in °C) at depths x (in cm) in the soil, t_0 is the maximum temperature rise measured at the soil surface at level 0, and a is the rate constant.

The determination coefficients r^2 varied from 0.68 to 0.99, in 61% of cases r^2 was greater than 0.89. From equation (1), the temperature rises at different depths during the experiments can be calculated using the values of t_0 measured in each experiment and the rate constants a calculated in each experiment (excluding from the analyses the data relating to level 0 since they form one of the parameters of the equation). The following relation is thus obtained:

estimated y = 0.885 x measured y
($n = 323$; $r^2 = 0.84$; $p < 0.001$)

For all the experiments combined, equation 1 therefore provides a reasonable estimate of the temperature rise distribution with depth in the soil, but slightly underestimates the true temperature values.

Role of the soil moisture content

The rate constants a calculated with equation 1 for each fire, varied from 0.10 to 10.82. They depend mainly on the initial temperature rises at level 0 t_0 and on the soil moisture: a multiple regression analysis carried out on the rate constants showed that 62% of the variance is explained by the temperature rise at level 0 t_0 and 67% if the soil moisture content H is added. The rate constants a can therefore be predicted, for the type of soil used in this study and for the moisture values encountered in the experiment, by the following relation:

$a = 0.139 \times H + 0.011 \times t_0 - 1.386$
($n = 57$; $r^2 = 0.67$; $p < 0.001$)

The rate constants a, which reflect the extent to which temperatures are moderated with depth, depend mainly on the temperature rise at level 0 t_0; so the analysis of variance of the rate constants in terms of the moisture classes was therefore carried out using t_0 as a covariate. This showed that, for a mean temperature rise at level 0 of 104°C, the rate constants were significantly different for each moisture content class ($F = 7.80$, $p = 0.007$, $n = 58$). The resulting mean rate constant was 0.96 (SE = 0.22) in dry soil (6 to 12% moisture content) and 1.97 (SE = 0.28) in wet soil (12 to 18%).

The resulting mean profiles are given in Figure 3. It shows that the decrease in temperature rise with depth was much greater in wet soil than in dry soil. It also demonstrates that the difference in temperature rise between dry and wet soils was greatest in the upper 2 cm of soil, the temperatures transmitted to below -3 cm being relatively stable, irrespective of the soil moisture content.

For all experiments combined, the mean temperature rises measured at 1 and 2 cm depth were significantly different between dry and wet soils but not for depths greater than 3.5 cm (Table 5). The analysis of variance carried out on all temperature rises measured at various depths in the soil, with t_0 as a covariate, showed they were significantly different with respect to depth and soil moisture content. There was a significant interaction between depth and soil moisture; this reflects both the very rapid buffering of temperature rises in wet soil and the constancy of the temperatures transmitted to depths of 3 cm, irrespective of the soil moisture content.

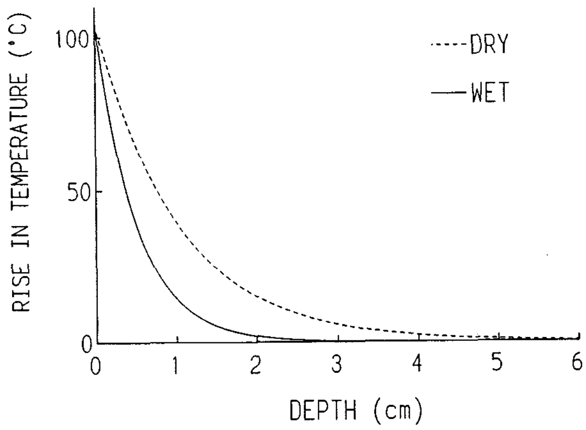

Figure 3. Relationships between temperature rise (°C) and depth in dry and wet soil.

Insulating role of the soil

The low thermal conductivity of the soil plays an effective role in restricting the transmission of high temperatures with depth. In the experiments conducted with fires of intensity 1 on soil blocks without duff, where the temperatures recorded at the soil surface were high (362°C on average), the maximum temperature rises did not exceed a mean value of 46°C at 1 cm depth, 17°C at 2 cm and 7°C at more than 3.5 cm (Table 6). Thus, in fires of the same intensity, but applied to soils either protected by a duff layer or not, the maximum temperature rises at 1 cm depth only differed by about 30°C, whereas the differences were of the order of 350°C at the soil surface. At 2 cm depth, the mean differences were only 10°C, and below 3.5 cm the temperature rises were similar.

