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Changes in organic matter, nitrogen, phosphorus and cations in soil as the result of fire and water erosion in a Mediterranean landscape

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Summary

Fire affects large parts of the dry Mediterranean shrubland, resulting in erosion and losses of plant nutrients. We have attempted to measure these effects experimentally on a calcareous hillside representative of such shrubland. Experimental fires were made on plots (4 m x 20 m) in which the fuel was controlled to obtain two different fire intensities giving mean of soil surface temperature of 439ºC and 232ºC with temperatures exceeding 100ºC lasting for 36 minutes and 17 minutes. The immediate and subsequent changes induced by fire on the soil's organic matter content and other soil chemical properties were evaluated, together with the impact of water erosion.

Seven erosive rain events, which occurred after the experimental fires (from August 1995 to December 1996) were selected, and on them runoff and sediment produced from each plot were measured. The sediments collected were weighed and analysed. Taking into account the variations induced by fire on the soil properties and their losses by water erosion, estimates of the net inputs and outputs of the soil system were made. Results show that the greatest losses of both soil and nutrients took place in the four months immediately after the fire. Plots affected by the most intense fire showed greater losses of soil (4077 kg ha^{-1}) than those with moderate fire intensity (3280 kg ha^{-1}). The unburned plots produced the least sediment (72.8 kg ha^{-1}). Organic matter and nutrient losses by water erosion were related to the degree of fire intensity. However, the largest losses of N-NH_4^+ and N-NO_3^- by water erosion correspond to the moderate fire (8.1 and 7.5 mg N m^{-2} respectively).

Introduction

During the last two decades, environmental scientists have come to realise that fire is a dominant control on the forest landscapes in Southern Europe, especially in the Mediterranean basin where it is been considered a major environmental problem.

The temperatures of the soil and the burned vegetation produce changes in soil chemical and physical properties. The magnitude of these changes greatly depends on fire and soil characteristics, vegetation cover and the weather (Blank & Zamudio, 1998). Fires not only cause changes in soil and environmental properties, they could also increase net losses of nutrients by volatilization, leaching and water erosion. These losses depend on the intensity of fires (peak temperatures reached on the soil surface and their duration). In fires of medium and high intensity, the disappearance of the vegetal cover and the partial combustion of the soil organic matter could alter soil structure, thereby affecting the porosity and other hydrological characteristics (Andreu *et al*., 1994; Giovannini & Lucchesi, 1997), and enhance the accumulation of hydrophobic substances at several centimetres depth and thereby reduce infiltration and increase runoff (De Bano, 1971; Imeson *et al*., 1992). These conditions enhance the susceptibility of soil to erosion and they generally cause an increase in runoff and soil loss. Nutrients are then lost as they are transported with the solids by runoff (Andreu *et al*., 1996; Rubio *et al*., 1996). Andreu *et al*. (1996) showed after a so called ‘intense fire’, erosion was more intense than for a ‘light or moderate fire’, producing significant losses in chemical elements removed with the sediment or dissolved in runoff. Thus, the effect of fire on soil erosion depends mainly on its intensity and on the intrinsic characteristics of any subsequent rain event (intensity, duration, etc.) (Rubio *et al*., 1996).

This problem becomes important in the Mediterranean basin where the impact of continuous and repeated fires, mainly in summer, followed by torrential rains in autumn results in intense erosion (Giovannini *et al*., 1990; Andreu *et al*., 1996).

We have studied the immediate changes in soil organic matter content, total and mineral soil nitrogen, available phosphorus and exchangeable cations induced by fire. The temporal variation of erosion rates on burned plots, with varied intensities of fire under similar environmental conditions was also studied. Sediments generated by runoff in the erosive rain events are analysed to determine the soil organic matter and nutrient losses by water erosion. Taking into account the variations of these soil losses induced by fire, an analysis of net inputs and outputs of organic matter and nutrients is made.

Materials and methods

Study site

The study area of ‘La Concordia’ is in the municipality of Lliria (Valencia, Spain), 50 km NW of Valencia city. It is 575 m above the sea level, on land ceded by the Forestry Services of the Valencian Government (Generalitat Valenciana). The experimental fires were made under field conditions on a forested hillside facing South South East, with a sclerophyllous shrub cover regenerated after a previous wildfire occurred in 1978. The dominant vegetation type belongs to the *Rhamno lycioidis*-*Quercetum cocciferae* association, which is typical of semi-arid Mediterranean areas. The most abundant species include *Rosmarinus officinalis*, *Ulex parviflorus*, *Quercus coccifera*, *Rhamnus lycioides*, *Stipa tenacissima*, *Globularia alypum*, *Cistus clusii* and *Thymus vulgaris*.

Climatically the area belongs to the dry ombroclimate of the lower mesomediterranean belt, according to Thornthwaite’s classification. The average annual precipitation is around 400 mm with two maximums, autumn and spring, and a dry period from June to September. Mean monthly temperatures range from 13.3ºC in January to 25.8ºC in August.

