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EFFECTS OF A FIRE ON RUNOFF AND EROSION ON MEDITERRANEAN FOREST SOILS IN SE-SPAIN[1]

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ABSTRACT.- From 1985 to 1990, precipitation, runoff and soil erosion have been studied on experimental plots in a locality of Alicante (SE-Spain). A prescribed burning was carried out in September of 1989, (maximum temperature was moderate). In order to know soil evolution, soil was sampled three times: before fire, one day after fire and six months later.

One day after fire, a significant increase in organic matter content, total nitrogen, available phosphorus and the cations: K^{+}, Mg^{+2} and N^{+}, was found. On the other hand, Ca^{+2} and C.E.C. showed an opposite pattern. The modified values after fire tended to go back to the initial levels in the case of organic matter, phosphorus, Na^{+}, Ca^{+2} and C.E.C.

Annual runof after fire is significantly lower than in the year before fire, whilst average runoff in the year after fire is only significantly different when the most erosive year (October 1987-September 1988) is not considered. The runoff decrease will be related with a lower average precipitation after fire. There are no significant differences in the sediment yield between the year before and after the fire.

The nutrient outputs and runoff decrease is greater than the nutrient inputs and precipitation decrease after fire. Nutrient output in runoff after fire ranges between 8 to 35 % of the previous year, whilst volume of runoff is only 3 %, implying a greater concentration.

RESUMEN.- Se han estudiado los flujos de escorrentía y remoción de suelo, así como su composición química durante cinco años (1985-1990) en unas parcelas de erosión en una localidad de la provincia de Alicante (SE-España). En septiembre de 1989 se incendió la vegetación de las parcelas registrándose temperaturas moderadas. Se ha realizado un seguimiento de la química del suelo mediante tres muestreos: previo al fuego, al día siguiente y 180 días después.

Al día siguiente del incendio se ha producido en el suelo un incremento estadísticamente significativo del contenido en materia orgánica, nitrógeno total, fósforo asimilable y los cationes cambiables: K^{+}, Mg^{+2} y Na^{+}. Por el contrario, hay una disminución de Ca^{+2} y de la C.I.C. Los valores modificados tras el incendio tienden a recuperar su nivel inicial en el caso de materia orgánica, fósforo, Na^{+}, Ca^{+2} y C.I.C.

La escorrentía anual tras el incendio es significativamente menor que la del año anterior al incendio, mientras que la escorrentía media es

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significativamente menor sólo en el caso de no considerar el año más erosivo (Octubre 1987-Septiembre 1988), lo que estaría asociado con una disminución de la precipitación media tras el incendio. Por su parte, la producción de sedimentos del año posterior al incendio no presenta diferencias significativas respecto al año anterior.

La disminución en la salida de nutrientes y en el volumen de escorrentía es más acentuada que la disminución en la entrada de nutrientes y en el volumen de la precipitación después del incendio. La salida de nutrientes por escorrentía tras el incendio presenta un rango entre 8 y 35 % del año anterior, cuando el volumen sólo representa el 3 %, lo que implica un aumento en su concentración.

RÉSUMÉ.- On a étudié les flux de ruissellement et de transport du sol, ainsi que sa composition chimique, pendant cinq ans (1985-1990), dans des parcelles d'érosion dans une localité de la Province d'Alicante (SE-Espagne). En septembre 1989, on a brûle la végétation des parcelles, en enregistrant des températures modérées. On a réalisé un suivi de la chimie du sol par trois échantillonnages: avant le feu, le jour suivant et 180 jours plus tard.

Le jour après l'incendie, il s'est produit dans le sol une augmentation statistiquement significative de la teneur en matière organique, azote total, phosphore assimilable, et des cations changeables: K^+, Mg^{+2} et Na^+. Au contraire, il y a une diminution de Ca+2 et de la C.I.C. Les valeurs modifiées après l'incendie tendent à reprendre leur niveau initial dasn le cas de la matière organique, phosphore, Na^+ Ca^{+2} et C.I.C.

Le ruissellement annuel après l'incendie est significativement moindre que pour l'année avant l'incendie, cependant que le ruissellement moyen est significativement plus faible uniquement dans le cas où l'on ne considère pas l'année où l'érosion a été maximale (octobre 1987-septembre 1988), ce qui serait associé à une diminution de la précipitation moyenne après l'incendie. D'autre part, la production de sédiments pendant l'année postérieure à l'incendie ne présente pas de différences significatives par rapport à l'année précédente.

La diminution de l'exportation d'éléments nutritifs et du volume de ruissellement est plus accentuée que la diminution de l'entrée d'éléments nutritifs et que le volume de la précipitation après l'incendie. L'exportation d'éléments nutritifs par ruissellement après l'incendie reste dans une gamme de 8 à 35% par rapport à l'année précédente, tandis que le volume ne représente que 3%, ce qui implique une augmentation de la concentration.