Table 5. Mean maximum temperature rises, measured during all experiments at three depth levels in dry and wet soil and analysis of covariance testing the effect of soil moisture and depth on temperature rises in the soil.

The mean temperature rise at level 0 is taken as a covariate. Standard errors are given in brackets; (Cov = covariate). Mean values followed by the same letter are not significantly different from another at a probability of 5%.

ALL FIRES
(Mean temperature rise at level 0 = 104.5°C)

Depth (cm)	Soil Moisture content (SMC) (%) [6-12]	[12-18]	Results of ANCOVA	F	p
-1	34.6 a (1.8)	14.2 bc (2.3)	D	28.0	0.0001
			SMC	30.2	0.0001
-2	15.7 b (2.3)	8.6 cd (2.5)	DxSMC	7.9	0.0005
			Cov	43.5	0.0001
< -3.5	11.2 bcd (2.1)	6.9 d (2.4)			

Table 6. Mean maximum temperature rises, measured during fires of intensity 1 at three depth levels in dry and wet soil, with and without duff.

Standard errors are given in brackets; (Cov = covariate). Mean values followed by the same letter comparing maximum temperatures or temperature rises within each fire category are not significantly different from one another at a probability of 5%.

FIRES INTENSITY 1 WITH DUFF
(Mean temperature rise at level 0 = 17.0°C)

Depth (cm)	Soil Moisture content (SMC) (%) [6-12]	[12-18]
-1	12.1 a (0.5)	8.0 b (0.5)
-2	6.3 c (0.7)	5.9 c (0.5)
< -3.5	3.4 d (0.6)	3.7 d (0.5)

FIRES INTENSITY 1 WITHOUT DUFF
(Mean temperature rise at level 0 = 361.6°C)

Depth (cm)	Soil Moisture content (SMC) (%) [6-12]	[12-19]
-1	45.7 a (2.5)	36.0 a (4.7)
-2	16.7 b (2.8)	13.0 bc (4.7)
<-3.5	6.6c (3.6)	6.0bc (6.6)

Effects of fires on duff and soil moisture content

Water losses from the duff were low in fires of intensity 1: they amounted on average to 15% of the initial moisture content of the duff layer (Table 7). In contrast, they were significantly higher in fires of greater intensity: on average nearly 60% of the initial moisture content of the duff evaporated with the passage of fires of intensity 2 and 3.

The moisture content of the superficial soil layer (horizon OH), was only changed by the passage of fires of low intensity (< 35 kW m^{-1}) when the duff layer was absent. On the other hand, even when this layer was present, decreases in the moisture content of the OH horizon of the same magnitude were recorded with fires of intensities 2 and 3 (Table 7). The soil moisture content in the mineral soil at 5 cm depth was never affected in a significant way by the passage of fire, irrespective of its intensity.

Table 7. Mean ratios of water losses to initial moisture content in the duff layer, in OH horizon and in the soil at 5 cm depth. Mean values followed by the same letter in the same column, comparing the different types of fire are not significantly different from one another at a probability of 5%.

Fire types	duff	OH	soil	n
Intensity 1				
with duff	15.9 a (5.3)	-7.8 a (7.8)	-4.3 a (4.2)	34
without duff	-	37.6 b (5.2)	-3.0 a (4.0)	12
Intensity 2	57.9 b (15.4)	21.7 ab (18.1)	2.1 a (6.0)	9
Intensity 3	58.6 b (30.4)	71.8 b (8.7)	-23.2 a (26.4)	3
F	6.19	5.95	0.92	
p	0.004	0.001	0.44	

Illustrations of the insulating role of dry and wet soils

Figure 4 presents the temperatures recorded at four levels during tests conducted without OF layer and presenting the same characteristics (fire intensity, rate of spread, residence time,...). One has been realized with a fairly dry soil (moisture content equal to 14%) and the two others with a fairly wet soil (moisture content equal to 28%). It was not possible to find among the "wet" tests only one test where the thermocouples were located exactly at the same distance from the soil surface as those of the "dry" test. "Wet" records of charts (a) and (d) are related to one test, "wet" records of charts ((b) and (c) are related to another. This explains the difference between the initial temperatures, respectively 13°C and 12°C.