The soil is a Rendzic Leptosol (FAO-UNESCO, 1988) developed on Jurassic limestone. This soil has a variable depth, always less than 40 cm, many stones (≅ 40%), good drainage, a sandy-loam texture, and an alkaline pH (7.4).

Experimental plots and fire treatments

The experimental set-up consists of nine plots, each 20 m long by 4 m wide, with similar morphology, slope gradient, rock outcrops, soil and vegetation cover. The location of each plot was made after intensive survey of the vegetation, soil and morphology patterns, based on across-slope transects every 2 m.

The plots were oriented parallel to the slope and bounded by bricks. At the foot of each plot a 2-m wide collector ran into a 1500-l tank to collect all the runoff and sediment produced during each rain event. Inside this tank a 30-l tank facilitates the collection of sediments produced.

A design of two different fire intensity treatments, with three plots each, was used. Contrasting amounts of fuel, obtained from the surrounding shrub, were added to obtain two different fire intensities. One consists in the addition of 20 t biomass ha^{-1} (F1 treatment). The second consisted in the addition of 40 t biomass ha^{-1} (F2 treatment). The fuel was spread uniformly on the plots. The remaining three plots were used as control (F0 treatment). The assignation of fire treatment to each plot was made by lot. We assigned the treatments to the plots completely at random without blocking.

The composition and the spatial distribution of the vegetation in each plot were determined by intensive field survey, counting the individuals identified to species and measuring their size (height, maximum and minimum diameter) as well as the percentage of soil covered by plants on a 1m x 1m basis. This information was used to map dry biomass and vegetation cover (visual estimation) present in each 1m^2 and to calculate the mean dry biomass present in the plots. The biomass was estimated by using a non-destructive method similar to the proposed by Etiene & Legrand (1994). Moreover, under the two species that cover large percentage of soil surface (*Ulex parviflorus* and *Rosmarinus officinalis*), eight litter samples on a 25 cm x 25 cm were collected, and the biomass was also directly estimated. The biomass present in the plots range from 5 t ha^{-1} to 8 t ha^{-1}. Approximately the 50% of the plots surface have a quantity of natural biomass $\leq$ to 5 t ha^{-1}. The most abundant species and their mean frequencies are: *Rosmarinus officinalis* 34%, *Ulex parviflorus* 21%, *Globularia alypum* 27%, *Rhamnus lycioides* 4%, *Cistus clusii* 3%, *Quercus coccifera* 3.5% and *Thymus vulgaris* 6%.

To measure the temperatures on the soil surface and their duration, thermosensitive paints and thermocouples were used. Six thermocouples (type K Inconel 600-insulated) per plot were installed at ground level along parallel lines running downslope and separated from one another by 3 m. From these measurements direct estimates were made of the time that temperature exceeded 100ºC. We chose this value because it seemed to be that it is which the most significant changes begin, starting with the water evaporation.

To obtain the spatial distribution of temperatures on the soil surface, a set of twenty-four thermosensitive paints were used (Omega Stik Crayons) ranging between 100ºC and 677ºC, in increments of approximately 25ºC. They were applied on iron rods each covered with another identical rod, but not painted, to protect them from ashes and flames. The system was tied with two pieces of wire. Just before the experimental fire one iron rod per square metre was placed (a total of 80 iron rods per plot) with the painted side in contact with soil. Immediately after the passage of fire the iron rods were collected and they were read.

We lit the fires on 20 and 21 June 1995. Weather and the characteristics of the different rainfall events were monitored by a logging system of sensors placed close to the plots. The weather at the time of burning is recorded in Table 1.

When the thermocouples and the thermosensitive paints were in place and the extra biomass had been spread on the plots, a small amount of fuel oil was applied at the bottom of the plots and fire started. The fires progressed upslope, and their behaviours were uniform in all the plots, except in plot 6 that suffered repeated changes in wind direction. In all cases, the fires progressed from their starts to the middle parts of the plots, faster in the centre of fire front than on their flanks. Once the fires had passed the half-way marks they progressed uniformly thereafter.

Immediately before the fires we took 36 soil samples (four per plot) 0 to 5 cm depth. Due to the distribution of vegetation in a patchy shrub mosaic we chose two different soil microenvironments for sampling: underneath plant canopies and in the centres of openings. Openings with a minimum diameter greater than 0.5 m were sampled and openings located less than 1 m from shrubs were excluded. Litter was removed prior the sampling. The sampling points were marked with pins so that we could sample again at the same microsites after burning. Two hours after the fires we took four samples of ash per plot to be analysed and another 36 soil samples.