Key-words: *Fire, runoff, erosion, soil, nutrients,* Pinus halepensis.

Soil erosion is extremely intense in large areas of Mediterranean Europe. Soil losses between 277 and 655 g/m^2 have been measured in some areas of Alicante (SÁNCHEZ *et al.*, 1990) and losses of 230 g/m^2 have been measured in Valencia (SANROQUE *et al.*, 1985).

Forest fires are frequent in the areas with Mediterranean climate, and they greatly affect the Region of Valencia (Eastern Spain): between 1976 and 1986 an average of 30,024 has/year were burnt (REYNA, 1988), whereas in the region of Catalonia (NE Spain) an average of 21,000 has/year (MARQUES, 1991). Sometimes a single fire may affect a wide area, as happened in the summer of 1991 in Buñol (Valencia).

Fire is an important mineralizing agent which may induce some changes in the physical and chemical characteristics of soil. Several authors have studied the role of fire in vegetation, soil and dissolved and particulate fluxes (TRABAUD, 1979; DE BANO, 1988; ALBADALEJO *et al.*, 1991; FERRÁN & VALLEJO, 1991). It is know that the proportion of ashes depends on the temperature of the fire, the organic matter rising due to the contribution of the urburnt parts of the plants when the intensity of fire is low. If it rises, there is a significant increase in some soil nutrients, although in ecosystems subject to severe fire there may be important losses through smoke (RAISON *et al.*, 1985; GIOVANNINI, 1991). When the fire is finished, and depending on the pluvial regime or as a consequence of intense winds which displace the ashes, the losses of some nutrients may rise through washout. As to the generation of runoff and sediment yield, the effect of the fire depends mainly on the intensity of the rain, the intensity and type of fire and the slope of the land (SIRUCEK, 1987; BENITO *et al.*, 1991; SOLER *et al.*, 1991). The role of fire in the impermeabilization of soil surface and in the change of its structural stability has been discussed (DÍAZ FIERROS *et al.*, 1987; SEVINK *et al.*, 1989).

The present paper studies the effect of the fire on the soil and the fluxes dissolved and particulate on a semiarid area of scrub afforested with *Pinus halepensis* Miller.

1. Study area

The study area is located in Albatera, 50 km. south of Alicante, 475 m. altitude, 26° slope and the bedrock is a marllime of Tertiary. Soil type is silty-loamy with a maximum dept of 45 cm and bedrock emerges in some places. The vegetation cover, approximately 39%, was formed by *Brachypodium retusum, Stipa tenacissima, Teucrium polium* y *Rosmarinus officinalis.* The average biomass was 237.9 g/m^2.

2. Methods

The afforestation with *Pinus halepensis* took place 5 years ago by two techniques of soil preparation: terraces along contour lines of the slope and ploughed linearly along maximum slope. Experimental plots to study soil erosion were set up on these areas with forest treatment, and also on a third one in which vegetation had not been disturbed in order to be used as control. The plots measure 20 m x 4 m. Runoff and sediment yield have been measured on them for five years, every time an erosive rainfall took place.

The plots were subjected to an experimental fire. Nearby areas were also burnt so that soil could be sampled after the fire, thus avoiding the disturbance of the erosion plots. The burning was carried out on September 21st, 1989 at 11 a.m. The air-temperature was 21°C and the relative humidity was 61%. The wind speed was low. Vegetation water content varied from 35 % in *Stipa* and *Brachypodium* to 61% in the twigs of *Pinus.* Soil water content was 13.5%, the field capacity was 25.9%. A few days before the fire, on September 5th and 7th, 240 mm of precipitation was registered.

The temperature of fire was determined by thermocouples and 8 asbestos plates per plot impregnated with thermosensitive paint. The latter were placed on the soil surface to determine the maximum temperature reached.

The soil samples were taken from the three treatments (control, ploughed and terraces) at two different depths: 0-5 cm and 5-15 cm, although average values are offered in the results.

The variables and methods employed in the analysis of the soil were as follows: organic matter (Walkley-Black), total nitrogen (Kjeldahl), available phosphorus (Olsen), texture (Bouyoucos densimeter), available cations were extracted with baritriethilamine and determination was made by atomic absorption spectrophotometry. The content of dissolved ions in the runoff water was determined by atomic absorption spectrophotometry for the cations: Na^{+}, K^{+}, Ca^{+2}, Mg^{+2} and by ionic chromatography for the anions: Cl, SO_4^{-2}, No_3^{-}.

As the fire took place at the end of the summer, the periods of time employed to compare the effects of the fire are set from October to the following September, except for soil analyses, which were made before the fire, one day after it and 180 days after the fire.

