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Influence of wildland fire on surface runoff from a hillslope

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ABSTRACT

Surface runoff from three adjacent hillslope plots, unburnt or subjected to light or moderate prescribed burns, was monitored over a four-year period. All plots initially bore Ulex scrub. In the first year, runoff from the unburnt plot was about 3.5% of rainfall, while that from the burnt plots was between 5.2 and 6.6% of rainfall. Runoff from the burnt plots gradually dropped over the study period, and we estimate that preburn values are reattained within four to five years (corresponding to the time required for re-establishment of the vegetation cover). The water repellency of the soil was not appreciably increased by either light or moderate burns, indicating that wildfire-induced increases in runoff in this region are due largely to reduced interception as a result of the destruction of vegetation. Finally, although burning caused clear relative increases in runoff, the absolute increases were small (2 - 3% of rainfall), suggesting that wildfire-induced increases in runoff are unlikely to have major effects on the flow regimes of receiving rivers. The estimated postfire increases in infiltration, on the other hand, were much more marked, and it is possible that wildfire-induced increases in subsurface flow have important effects on watershed hydrology.

INTRODUCTION

One of the most evident effects of wildland fire on hillslope hydrology is to increase surface runoff. A number of authors have attributed this to a fire-induced increase in the water repellency of the surface layers of the soil (Ferreira, 1990; Imeson et al., 1992; Shahlaee et al., 1991). However, other studies have indicated that the physical properties of the soil are scarcely affected by fires of light to moderate intensity (Hudson et al., 1983; MarquÇs and Mora, 1992); in such cases, the time taken for surface runoff to return to prefire levels will be largely governed by the rate of recovery of vegetation cover and by the interception characteristics of the vegetation.

In the northwest Iberian Peninsula, Ulex scrub occupies a total of about one million ha. Wildfires are very frequent in these areas, as a result of the high flammability of this vegetation type (Casal et al. ,1984; Vega, 1985), the region's pronounced summer drought, and the high incidence of fire-starting due to negligence or criminal intent.. Ulex scrub has high biomass (25 - 60 t ha-1) and a characteristically stratified structure, generally comprising a herb layer (species such as Agrostis canina, A. setacea and Pseudarrenatherum longifolium), an intermediate layer (species such as Daboecia cantabrica, Erica cinerea and E. umbellata) and a shrub layer dominated by Ulex europaeus (Basanta et al., 1988). This well-developed stratification leads to high ground cover, with rainfall interception typically about 40%.

The characteristic pattern of postfire recovery of scrub communities of this type has been described by Casal et al. (1984). In the initial phase, typically lasting a few months, plant growth is largely restricted to resprouting of species such as Ulex europaeus and Agrostis setacea. Subsequently, the burnt area begins to be recolonized as a result of germination of heat-resistant seeds in the soil or of seed-led or vegetative expansion of nearby vegeta-

Table 1. Physicochemical characteristics at depths of 0-2.5 cm, 2.5-5.0 cm and 5.0-10.0 cm. of the soil at the study site.(standard deviation, into brackets)

	Depth		
	0-2.5	**2.5 - 5.0**	**5.0 - 10.0**
pH H20	4.44(0.14)	4.40(0.07)	4.41(0.07)
pH ClK	3.48(0.19)	3.51(0.06)	3.68(0.07)
% C	6.74(0.55)	7.91(1.18)	7.42(0.26)
% N	0.68(0.10)	0.58(0.06)	0.54(0.04)
C/N	10.1	14.0	13.8
Inorganic nitrogen (mg/100 gr)			
N-NH4+	2.00(0.79)	2.00(0.02)	1.82(0.16)
N-N03-	0.32(0.09)	0.32(0.04)	0.46(0.05)
Exchange cations (mg/100 gr)			
Na	5.01(0.75)	3.57(1.30)	3.30(0.88)
K	6.81(1.26)	3.73(0.60)	2.76(0.53)
Ca	4.56(1.16)	1.58(0.80)	0.62(0.40)
Mg	1.18(0.37)	0.13(0.10)	< 0.1
Total	17.57(2.87)	9.04(2.53)	6.78(1.75)
Available P (Bray-2) (mg/100 gr)			
2.75(1.29)	1.91(0.59)	1.20(0.35)	
Particle size distribution (%)			
Coarse sand	38.89(0.71)	38.81(4.17)	39.06(2.68)
Fine sand	26.31(1.41)	25.66(1.19)	27.96(1.65)
Coarse loam	8.32(0.22)	9.13(2.00)	8.42(0.98)
Fine loam	11.15(0.15)	11.93(0.94)	10.11(0.77)
Clay	15.32(0.78)	14.46(2.18)	14.44(1.09)

tion. Eventually, the scrub becomes so dense that the majority of the opportunist herb species disappear. The loss of this vegetation cover following burning leads to a marked increase in the proportion of rainfall reaching the soil surface, and a consequent increase in the risk of erosion due to surface runoff.