Soil and sediments analysis

The soil samples were air-dried, sieved to remove material with diameter >2 mm, and stored in air-tight plastic boxes until analysis. Organic matter content was determined by oxidation with potassium dichromate (Jackson, 1958). Total nitrogen was determined by micro-Kjeldahl automatic analyser using the Bremner method (Black *et al.*, 1965). Ammonium and nitrate nitrogen were extracted with 2 M KCl solution and determined by steam distillation by micro-Kjeldahl automatic analyser using the

Bremner method (Black *et al.*, 1965). Available phosphorus was determined colorimetrically according to method of Olsen and Dean (Black *et al.*, 1965). The exchangeable cations were extracted with 1 M ammonium acetate solution (Peech, 1954), and their contents were determined by flame atomic absorption spectrophotometry. These results are expressed in percentage of exchangeable cations with respect to the cation exchange capacity (CEC), to allow comparisons between different sampling periods. The CEC was determined according to the method of Bower *et al*. (1952).

The sediments and runoff generated from each rain event were quantified for all plots. The same methods described for the soil samples were applied to the collected sediments.

Statistics

Soil data were analysed by two-way analysis of variance (ANOVA) with sampling period (before or after fires) and fire treatment as the main effects. When main effects were significant ($p<0.05$) we used Tukey's test to compare the treatments.

Soil losses and runoff production data were analysed by ANOVA with repeated measures. These variables were measured after each rainfall event on the same experimental units. This design provides a control on the differences among units. Fire treatment was the grouping factor (between- subject effect) and the rainfall events were the repeated measures for each case, which vary within the grouping factor. When significant differences were detected among means, the minimum significant difference for the individual effects and their interaction was calculated using Tukey's test.

Results and discussion

Changes in soil organic matter and soil nutrients after fire

Progression of the fire on the plots was, in general, fairly uniform. The mean duration in the soil of temperatures greater than 100ºC was 17.6 minutes for F1 treatment, and 36.3 minutes for F2 treatment. Assuming that the temperature measured with one iron rod corresponds to 1 m^2 of the plot surface, we found that on the F1 plots 50% of their surface had temperatures between 200ºC and 400ºC (mean value 232ºC), whereas on the F2 plots more than 50% of the surface had temperatures between 400ºC and 600ºC (mean value 439ºC). Taking into account these results, we have considered that F2 plots suffered a high fire intensity and the F1 plots suffered a fire of moderate intensity.

Table 2 records the values of the soil variables before the fire. Immediately after the fires significant variations were observed for the variables studied, which can be related to fire intensity (Table 2).

Fire caused a sharp increase of soil ammonium-N on both fire intensities, but it was more accentuated for the high intensity (25 times greater than before burning). This result accords closely with those reported by other authors (Díaz-Fierros *et al.*, 1990; Giovannini & Lucchesi, 1993). The increase in ammonium-N is attributed to the transformation of organic matter, which occurs at temperatures greater than 210ºC. Soil nitrate-N decreased after burning (Table 2). Díaz-Fierros *et al.* (1990) and Wienhold &

Klemmedson (1992) similarly found a decrease in nitrate contents between 0.5 and 0.3 of the original quantity.

Available phosphorus concentrations increased markedly as a result of the fire, especially under the most intense one (Table 2). The increase of 55 mg kg^{-1} of available P for the F2 treatment and 32 mg kg^{-1} for F1 was induced mainly by combustion of soil organic matter and mineralization as consequences of the high temperatures.

The exchange complex in the calcareous soil of La Concordia is dominated by Ca^{2+} and Mg^{2+}. The exchangeable cations Na^{+}, K^{+} and Mg^{2+} increased as a result of the fires (Table 2), presumably because of their presence in the ash. However, the exchangeable Ca^{2+} decreased significantly after the fire for both intensities (Table 2), approximately in the same proportion (19% and 17%) as the reduction in the CEC.

We did not expect this result, because the temperature at which inorganic calcium volatilises is more than 1400ºC (Weast, 1980), although the temperatures required for volatilize cations bound in organic compounds may be significantly less (Raison *et al.*, 1985). Thus, it is possible that a fraction of calcium bonded to soil organic matter had been volatilized where soil surface temperature reached values greater than 677ºC, whereas other calcium fractions, in a chemically altered form, remained in the soil.

Water erosion effects

A total of 31 erosive rain events producing runoff were recorded for the complete study period, from August of 1995 to December of 1996 (Figure 1). Seven of them, the ones labelled in Figure 1, produced the greatest runoff and sediment transport, and we selected them for this study. The first five events occurred consecutively after the experimental fires to the end of 1995 (Figure 1). The other two occurred in 1996 and produced the greatest losses of soil. The characteristics of these events are listed on Table 3. The maximum volume of precipitation registered in 30 minutes (I_{30}) of these events ranged from 10.92 mm h^{-1} to 35.36 mm h^{-1}. Only four other rain events reached an I_{30} between 10 and 15 mm h^{-1} during the study period, but none of these produced enough sediment to be analysed.