3. Results and discussion

3.1. *Characteristics of the fire*

The fire was brief: less than ten minutes in each plot, due to the low content of biomass and the humidity conditions. The combustion followed a discontinuous pattern according to vegetation distribution. The temperature on the soil surface reached 340°C under *Pinus,* 740°C unde *Stipa,* 280°C under *Brachypodium* and 51°C on an area of bare soil. Figure 1 shows the evolution of temperature at soil level during the fire under different species.

The different patterns of temperature correspond to the structure of the plants. Under *Brachypodium* the maximum temperature is reached about two minutes after the beginning of the fire, then it quickly diminishes and four minutes after the fire it decreases slowly; this behaviour is probably related to a small biomass which is quickly consumed. Under *Pinus* there are two maximums at 2 and 5 minutes, which may be explained by the combustion of a plant with a greater biomass than *Brachypodium* and because its branches burn and go out progressively, being only partially consumed. Under *Stipa* the soil is isolated by the mass of plant which is first consumed in its outer part with a temperature below 100°C between 4 and 7 minutes after the fire. From that moment there is a strong increase, and highest temperature is reached in this species. From 10 minutes on the temperature diminishes because the biomass has been consumed.

Figure 2 shows the evolution of temperature of *Pinus* combustion at levels higher and lower than soil surface. In all the measured gradients the maximum temperature is reached at about 6 minutes after the fire, decreasing later. Only that of the greatest depth in soil keeps its temperature practically unaltered.

EVOLUTION OF TEMPERATURE OF THE FIRE ON SOIL SURFACE WITH DIFFERENT COVER

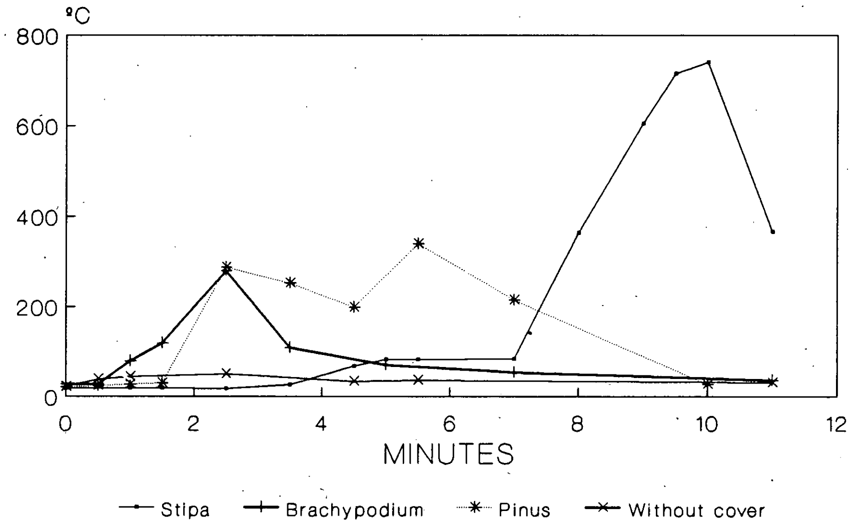

Figure 1.

EVOLUTION OF THE TEMPERATURE OF THE FIRE IN Pinus AT DIFFERENT HEIGH

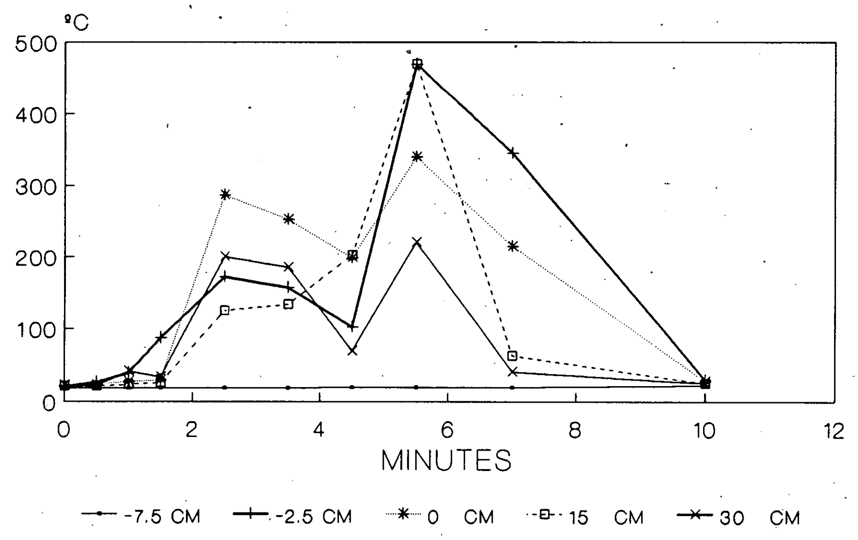

Figure 2.