In the work reported here we monitored surface runoff from three Ulex-scrub hillslope plots (one unburnt, one subject to a light burn and one subject to a moderate burn) over a 4-year period. Interception, evapotranspiration and water repellency were also monitored, with the aim of investigating the causes of fire-induced modifications of surface runoff patterns.

MATERIALS AND METHODS

Three adjacent 20 x 4 m plots, all bearing 8-year-old Ulex scrub and with 30% slope, were marked out on the west-facing slope of Monte Pedroso (Santiago de Compostela, northwest Spain; 4¯ 53’ W, 42¯ 54’ N) and separated by metal sheets. The soil is an umbric Leptosol over semioriented granite. Basic physicochemical properties at depths of 0-2.5 cm, 2.5-5.0 cm and 5.0-10.0 cm are listed in Table I. Each value is the mean for 5 samples (_+ standard deviation). Each set of 3 samples (for 3 depths) was obtained by driving an open-ended 20 x 20 cm. metal box into the ground, and collecting all soil within the box at each depth. Both the visual homogeneity of the study plots and the low standard deviations of the physicochemical properties determined (see Table I) indicate that these samples are representative of the study area.

Precipitation was recorded with two rainfall gauges, one at the top and one at the bottom of the study slope. Troughs for runoff collection (feeding via a 1/9 divider

Table 2. Monthly rainfall and monthly maximum and minimum temperatures recorded over the study period.

		Month											
		S	O	N	D	J	F	M	A	M	J	J	A
	Rainfall (mm)	0.0	233.5	117.4	58.4	28.5	177.5	109.3	87.1	191.7	0.0	25.2	42.8
88/89	T. max. (°C)	24.4	19.5	17.7	14.1	13.7	11.5	16.2	14.5	23.6	24.2	28.0	27.3
	T. min. (°C)	12.7	10.6	8.4	4.9	3.8	3.0	6.4	6.2	12.1	13.0 •	15.7	5.6
	Rainfall	0.0	177.7	280.9	661.5	193.4	155.7	48.7	74.6	31.9	12.0	0.0	0.0
89/90	T. max.	24.4	22.2	15.0	14.7	12.0	9.7	18.1	15.6	22.3	21.7	28.5	28.5
	T. min.	12.0	12.0	9.6	9.6	4.8	6.5	6.9	7.3	11.3	12.4	14.9	12.2
	Rainfall	138.3	333.9	167.0	159.9	251.2	212.0	139.4	20.9	55.2	40.0	46.2	33.8
90/91	T. max.	25.4	18.2	14.3	11.9	11.8	7.3	14.0	16.1	21.6	21.3	24.3	26.7
	T. min.	14.5	10.9	6.3	3.8	4.4	2.4	7.0	6.6	9.7	11.3	14.4	14.9
	Rainfall	137.4	129.4	195.1	87.3	78.3	0.0	72.5	102.5	104.5	43.0	30.8	121.4
91/92	T. max.	24.0	16.9	14.1	13.7	12.4	10.1	16.2	16.6	21.0	19.8	26.2	24.3
	T. min.	14.3	9.1	7.3	6.0	2.0	3.3	6.1	7.8	11.2	11.2	14.4	14.2

to a collection tank outside the plot) were installed at the bottom of each plot. Each plot additionally contained two 0.11 x 4 m troughs (30 cm above ground level to avoid splash-in, feeding to a common collection tank outside the plot): for each rainfall event,apparent interception by vegetation was estimated as the difference between gross rainfall and rainfall collected in the troughs (throughfall). Note that apparent interceptation is likely to be higher than interception sensu strictu.(i.e., rainfall minus , troughfall + stemflow). Stemflow is probably significant in this vegetation type, due tp high density of ascending stems; however, major-stem morphology was scarcely affected by our prescribed burns , so that the observed effects of fire on apparent interception (see below) are likely to be indicative of effects on interception sensu strictu.