Table 4 records the effect of the fire intensity on runoff and sediment production. The unburned plots generated the least runoff and lost the least soil. As an estimation of erosion impact, mean runoff and sediment yield on this plots, corresponding to the seven rainfall events were 2.1 L m-2 and 0.007 kg m^{-2}, respectively. In these plots, runoff generation was on average of 86% less than for the most intense fire and 82% less than for moderate fire. Likewise, there was 98% less sediment lost from the control plots after burning. This effect was accentuated after autumn rain, as observed by other authors working in Mediterranean areas (Giovannini & Lucchesi, 1993; Andreu *et al.*, 1996).

Figure 2 shows the mean values of runoff yield and sediment yield for the different fire treatments by each rainfall event. From the second rain event of 18 September 1995 to the last event recorded (6 December 1996) there are significant differences in runoff generated and sediment transported between the burned and unburned plots. In the plots subjected to the moderate fire, mean runoff yield was 12.1 L m^{-2} (6 times greater than for the control plots), and the mean sediment yield was 0.33 kg m^{-2} (46 times greater than for the control plots). The plots that suffered the high fire intensity produced mean runoff and sediment yield of 15.4 L m^{-2} and 0.41 kg m^{-2}, respectively. These values are about 1.2 times greater than those measured for the moderate fire intensity plots. This shows the significant differences between plots affected by fire and those unaffected in their response to water erosion processes.

Generally, the more intense fire resulted in the larger runoff and the greater loss of soil than the moderate fire (Table 4). The latter generated on average, 21.60% less runoff and 19.55% less sediment than the former. However, an inverse trend happened during the three rainfall events immediately after the fire. The cover given by the accumulation of ashes and partly burnt plant material, the decrease in soil porosity and the possible formation of a subsurficial hydrophobic layer in the soil could reduce infiltration, and favour runoff generation on the moderate fire intensity plots, as observed previously by DeBano (1971) and Mallik *et al*. (1984).

Application of ANOVA with repeated measures on the runoff and sediment yield data shows that there are statistically significant differences in these variables for fire treatment and for the interaction 'rain x fire' (Tables 5 and 6).

Organic matter and nutrient losses by water erosion after fire

The total content of organic matter in the sediments for the seven rainfall events was 9.72 kg from treatment F2, 8.78 kg for F1, and only 0.072 kg for the control plots. These amounts represent an organic matter loss of 39.91, 36.65 and 0.54 g m^{-2} for the three treatments (Table 7). The overall loss of nitrogen was greater for treatment F2 than for F1 (Table 7), representing a loss per unit area of 1.59 and 1.46 g N m^{-2}, respectively. In the control plots, the total N content in the sediments was significantly less at 0.023 g m^{-2}. The greatest losses of organic matter and total nitrogen occurred during the second rainfall event on 18 September (Figure 3).

The losses of both forms of mineral N in the eroded sediments of F1 plots are greater than for F2 (Table 7). This could be due to the differences in N volatilization during combustion. Mean soil temperature of the moderate fires was 240ºC, which is enough to volatilize N and to decompose nitrate (Raison, 1979). Nevertheless, the N lost by volatilization in these plots was less than for the intense fires. Chemical analysis of the ashes supports this, as the ashes of the moderate fire are richer in NH_4^+ (average value 51.7 mg N kg^{-1}) than in the ashes from the intense fire (35.7 mg N kg^{-1}). Thus, the proportion of these ash particles removed with soil by erosion could cause the greatest loss of NH_4^+ after the moderate fires.

In both fire treatments, the losses of ammonium N were greater than the losses of nitrate N. In treatment F2, rain on 18 September (II) 1995 and 6 May 1996 produced the greatest losses, between 2.2 and 2.4 mg N m^{-2} (Figure 4a). The greatest losses of nitrate N correspond to the last rainfall event (6 December 1996), with 2.3 mg N m^{-2} (Figure 4b). The losses of both forms of mineral N in the control plots were trivial compared with the losses from the burned plots.

The enrichment in mineral N in the sediments from burned plots is related to the increase or decrease of the mineral N concentration in the soil. After the intense rains of autumn (four months after the experimental fires), there was a sharp decrease in ammonium-N in the soil. This decrease was 73% in treatment F2 and 84% in F1. In contrast, increases of 88% and 64% in nitrate-N concentrations in the soil of treatments F2 and F1, respectively, were recorded 4 months after the fire respect to their levels immediately after burning. Thus, the dominance of ammonium or nitrate remaining in the soil results from their losses by erosion and appearing in the sediments.

Total loss of available phosphorus in the eroded sediments from the treatment F2 was, approximately, twice that lost from F1 (Table 7). Both were much larger than from the control plots. The greatest losses of available P occurred in the rainfall event of 18 September (II) (Figure 5). Further differences were maintained until the end of the study.

The losses of exchangeable cations showed the same trend as for other variables. Those for K^+ and Mg^{2+} of treatment F2 were approximately, twice the ones for F1 (Table 8). The greatest losses on all exchangeable cations correspond to the rainfall event of 18th September (II) (Figures 6 and 7).