The fire may be considered a low intensity one according to bibliography (TRABAUD, 1989; GIOVANNINI, 1991). The average maximum temperature on the soil surface reached 230°C on the areas with vegetation, and it remained below 100°C on bare areas.

3.2. *Effects of the fire on the chemical characteristics of soil*

One day after the fire, the organic matter, total nitrogen, available phosphorus and the exchangeable cations K^+, Na^+, and Mg^{+2} show a significant increase. However, calcium and the capacity of cationic exchange (C.E.C.), which seems dominated by that cation, decrease significantly, as Table 1 shows.

TABLE 1

Soil parameters: averages values and standard deviation. Different letters in the same line represent a significant difference between samples for that variable ($p <= 0.05$). *(Parámetros edáficos: valores medios y desviación típica. Las diferentes letras en la misma linea representan una diferencia significativa para esa variable).*

VARIABLE	DAYS AFTER THE FIRE					
	0 DAYS		1 DAY		180 DAYS	
M.O.	51.39	a	63.61	b	59.61	ab
mg/g	13.08		19.07		20.03	
N	2.34	a	3.18	b	2.86	c
mg/g	0.59		0.67		0.56	
P	5.72	a	8.84	b	5.14	ac
mg/kg	2.45		6.08		2.40	
K	0.32	a	0.75	b	0.55	c
cmol/kg	0.12		0.25		0.15	
Mg	0.67	a	0.96	b	0.82	c
cmol/kg	0.07		0.30		0.13	
Na	0.09	a	0.14	b	0.10	ac
cmol/kg	0.02		0.11		0.04	
Ca	15.65	a	8.64	b	14.70	ac
cmol/kg	1.74		3.82		2.37	
CIC	16.75	a	10.39	b	16.17	ac
cmol/kg	1.76		3.85		2.58	
pH H^2O	8.25	a	8.00	b	8.19	a
	0.16		0.19		0.18	
pH ClK	7.71	a	7.49	b	7.60	c
	0.10		0.12		0.11	
Sand	55.95	a	58.90	b	57.30	c
%	1.82		2.10		2.18	
Slit	19.20	a	20.75	b	20.05	ab
%	1.91		1.86		1.50	
Clay	24.85	a	20.35	b	22.65	c
%	2.16		1.98		2.03	

The concentrations of organic matter, available phosphorus, Na^{+}, Ca^{+2} and C.E.C. then to go back to their original levels six months after the fire. Other variables, as total nitrogen, K^{+} and Mg^{+2}, which are the most persistent ones, also show a decrease, but without reaching their original levels.

3.3. *Effects of fire on runoff and sediment yield*

The highest volume (mm) and intensity (mm in 30 minutes) values of the precipitation, from October 1986 to December 1990, mainly were registered in the autumns. Nevertheless, a few days before the fire, high values of volume and intensity of rain were measured, whereas after the fire the recorded values were lower (SÁNCHEZ *et al.,* 1991).

Figure 3 shows, for the same period of time, the runoff and sediment values on the control plot. Following the pattern of precipitation, Autumn is the season during which the greatest part of the runoff and sediment yield takes place, specially in 1987, except the year after the fire, in which the moderate precipitations produced very low levels.

In Table 2 annual values of precipitation, runoff and sediment yield are presented. Values are low compared to those of the preceding years. The year after the fire there was a significantly lower value of runoff (1.37 mm) than the two years before fire (47.52 y 67.90 mm). On the other hand, there is no statistical difference between the sediment yield of the years before and afther the fire. Only 1987-88, a very erosive year, is significantly different from the others.

If the data of the rains are taken individually (Table 3) it may be seen that the average precipitation per event is significantly lower during the year after fire than in the two years before. The runoff and the sediment yield on the control plot in 1989-90 is only significantly lower than those of 1987-88. If the data of 1987-88 is ignored, the runoff on the control plot is lower in 1989-90 than in 1988-89, whereas there are no significant differences between the years studied in regard to sediment yield.

These facts differ from those found in RIGGAN *et al.* (1990) in chaparral ecosystem, where even small or moderate storms during the succeeding winter after a fire produce great sediment losses. In other Mediterranean ecosystems the behaviour may be the same, but it is not easily noticeable when natural storms are studied, due to the great irregularity among years. The use of rain simulators may help to determine soil alteration after fire, which affects runoff and sediment yield.