Monthly rainfall, and maximum and minimum monthly temperatures, for the four years of study are listed in Table II.

Prescribed burns were carried out in September 1988. Plot L was burnt downslope early in the morning, with the aim of simulating a light-intensity fire. Plot M was burnt upslope at midday, with the aim of simulating a moderate-intensity fire. In both cases maximum temperature reached at the soil surface was about 250°C, with temperature rising only about 10°C at a depth of 2 cm (Díaz-Fierros et al., 1990). Plot C (control) was not burnt.

Water repellencies of the 0 - 2.5 cm, 2.5 - 5 cm and 5 - 10 cm layers of the soil were determined by King's (1981), modification of Watson and Letey's method. Briefly, droplets of ethanol at increasing concentrations (0.2 M steps) are pipetted onto the soil until that concentration is reached at which the droplet remains unabsorbed for 10 sec or more. On the basis of the molar concentration of ethanol required, we classify water repellency as low (0 - 1 M), moderate (1.2ˇ-ˇ2.2 M), severe (2.4 - 3 M) or very severe (3.2 M or more). For the purposes of this study, we have considered only severe or very severe water repellency to constitute a significant barrier to infiltration.

Water repellency was determined before and 24 h after burning (3 samples per burnt plot). In addition, repellency determined in another 30 samples taken from the control plot at different times of year showed a close linear relationship with soil water content (Fig. 1). Soil water content was thus used to predict water repellency in the three plots over the four years study.

Soil water content was determined from soil water tension (as measured with tensiometers at depths of 2.5, 5, 10, 20, 40 and 60 cm)with the aid of calibration curves constructed previously. Since the bedrock lies 60 cm below the surface, our soil water data can be considered representative of the root zone.

RESULTS

Before burning, water repellency in both plots L and M was "very severe" in the 0 - 2.5 cm layer and "severe" in the 2.5 - 5 cm and 5 - 10 cm layers. This high water

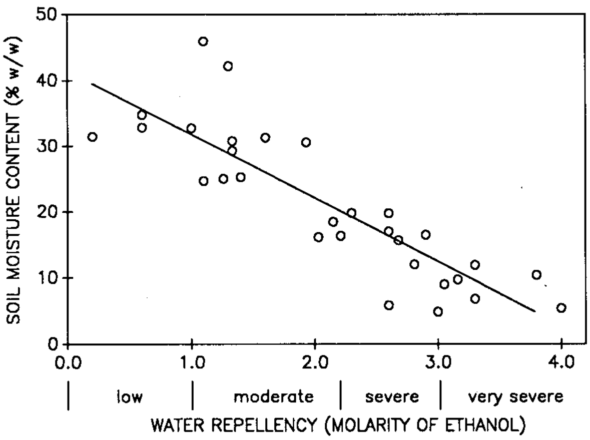

Figure 1. Water repellency (WR; estimated by a modification of Watson and Letey's method; see text) plotted against soil water content (SWC) for 30 top 2 cm soil samples taken from the study site at different times of year. Linear regression gives WR = 4.14 - 0.97 SWC, with r2ˇ=ˇ0.74.

repellency is as expected given that soil water content was very low (below wilting point) on the day of the measurement (10 September 1988). Twenty four hours after burning, water repellency in plots L and M was severe (2.9 M ethanol) in all three layers. Burning did not therefore lead to any increase in water repellency.

Actual evapotranspiration (ETa) over 16 rain-free periods (of between 2 and 9 days, in June 1989, March 1990 or May 1990) was determined for plots C and L on the basis of tensiometer measurements and of potential evapotranspiration (ETp) over these periods (estimated by the Penman method as per Smith, 1990). Mean ETa/ETp ratios in each plot in each month are listed in Table III. In plot C, ETa was higher than ETb in June 1989 and May 1990, though slightly lower than ETp in March 1990. In plot L , ETa never exceeded ETp. In June 1989, ETa/ETp was significantly higher ($p < 0.01$) for plot L than for plot C, during the other two pwriods, ETa/ETp was lower in plot L than in plot C, but the differences were not statisticallly significant at the 5% level.

Apparent interception in each plot in each year of study is listed in Table IV.Apparent interception was low in both burnt plots in the first and second years after burning, but by the third year was similar to that recorded

Table 3. Mean ratios of actual to potential evapotranspiration from plots C (control) and L (light burn) for the three periods during which evapotranspiration was estimated. The number of rain-free subperiods from which each mean value is calculated is also shown.