Net balance

A net loss of organic matter, total N, nitrate-N and exchangeable Ca^{2+} occurred under treatment F2, which seems mainly due to the high soil temperatures generated, rather than to the overall losses of these compounds produced by erosion (Table 8). Only losses of nitrate-N and Ca^{2+}, due to combustion, were detected in the plots that had the moderate fire, and they were always less than those observed after the more intense fire (Tables 8 and 9). The most notable difference observed, immediately after the fires, is the increase in 8091 kg ha^{-1} organic matter and 76.12 kg ha^{-1} total N for the moderate fire plots, whereas for the high intensity plots there was a decrease of organic matter (942.5 kg ha^{-1}) and total N (58.0 kg ha^{-1}) (Tables 8 and 9). The increase in organic matter and nitrogen after the moderate fire is attributable to the low combustion of the organic matter due to the short duration of high temperatures on the soil surface and to the deposition of partially burnt plant residues, as mention Andreu *et al.* (1996) and Giovannini & Lucchesi (1997).

The overall soil losses by erosion during the seven rainfall events were 4.1 t ha^{-1} for the plots in treatment F2, and 3.3 t ha^{-1} for F1 plots. The losses of organic matter and nitrogen in the sediments are reported in Tables 8 and 9. The greatest losses occurred after the intense fire.

Considering the changes in the amounts of organic matter and nutrients, immediately before and after fire, together with the losses produced by erosion, we estimated the inputs and outputs to the soil system, as follows. There was a net loss of 1341 kg ha^{-1} organic matter and 73.97 kg ha^{-1} of total N for the intense fire treatment (Table 8), and for the moderate fire, an input of 7724 kg ha^{-1} organic matter and 61.5 kg ha^{-1} total N (Table 9). In both treatments there was a net loss of nitrate-N, whereas for ammonium-N there was a net gain (Tables 8 and 9). These variations in mineral N contents are strongly related to the intensity of fire.

We did not consider nutrient losses as soluble elements in runoff water in the balance because they were much smaller than the losses in the sediments. For example, we measured a maximum loss of water-soluble mineral N of 3.11 mg kg^{-1} in the high intensity plots for the rainfall of 6 May 1996 compared with 37.2 mg kg^{-1} in the eroded sediment. Other authors found that the soluble forms of these elements in runoff water represent only 1.5% of the total losses (Soto *et al.*, 1995).

Net inputs of available phosphorus and exchangeable cations, except Ca^{2+} to the soil system are estimated for both fire treatments (Table 8 and 9). Exchangeable Ca^{2+}

shows a net loss of 598.4 and 497.2 kg ha^{-2} for the high and moderate fire intensity plots, respectively.

These results accord well with the data reported by several authors (Giovannini *et al*., 1990; Soto *et al*., 1995; Andreu *et al*., 1996), and they confirm that the modifying processes occurring in the soil, and the increase in erosion rates and nutrient losses are related mainly to the intensity of fire.

Conclusions

Fire caused an increase of ammonium N, available phosphorus and Na^+, K^+ and Mg^{2+} on the soil surface, whereas the nitrate-N content, the CEC and the exchangeable Ca^{2+} in the soil decrease after both intense and moderate fire. The combustion caused the losses of organic matter, total N, nitrate N and exchangeable calcium in the most intense fire.

Organic matter and nutrients removed with the sediments are closely related to the degree of fire intensity. Soil lost by water erosion took with it organic matter and nutrients. Four months after the fires, a sharp decrease of these constituents in the soil was recorded, which coincides with the highest soil losses produced by the most erosive rainstorms. In a unique rainfall event (18 September, I_{30} 35.36 mm h^{-1}), the greatest losses of organic matter and nutrients were detected, which represent around 50% of the total losses from the burned plots for the whole study period.

The calculated net balances show a net loss of organic matter and total nitrogen for plots burned with the most intense fire, whereas an increase in these variables occurred on plots having fire of moderate intensity. Both fire treatments show a net loss of nitrate-N and exchangeable Ca^{2+}, whereas an increase of ammonium-N, available phosphorus and the other cations was found.

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Table 1 Weather at the time of burning

Date	Burned plots	Air temperature / ºC	Relative humidity / %	Wind direction	Wind speed / m s^{-1}
20 June 1995	1	21	71	SE	0.3
	2	22	71	SE	0.3
	4	20	85	SE	0.3
21 June 1995	6[a]	24	79	SE and SW	0.3 - 1.4
	7	22	82	SE	0.3
	8	22	83	Se	0.3

[a] Plot number 6 suffered repeated changes of speed and wind direction when burning

Table 2 Mean values of soil variables for the different treatments, before and after fire