In dry soil, heat needs less than 60 seconds to move from level -0.5 to level -2.0 cm (sudden increase of temperature). In wet soil, it needs about 90 seconds. In dry soil, the maximums of the temperatures are 72°C (a), 55°C (b), 38°C (c) and 30°C (d) and respectively 73°C, 39°C, 32°C and 28°C in wet soil.

The slope of the rises in temperature decreases with the depth and is equal (a) or higher (b, c, d) in dry soil than in wet soil.

Temperatures are equal at level -0.5 cm, close to the soil surface where energy is released, and at level -2 cm, fairly far from the heating source. At the intermediate levels, they are always higher in dry soil, but the difference between "dry" and "wet" records is higher at level -1.0 cm than at level -1.5 cm.

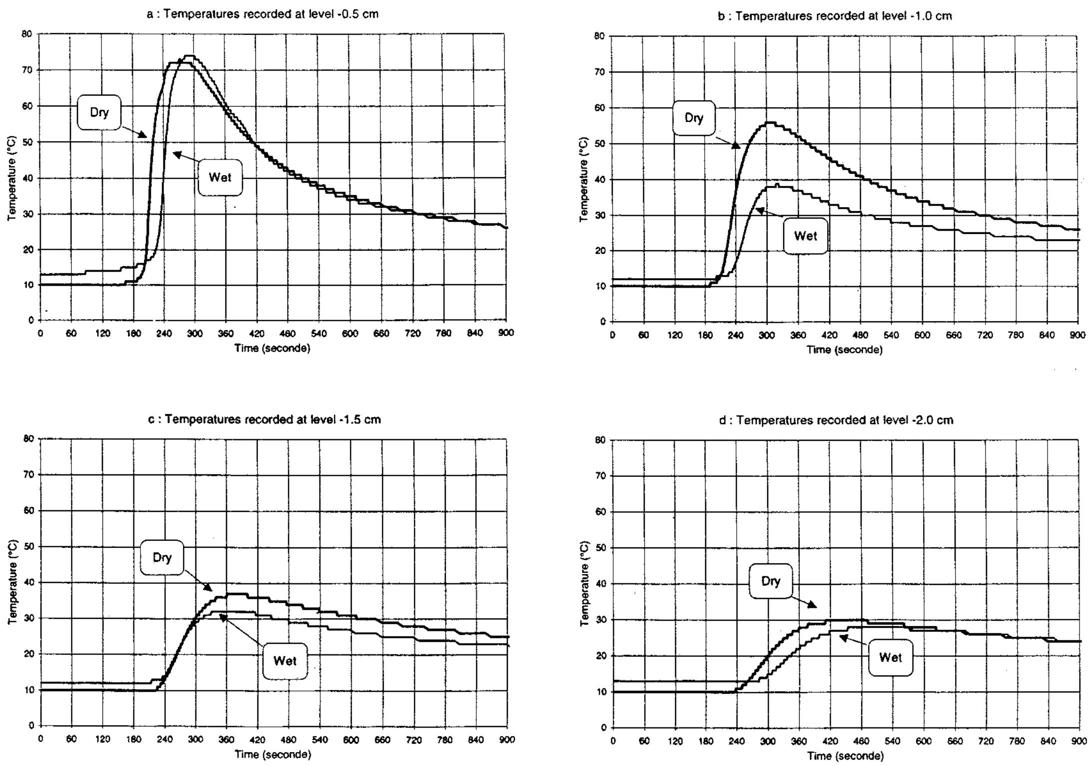

Figure 4. Temperatures recorded in dry and wet soils at (a) : level -0.5 cm; (b) : level -1.0 cm; (c) : level -1.5 cm; (d) : level -2.0 cm

Discussion

This study demonstrated the insulating role of the duff layer during fires. For low-intensity fires (25 to 35 kW m^{-1}), the presence of a duff layer was sufficient to lead to a reduction in the temperature at the soil surface of at least 330°C. The temperature rise at soil level (level 0) did not exceed 26°C. In contrast, the duff moisture content reinforced the moderating effect; compare to dry duff, with wet duff the temperature rise was 2.5 times lower at 1 cm within the duff (37/15°C) and 9 times lower at the soil surface (26/3°C). These results support the field observations of Van Wagner (1970) and Raison et al. (1986) and those of Frandsen and Ryan (1986) conducted under experimental conditions with artificially reconstituted duff and mineral soil. For more intense fires (> 50 kW m^{-1}), which cause longer lasting surface heating, the moderating effect of the duff was not always sufficient to prevent major increases in temperature at the soil surface, of up to 140°C (fires of intensity 2) and 210°C (fires of intensity 3). In these cases the thickness of the duff and its moisture content both played an important role. Their maximum combined effect significantly reduced the temperature rise at the soil surface from 140°C to 28° during fires of intensity 2.