Period	ETa/ETp Plot C	ETa/ETp Plot L	Number of subperiods
June 89	0.88	1.28	6
Marzo 90	0.89	0.91	3
May 90	1.00	1.13	7

in the control plot. The between-year differences in interception in the control plot can be attributed to between-year variations in rainfall distribution (Rutter and Morton, 1977). Cumulative gross rainfall and througgfall curves for each plot and each year are shown in Fig. 2, and again illustrate how interception in the burnt plots approached near-normal values within three years of burning.

Surface runoff over the four years of study were divided into 100 events (Fig. 3). Runoff events during which the soil displayed severe or very severe water repellency (estimated on the basis of soil moisture content as shown in Fig. 1) are marked '1' in Fig. 3. These events (occurring mostly in the period May - October) accounted for 27.9%, 40.4% and 32.9% of total runoff over the four years from plots C, L and M respectively. The corresponding rainfall events, however, accounted for only about 15% of total rainfall over the four-year period . Runoff events during which soil water content was at saturation are marked '2' in Fig. 3. As is apparent from the figure, the majority of major rainfall events are attributable either to high water repellency or to soil water content being at saturation. During the first year post-burn, high water repellency appears to have been a more frequent cause of high runoff.

Runoff percentages for the burns plots showed a tendency to decrease over the years subsequent to the fire, reflecting the gradual establishment of vegetation cover

Table 4. Percentage apparent interception (see text) of rainfall in each plot in each year of study.

Year	Total rainfall	Interception (%)		
		C plot	L plot	M plot
1988/89	1071.4	43.7	13.8	10.7
1989/90	1636.4	42.3	24.3	23.8
1990/91	1597.8	38.4	31.9	36.3
1991/92	1100.2	51.0	40.0	48.6

Table 5. Runoff (expressed as a percentage of gross rainfall) from each plot in each year of study.

Year	Control Plot	L Plot	M Plot
1988/89	3.5	6.0	5.2
1989/90	2.8	4.0	2.9
1990/91	1.5	2.8	1.8
1991/92	1.9	2.4	2.3

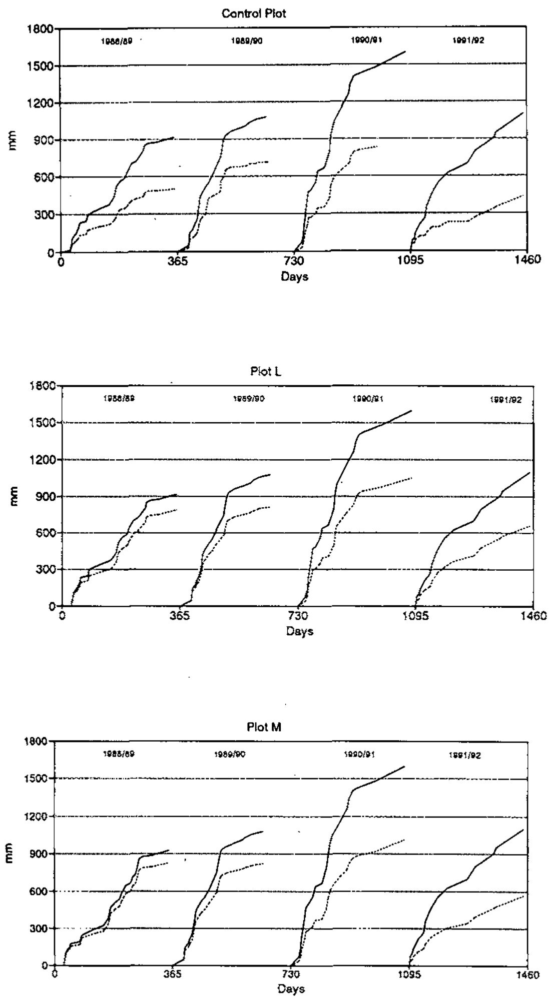

Figure 2. Cumulative gross (solid line) and net (dotted line) rainfall curves for each plot and each year of study.

(Table V). Note, however, that runoff percentages for the control plot also show a decreasing trend (which is, however, less marked than of the burnt plots): this can be attributed to between-year variability in rainfall distribution and thus in the factors affecting interception.