	Before fire				After fire[a]			
Variable	High	Moderate	Control	Standard error	High	Moderate	Control	Standard error
Organic matter /%	11.47	9.28	10.15	1.21	11.21 a	11.52 a	10.15 a	1.02
Total N /%	0.43	0.38	0.44	0.04	0.42 a	0.40 a	0.44 a	0.03
NH_4^+-N /mg kg^{-1}	3.54	4.71	2.16	0.09	87.27 c	52.36 b	2.16 a	0.98
NO_3^--N /mg kg^{-1}	27.39	26.72	19.39	0.75	7.59 b	15.96 b	19.39 a	0.51
$P_{available}$ /mg kg^{-1}	11.62	6.41	8.08	0.21	66.44 c	38.34 b	8.08 a	1.13
CEC /cmol$_c$ kg^{-1}	31.25	28.83	27.15	1.81	25.23 b	24.98 b	27.15 a	2.02
Na^+ /%	1.51	2.00	1.09	0.57	4.84 b	5.54 b	1.09 a	0.69
K^+ /%	4.43	4.75	4.63	0.51	8.34 b	8.139 b	4.63 a	1.01
Mg^{2+} /%	13.67	12.47	12.79	1.32	18.50 b	16.34 b	12.79 a	1.83
Ca^{2+} /%	80.39	80.79	81.48	1.72	68.32 b	69.94 b	81.48 a	3.40

[a] Means not sharing the same letter indicate significant differences for the different fire treatment judged using Tukey’s test ($p < 0.05$)

Table 3 Characteristics of the rainfall events

Data	Days after fire	Precipitation /mm	Duration /minutes	I_{30} /mm h^{-1}
23 Aug 1995	63	26.26	90	20.80
31 Aug 1995	71	9.36	285	14.56
18 Sep 1995 (I)	88	7.54	135	10.92
18 Sep 1995 (II)	88	18.72	95	35.36
4 Oct 1995	104	22.62	280	22.40
6 May 1996	316	22.62	165	26.00
6 Dec 1996	526	26.10	210	30.20

Table 4 Mean values of runoff (l) and sediment (kg) production of the selected rain events for each fire intensity treatment and general mean of runoff yield (l m^{-2}) and sediment yield (kg m^{-2})

	Runoff				Sediment			
Data	High	Moderate	Control	Standard error	High	Moderate	Control	Standard error
23 Aug 1995	16.4	28.2	15.2	5.8	0.27	0.89	0.21	0.3
31 Aug 1995	6.7	10.6	3.6	2.3	0.08	0.19	0.03	0.04
18 Sep 1995 (I)[a]	8.9	12.2	3.8	4	0.04	0.08	0.01	0.03
18 Sep 1995 (II)[a]	312.2	267.6	21.4	38.3	14.9	12.6	0.08	4
4 Oct 1995	249.2	242.8	36.9	34.4	4.81	4.73	0.03	1.2
6 May 1996	289.6	198.8	41.2	37.8	7.43	4.98	0.15	2
6 Dec 1996	350.9	210.2	44.3	64.8	5.05	2.76	0.08	1.2
General mean	176.3	138.6	24.5		4.66	3.75	0.08	
General yield mean	15.4	12.1	2.14		0.41	0.33	0.01	

[a] (I) and (II) are two different rain events on the same day

Table 5 Analysis of Variance with repeated measures for the runoff yield

a) Tests of Between-Subject Effects

Source of variation	df	MS	F	Probability
Fire treatment	2	22.448	18.526	0.003
Error	6	1.212		

b) Tests involving ‘rainfall event’ Within-Subject Effect

Source of variation	df	MS	F	Probability
Rainfall event	6	11.98	55.015	0.000
Rainfall x fire treatment	12	2.429	11.152	0.000
Error	36	0.218		

Table 6 Analysis of Variance with repeated measures for the sediment yield

a) Tests of Between-Subject Effects

Source of variation	df	MS	F	Probability
Fire treatment	2	19262.6	8.172	0.019
Error	6	2357.1		

b) Tests involving ‘rainfall event’ Within-Subject Effect

Source of variation	df	MS	F	Probability
Rainfall event	6	14898	28.74	0.000
Rainfall x Fire treatment	12	3936	7.59	0.000
Error	36	518.28		

Table 7 Total losses of organic matter and nutrients per unit area by water erosion

	Fire treatment			
	High intensity	Moderate intensity	Control	Standard error
Organic matter /g m^{-2}	39.91	36.65	0.59	0.49
Total N /g m^{-2}	1.59	1.46	0.023	0.02
NH_4^+ -N /mg m^{-2}	7.13	8.12	0.214	0.14
NO_3^- -N /mg m^{-2}	4.82	7.45	0.146	0.23
$P_{\text{available}}$ /mg m^{-2}	24.17	11.70	0.137	0.44
Na^+ /mg m^{-2}	17.38	12.37	0.067	0.22
K^+ /mg m^{-2}	178.50	103.93	0.421	3
Mg^{2+} /mg m^{-2}	143.75	77.94	0.295	2.17
Ca^{2+} /g m^{-2}	3.95	3.25	0.018	0.05

Table 8 High fire intensity plots. Mean contents of organic matter and nutrients in the soil (kg ha^{-1}) before and after fire; gains or losses due to combustion processes (kg ha^{-1}); losses by transported sediment (kg ha^{-1}) for the seven rainfall events; net balance in the soil system (kg ha^{-1})