The soil, because of its low thermal conductivity, also moderates temperatures with depth. In fires of intensity 1, in the absence of duff, the maximum temperatures transmitted were reduced by a factor of about 50 from the soil surface to 3.5 cm depth and below (from 350°C to 7°C, respectively), confirming the observations of Packham (1971), Aston and Gill (1976) and Dimitrakopoulos and Martin (1990). Soil moisture contributed in decreasing the maximum temperature rise in the top few centimetres of soil, part of the heat being used to evaporate water. A much greater decrease in the moisture content of the superficial soil layer, the OH horizon, was measured in experiments which led to strong heating of the soil surface (fires of intensity 1 without duff layer, intensity 2 and 3 fires). Below 3.5 cm depth however, the same level of maximum temperature rises were recorded in both dry and wet soils. The temperature rise in the soil decreased with depth according to a negative exponential function. The rate constant of this function being greater the higher the initial surface temperature and the higher the moisture content of the soil. For the soil studied and the moisture conditions encountered, this rate constant could be predicted with an acceptable precision, if the temperature rise at level 0 and the moisture content of the soil are known.

It is known that heating to about 60°C leads to mortality of plant tissues (Levitt, 1980). This study has shown that the presence of a duff layer in low-intensity fires reduces the temperatures of the soil to the extent that lethal values are not reached; provided that the air temperature does not exceed 20°C, a temperature frequently attained in autumn, winter and spring in the French Mediterranean region, the season during which prescribed burnings can be conducted. A wet duff and soil can contribute to moderating soil temperatures. Nevertheless, lethal temperatures, more than 60°C, were measured in the top few centimetres of duff in fires of very low intensity, and in the top few centimetres of soil during slightly more intense fires. Although only a small proportion of roots are located in the top few centimetres of soil, the highest concentrations of nutrients and the most intensive biological activity occur in the duff and superficial soil horizons. On the other hand at soil depths > 3.5 cm, prescribed burnings conducted under the conditions of the experiments, probably have no significant effect on the biological activity of the microfauna and microflora and on root tips. In addition, in very low-intensity fires, the surface heating did not lead to major dehydration of the duff and had no effect on the moisture content of the lower horizons when duff was present. In contrast, with fires of higher intensity the duff lost nearly 60% of its moisture and the adjacent OH horizon lost between 30 and 70%. These levels of water loss reduce soil wettability, and the temperature levels recorded in the duff could produce water repellency, increased erosion and some delay in revegetation (see Savage, 1974; Scholl 1975; DeBano and Rice 1973; DeBano et al. 1970, 1976; McNabb et al. 1989).

The different fuel loads and fuel qualities used in this study reflected the heterogeneity of conditions encountered on the forest floor. The impacts of fire on the soil are therefore variable and distributed in a mosaic pattern within any one stand (Hobbs and Atkins 1988). In our experimental fires, in which intensities were always within the range recorded during prescribed burnings, lethal temperatures for roots and soil biota are sometimes reached. The effects of these on forest nutrition and long-term productivity need to be assessed.

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References

Artley, D.K., R.C. Shearer and R.W. Steele. 1978. Effects of burning moist fuels on seedbed preparation in cutover western larch forests. United States Department of Agriculture, Forest Service, Research Paper INT-211, 14 p.

Aston, A.R. and A.M. Gill. 1976. Coupled soil moisture, heat and vapour transfers under simulated fire conditions. Aust. Journal of Soil Research 14: 55-66.

Beadle, N.C.W. 1940. Soil temperatures during forest fires and their effect on the survival of vegetation. Journal of Ecology 28: 180-192.

Blackwell, B., M.C. Feller, and R. Trowbridge. 1992. Conversion of dense lodgepole pine stands in west-central British Columbia into young lodgepole pine plantations using prescribed fire. 1. Biomass consumption during burning treatments. Canadian Journal of Forest Research 22: 572-581.

Bradstock, R.A., T.D. Auld, M.E. Ellis and J.S. Cohn. 1992. Soil temperatures during bushfires in semi-arid, mallee shrublands. Australian Journal of Ecology 17 : 433-440.