RUNOFF AND SEDIMENT YIELD
OCTOBER 1986-DECEMBER 1990

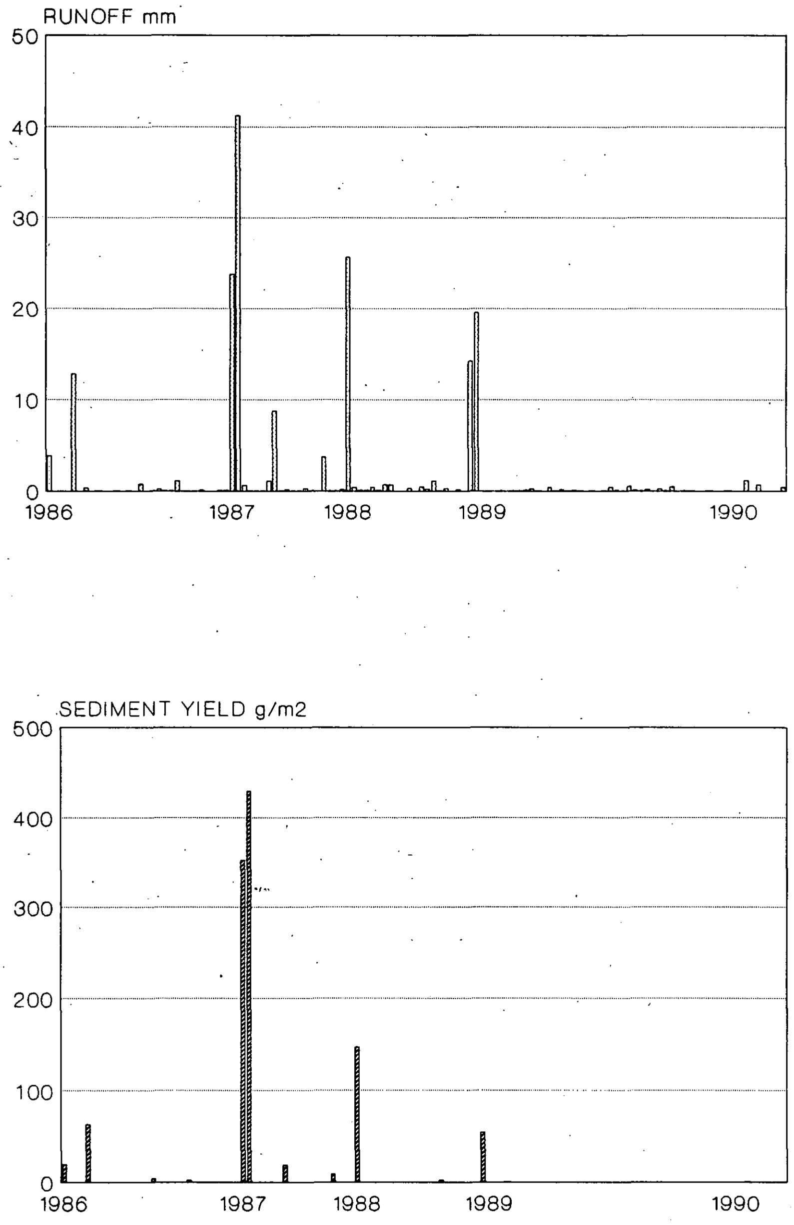

Figure 3.

TABLE 2

Annual values of precipitation, runoff and sediment yield. The values in a column are significantly different if they have different letters ($p <= 0.05$). *(Valores anuales de precipitación, escorrentía y producción de sedimentos. Los valores en una columna son significativamente diferentes si tienen distintas letras).*

YEAR	PRECIPITATION mm	RUNOFF mm		SEDIMENT YIELD g/m²	
1986-87	196.4	11.61	a	54.22	a
1987-88	459.1	67.90	b	569.67	b
1988-89	678.8	47.52	b	150.43	a
1989-90	415.7	1.37	a	0.46	a

TABLE 3

Average values per storm of precipitation, runoff, and sediment yield. The values in a column are significantly different if they have different letters ($p <= 0.05$). *(Valores medios de precipitación, escorrentía y producción de sedimentos por tormenta. Los valores en una columna son significativamente diferentes si tienen letras distintas).*

YEAR	PRECIPITATION mm		RUNOFF mm		SEDIMENT YIELD g/m²	
1986-87	6.55	a	0.65	a	2.99	a
1987-88	24.16	b	4.22	b	42.58	b
1988-89	29.51	b	2.80	ab	8.87	a
1989-90	6.55	a	0.08	a	0.02	a

3.4. *Runoff chemistry*

The values of the concentration of cations and anions, expressed in ppm, obtained when analyzing the samples of runoff water from the year 1987-88 to 1990-91 are shown in Figure 4.