CONCLUSIONS

Various authors have reported increases in the water repellency of the surface layers of the soil following fire (see for example DeBano et al., 1981). The prescribed burns carried out in this study did not cause increased water repellency at any depth, which is probably attributable to the low maximum temperatures attained. In fact, burning caused water repellency in the 0 - 2.5 cm layer to drop slightly, possibly due to volatilization of the apolar compounds responsible for water repellency.

In the experiments reported here, burning led to an approximately twofold increase in runoff. However, the absolute increase was small (about 2 - 3% of rainfall), suggesting that wildfire-induced runoff is unlikely to have much influence on the flow regimes of Galician rivers, since quickflow (generally accounting for about 20 - 25% of total flow in this region) largely takes a subsurface route. The effects of wildfires on the water repellency of the soil, leading to increased surface runoff, can thus be expected to have little impact on river flow regimes; this contrasts with previous studies (such as Scott and Van Wyk, 1990), which have found that wildfires, by increasing the water repellency of the soil and thus increasing runoff, have a major impact on the flow regime of receiving rivers.

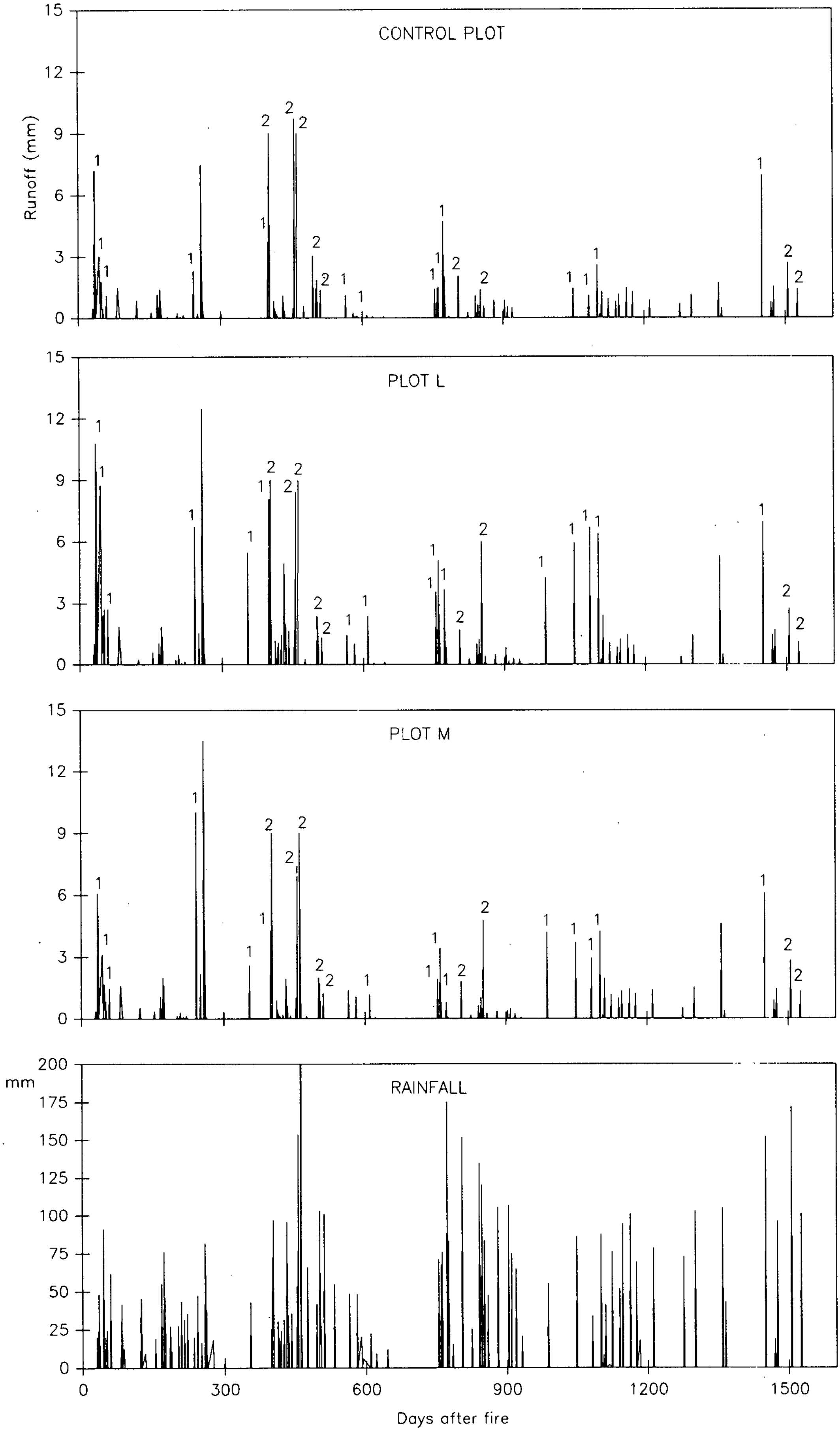

Figure 3. Temporal distribution of runoff from each plot over the study period. Runoff events marked '1' occurred during periods when water repellency of the soil was severe or very severe (see text). Runoff events marked '2' occurred during periods when soil water content was at saturation.

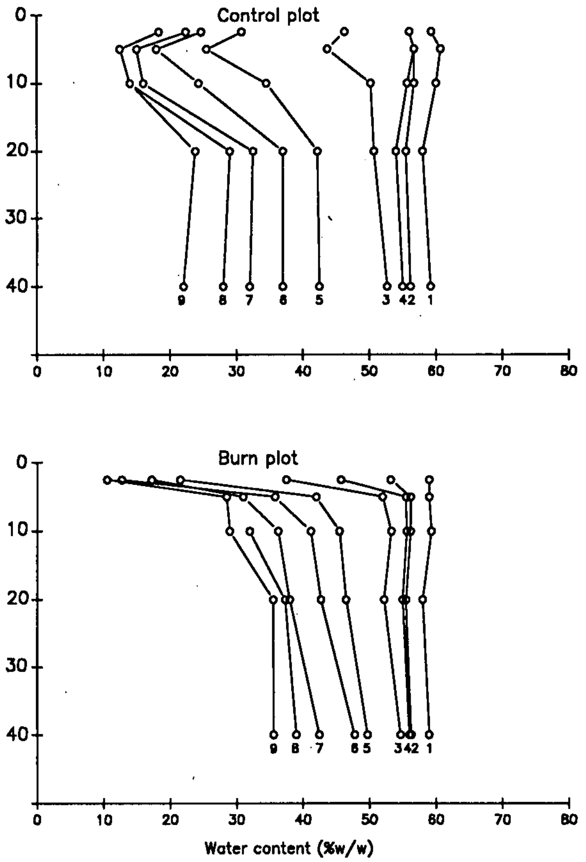

Figure 4. Soil water content profiles for the control plot C and the burn plot L, 9 months post-burn (june 1989). Soil water content was determined on the basis of tensiometers readings.