	High fire intensity					
	Soil [a]		Combustion		Sediment	Net balance [b, c]
	Before fire	After fire	Gains	Losses	Losses	
Organic matter	41 597	40 654	-	942	399	(-) 1 341
Total N	1 566	1 508	-	58.0	15.9	(-) 73.9
NH_4^+ -N	1.28	31.6	30.3	-	0.07	(+) 30.2
NO_3^- -N	9.93	2.75	-	7.18	0.04	(-) 7.22
$P_{available}$	4.21	24.1	19.9	-	0.24	(+) 19.6
Na^+	39.2	98.4	59.2	-	0.17	(+) 59
K^+	196	294	98	-	1.78	(+) 96.2
Mg^{2+}	188	202	14.2	-	1.44	(+) 12.7
Ca^{2+}	1 821	1 271	-	550	39.5	(-) 589

[a] Soil density of the first 5 cm of soil was used for calculation (0.725 g cm^{-3})

[b] Inputs (+)

[c] Outputs (-)

Table 9 Moderate fire intensity plots. Mean contents of organic matter and nutrients in the soil (kg ha^{-1}) before and after fire; gains or losses due to combustion processes (kg ha^{-1}); losses by transported sediment (kg ha^{-1}) for the seven rainfall events; net balance in the soil system (kg ha^{-1})

	Moderate fire intensity					
	Soil [a]		Combustion		Sediment	Net balance [b, c]
	Before fire	After fire	Gains	Losses	Losses	
Organic matter	33 662	41 752	8 091	-	366	(+) 7 725
Total N	1 377	1 454	76.1	-	14.6	(+) 61.5
NH_4^+ -N	1.70	19.0	17.3	-	0.08	(+) 17.2
NO_3^- -N	9.68	5.78	-	3.90	0.07	(-) 3.97
$P_{available}$	2.32	13.9	11.6	-	0.12	(+) 11.7
Na^+	48.1	109	61	-	0.12	(+) 61.1
K^+	194	267	73	-	1.04	(+) 71.9
Mg^{2+}	158	172	14	-	0.78	(+) 13.2
Ca^{2+}	1 689	1 224	-	465	32.5	(-) 497.5

[a] Soil density of the first 5 cm of soil was used for calculation (0.725 g cm^{-3})

[b] Inputs (+)

[c] Outputs (-)

Figure captions

Figure 1 Quantity and intensity (I_{30}) of rain of each erosive rainfall event for the studied period

Figure 2 Mean values of (a) runoff yield and (b) sediment yield registered in ‘La Concordia’ plots for the different fire treatments by each studied rainfall event. Mean values not sharing the same letter indicate significant differences for the interaction ‘tratment x rainfall’ using Tukey’s test.

Figure 3 Organic matter (a) and total N (b) losses per unit area in each studied rainfall event

Figure 4 Ammonium-N (a) and nitrate-N (b) losses per unit area in each studied rainfall event

Figure 5 Available phosphorous losses per unit area in each studied rainfall event

Figure 6 Exchangeable Na^+ (a) and exchangeable K^+(b) losses per unit area in each studied rainfall event

Figure 7 Exchangeable Mg^{2+} (a) and exchangeable Ca^{2+}(b) losses per unit area in each studied rainfall event

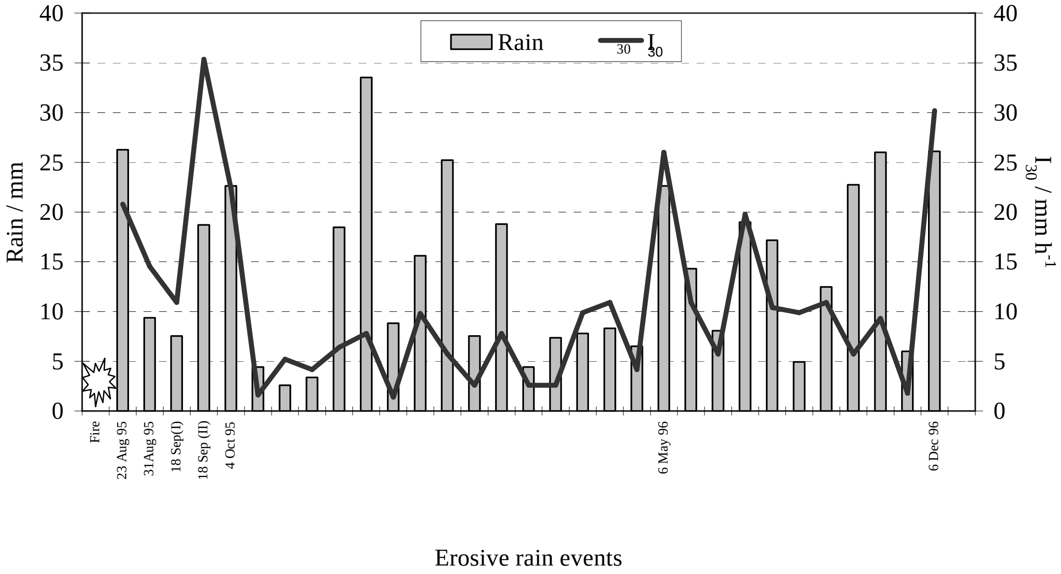
Rain
I30
Rain / mm
I30 / mm h-1
40
35
30
25
20
15
10
5
0
Fire
23 Aug 95
31Aug 95
18 Sep(I)
18 Sep (II)
4 Oct 95
6 May 96
6 Dec 96
Erosive rain events