The year after the fire there is an increase in the concentrations of Cl^-, NO_3^-, SO_4^{-2}, Ca^{+2} and Mg^{+2}, in relation to the previous year (Figure 5), as a consequence of the increase of runoff water mineralization (concentrations and percentages in relation to the year before fire). The amount of the increase is 200% in the case of Cl^- and that of Mg^{+2} exceeds 150%, followed by No_3^- and SO_4^{-2}, which reach values close to 150%.

When analyzing the variance with the values of all the runoff recorded each year, it may be seen that only the concentrations of Cl^- and Mg^{+2} are significantly higher after the fire. If we compare the two years before the fire with the two after it, it is found that the concentration of K^+ is significantly lower after the fire, whereas those of Ca^{+2}, Mg^{+2}, Cl^- and NO_3 are significantly higher.

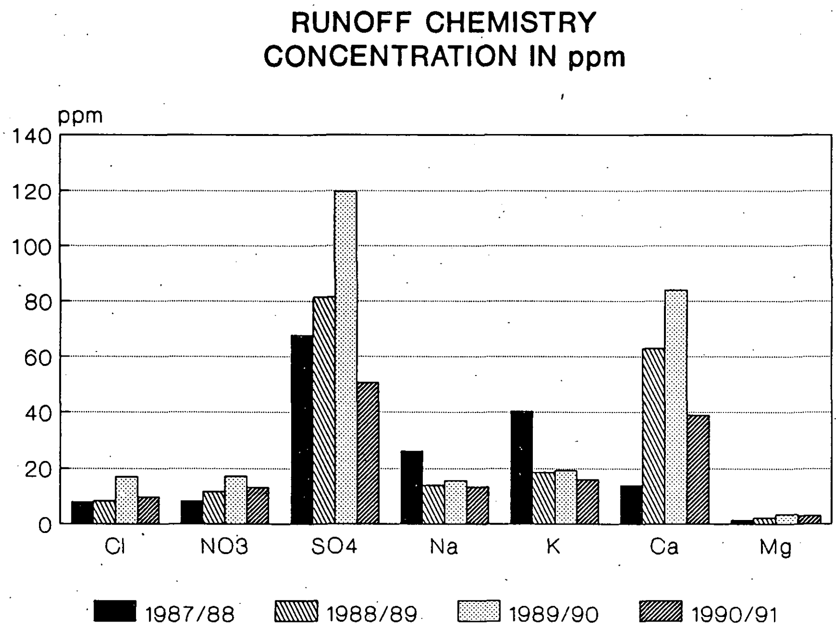

Figure 4.

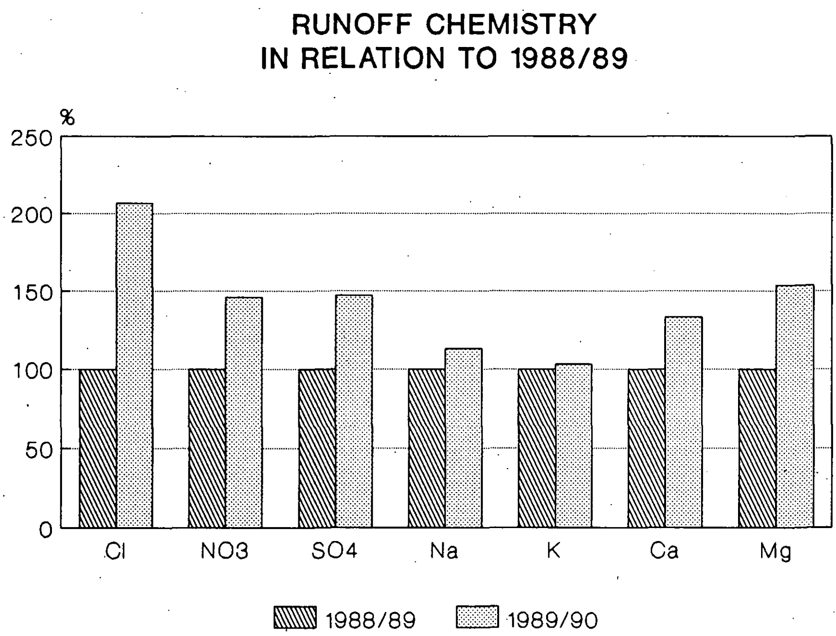

Figure 5.

The year 1990-91, two years after the fire, shows a decrease of all the elements analyzed in regard to the year after the fire, 1989-90, decrease which is only statistically significant for Cl^-, SO_4^{-2} and Ca^{+2}.

When studying the results of the chemical analyses of the runoff water in autumn (Table 4), since this is the season following the fire, it may be seen that, in general, the average autumn concentrations of nutrients are lower than the annual average. The variance analysis confirms a significant increase (almost the double) in the concentration of Cl^- after fire, recovering in autumn two years after the fire the value of the autumn before it. No significant differences are observed when comparing the concentrations of the autumn before the fire and those of the autumn after it for the rest of the nutrients analyzed, and the concentrations of Na^+ and K^+ are the most homogeneous ones throughout the four autumns studied. This stable behaviour is found by MARTIN *et al.* (1991) for Na^+ and Cl^-.