The same cannot be said of the effects of wildfire on evaporation from the vegetation canopy (i.e. interception) and on evapotranspiration of the soil water reserve. In the first year of the experiments reported here, loss of water to the atmosphere as a result of interception was 10.7 - 13.8% of rainfall in the burnt plots (as opposed to 43.7% in the unburnt plot). Similarly, burning led to reductions of about 30% in evapotranspiration losses over the first year. In view of the relatively minor increases in runoff from the burnt plots, these data suggest major increases in infiltration; this in turn suggests that wildfires may have a major impact on subsurface and groundwater flow, and thus on the flow regimes of Galician rivers. Responses to wildfire of this type may lead to increases in annual contribution of the order (about 25 - 30%) reported by Lavabre et al. (1993) for the south of France.

In cases in which the hydrological effects of wildfire are largely due to reductions in vegetation cover, the time required for recovery of prefire hydrological conditions can be expected to depend on the time required for recovery of the vegetation. In a study carried out in a region of Mediterranean climate and vegetation, Helvey (1980) found that prefire conditions had still not been attained seven years after the fire. The Ulex scrub studied by us, however, regenerates more rapidly (Casal, 1987), and we consider it likely that prefire conditions are reattained within about five years.

In Galicia, over the period 1985-1993, approximately 500.000 has were affected by wildfire. The degree to which the conclusions of the present study are valid for the region in general is currently unclear. Certainly, most fires lead to reductions in vegetation cover of similar magnitude to that observed in the present study, suggesting that similar effects on interception and evapotranspiration may be expected. On the other hand, fire characteristics, together with topografic , geological and climatic conditions , may all show considerable variation; furthermore, the eventual effect on watershed hydrology will depend

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