Brown, J.K., E.D. Reinhardt and W.C. Fischer. 1991. Predicting duff and woody fuel consumption in Northern Idaho prescribed fires. Forest Science 37: 1550-1566.

Byram, G.M. 1959. Combustion of forest fuels. In: Forest Fire: Control and Use (edited by K.P. Davis), McGraw-Hill, N.Y. pp. 61-89.

DeBano, L.F., L.D. Mann and D.A. Hamilton. 1970. Translocation of hydrophobic substances into soil by burning organic litter. Proceedings - Soil Science Society of America 34: 130-133.

DeBano, L.F. and R.M. Rice. 1973. Water-repellent soils: their implications for forestry. Journal of Forestry 71: 220-223.

DeBano, L.F., S.M. Savage and D.A. Hamilton. 1976. The transfer of heat and hydrophobic substances during burning. Soil Science Society of America Journal 40: 779-782.

Dimitrakopoulos, A.P. and R.E. Martin. 1990. Measuring and modelling soil temperature profiles during simulated wildland fire conditions. Proceedings - International Conference on Forest Fire Research, 19-22 Nov., 1990, Coimbra, Portugal: B.21 1-17.

Doat, J. and J.C. Valette. 1981. Le pouvoir calorifique supérieur d'espèces forestières méditerranéennes. Annales des Sciences Forestières 38: 469-486.

Frandsen, W.H. 1987. The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. Canadian Journal of Forest Research 17: 1540-1544.

Frandsen, W.H. and K.C. Ryan. 1986. Soil moisture reduces belowground heat flux and soil temperatures under a burning fuel pile. Canadian Journal of Forest Research 16: 244-248.

Hobbs, R.J. and L. Atkins. 1988. Spatial variability of experimental fires in south-west Western Australia. Australian Journal of Ecology 13 : 295-299.

Levitt, J. 1980. Responses of plant to environmental stresses. Academic Press, New York.

McNabb, D.H., F. Gaweda and H.A. Froehlich. 1989. Infiltration, water repellency and moisture content after broadcast burning a forest site in southwest Oregon. Journal of Soil and Water Conservation 44: 87-90.

Norum, R.A. 1977. Preliminary guidelines for prescribed burning under standing timber in Western Larch/Douglas-Fir forests. United States Department of Agriculture, Forest Service, Research Note INT-229, 15 p.

Packham, D.R. 1971. Heat transfer above a small ground fire. Australian Forest Research 5: 19-24.

Raison, R.J. 1979. Modification of the soil environment by vegetation fires, with particular reference to nitrogen transformations: a review. Plant and Soil 51: 73-108.

Raison, R.J., P.V. Woods, B.F. Jakobsen and G.A.V. Bary. 1986. Soil temperatures during and following low-intensity prescribed burning in a Eucalyptus pauciflora forest. Australian Journal Soil Research 24: 33-47.

Rundel, P.W. 1981. Fire as an ecological factor. In Physiological Plant Ecology I- Responses to the physical environment (edited by O.L. Lange, P.S. Nobel, C.B. Osmond and H. Ziegler) Springer-Verlag, Berlin, pp. 501-538.

Sandberg, D. 1980. Duff reduction by prescribed underburning in Douglas-fir. United States Department of Agriculture Forest Service, Research Paper PNW-272, 17 p.

Savage, S.M. 1974. Mechanisms of fire-induced water repellency in soil. Proceedings - Soil Science Society of America 38: 652-657.

Scholl, D.G. 1975. Soil wettability and fire in Arizona chaparral. Proceedings - Soil Science Society of America 39: 356-361.

Shearer, R.C. 1975. Seedbed characteristics in Western Larch forests after prescribed burning. United States Department of Agriculture, Forest Service, Research Paper INT-167, 26 p.

Sweeney, J.R. and H.H. Biswell. 1961. Quantitative studies of the removal of litter and duff by fire under controlled conditions. Ecology 42: 572-575.

Van Wagner, C.E. 1970. Temperature gradients in duff and soil during prescribed fires. Canadian Forest Service Bimonthly Research Notes 26: 42.

Van Wagner, C.E. 1972. Duff consumption by fire in Eastern pine stands. Canadian Journal of Forest Research 2 : 34-39.

Walker, J., R.J. Raison and P.K. Khanna. 1983. Fire. In: Australian Soils. The Human Impact (edited by Russell J.S. and R.F. Isbell), University of Queeensland Press, St Lucia, Queensland, Australia, pp. 186-216.