TABLE 4

Average concentrations of the runoff water in autumn in the years studied (ppm). Columns with a common letter are not significantly different (p <= 0.05). *(Concentraciones promedio del agua de escorrentía en otoño en los años estudiados (ppm). Las columnas con letra común no son significativamente diferentes).*

AUTUMN	Cl		NO_3		SO_4		NA		K		Ca		Mg	
1987	2.10	a	2.13	a	13.23	a	13.97	a	20.10	a	6.93	a	0.79	a
1988	9.15	a	11.51	ab	49.96	b	16.41	a	24.58	a	18.46	ab	1.22	ab
1989	16.75	b	16.28	b	44.44	b	20.17	a	27.71	a	68.63	b	2.81	b
1990	9.29	a	8.04	ab	21.03	a	12.97	a	17.29	a	31.59	ab	4.47	c

NUMBERS OF EVENTS 1987 = 4, 1988 = 4, 1989 = 9, 1990 = 7

The pH of the runoff water does not seen to be affected by the fire, and only the pH of the year 1990-91 is significantly higher than in the previous years (Table 5). As to the data which refer to the autumn, the pH is only significantly higher in 1990 than in the year before the fire.

The conductivity of the runoff water shows oscillations in the mean annual and autumn values; those of the years 1988-89 and 1990-91 are similar, as well as those of the autumns of 1988 and 1990. On the other hand, the conductivity of the year after the fire is significantly higher than that of the previous year, a difference which becomes more noticieable when comparing the autumns of those same periods. Alkalinity also shows oscillations both in annual and autumn values (Table 5). The average alkalinity of the year before the fire is significantly higher than the year after. However, the difference between the autumns of those same periods is not significant.

The fire, consequently, seems, to affect mainly the conductivity of the runoff water, increasing it significantly, whereas the alkalinity decreases the year after the fire and the pH does not vary after the fire. Nevertheless, the fact than the conductivity of the year 1987-88 is statistically similar to that of 1989-90 may indicate the convenience of contrasting the input and output of dissolved matter.

TABLE 5

Average annuals and autumn values of pH, conductivity (μmhos) and alkalinity (meq of CO_3) of the runoff water. Columns with a common letter are not significantly different ($p <= 0.05$). *(Valores promedio anuales y de otoño de pH, conductividad y alcalinidad del agua de escorrentía. Las columnas con letra común no son significativamente diferentes).*

PERIOD	pH	Conductivity	Alkalinity
1987-88	7.43 a	682.1 a	1.04 a
1988-89	7.42 a	339.0 b	0.79 b
1989-90	7.33 a	603.6 a	0.64 c
1990-91	7.70 b	287.7 b	0.73 bc
NUMBERS OF EVENTS	1987-88 = 19, 1988-89 = 18 1989-90 = 31, 1990-91 = 22		
AUTUMN 87	7.62 ab	735.0 ab	1.10 a
AUTUMN 88	7.29 a	295.0 a	0.76 b
AUTUMN 89	7.43 ab	1155.7 b	0.82 ab
AUTUMN 90	7.75 b	245.4 a	0.80 ab

NUMBERS OF EVENTS 1987 = 4, 1988 = 4, 1989 = 9, 1990 = 7

The annual balance of nutrient input in precipitation and output in runoff, in mg/m^2, before and after fire are compared in Figure 6. The values of the year before the fire are higher than those obtained the year after it, except for Mg^{+2} in input. When studying the content of rain and runoff per event, in mg/m^2, we can see that anions No_3^- and SO_4^{-2} and the cation Na^+ show significantly higher inputs the year before the fire than the year after, whereas for Cl^-, No_3^-, Na^+, K^+, Ca^{+2} and Mg^{+2} the outputs of the year before the fire are significantly higher than in the year after it.

The year after the fire a precipitation of bout two thirds of the year before the fire, produces the input of half the nutrients, except for the bivalent cations. On the other hand, a runoff 35 times lower after fire produces a nutrient output between 2.9 and 12 times lower, which implies more concentrated outputs. The runoff collected the years before and after the fire amounts to 7.0 and 0.3%, respectively, of the rain (Table 2), so that after fire the surface runoff decreases, although there are no significant differences when comparing the average runoff per event in the years before and after fire. This lack of significance also shows in the sediment yield, despite the fact thant the average precipitation per event is significantly higher before the fire than after it.

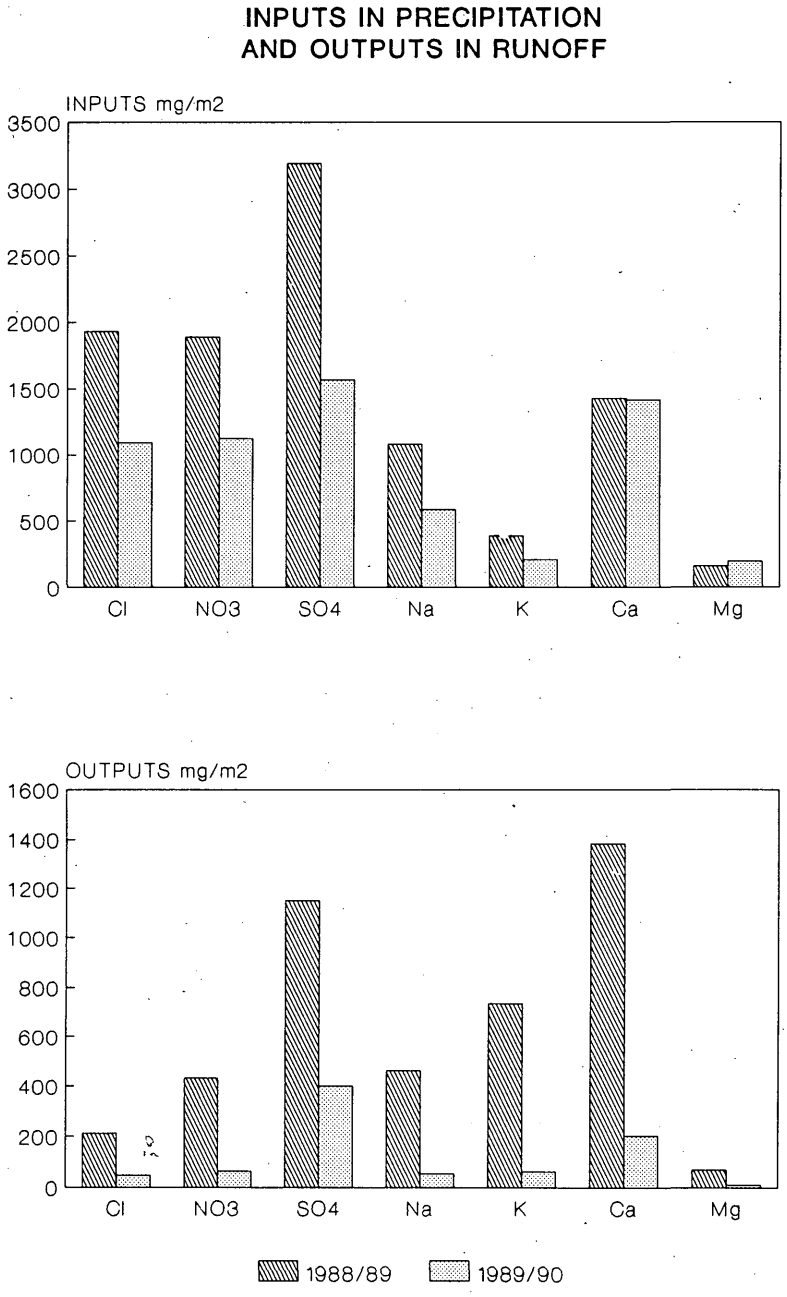
INPUTS IN PRECIPITATION
AND OUTPUTS IN RUNOFF
INPUTS mg/m2
3500
3000
2500
2000
1500
1000
500
0
Cl
NO3
SO4
Na
K
Ca
Mg
OUTPUTS mg/m2
1600
1400
1200
1000
800
600
400
200
0
Cl
NO3
SO4
Na
K
Ca
Mg
1988/89
1989/90

Figure 6.

4. Conclusions

The observations indicate that the fire incorporates most of the analyzed nutrients from the vegetation to the soil. Afterwards, the nutrients are consumed by the resprout of the vegetation and washed from the soil. Consequently, the level before the fire of the majority of nutrients is recovered.

The effects of the fire on the lower volume of the runoff and the lower production of the sediments remains masked by the fact that it produces a lower mean precipitation during the year after the fire. The effect of the fire on the runoff is shown in the higher concentration os some nutrients. The fact of it being a fire on a scarce vegetal biomass and soil and vegetation with high humidity conditions, produces moderate temperatures and a short duration of the fire, which seems to explain a quick response in the incorporation of the nutrients into the soil and the recovery of the vegetation. On the other hand, the characteristics of the fire and/or the negligible precipitation after it, seem to explain the small change in the physical conditions of the soil, as may be deduced from the negligible induction of the runoff and the sediment yield.

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