Fig. 1

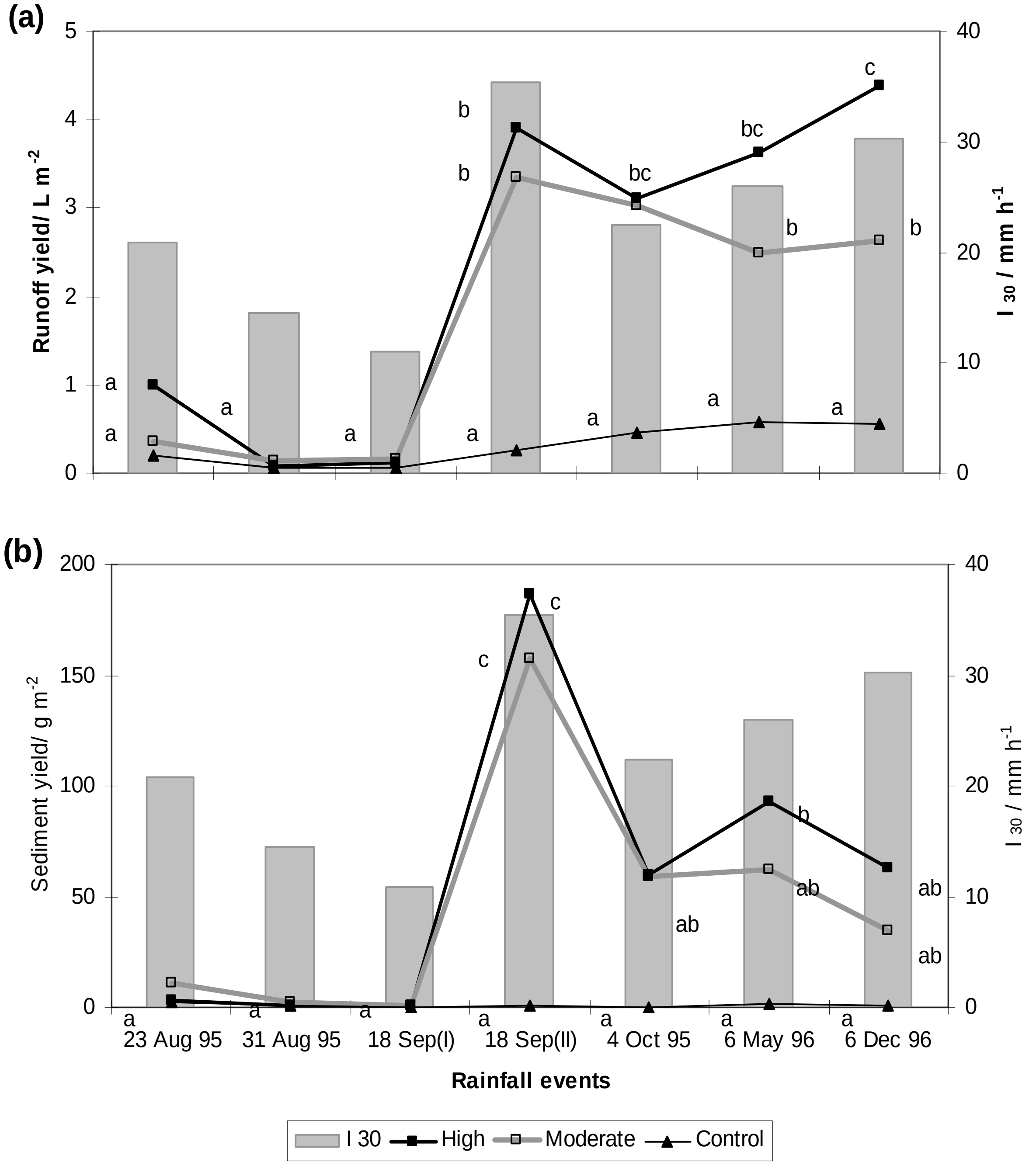
(a)
Runoff yield/ L m^{-2}
I $_{30}$ / mm h^{-1}
0
1
2
3
4
5
0
10
20
30
40
a
a
a
a
a
a
b
b
a
bc
bc
a
bc
b
a
c
b
(b)
Sediment yield/ g m^{-2}
I $_{30}$ / mm h^{-1}
0
50
100
150
200
0
10
20
30
40
c
c
b
ab
ab
ab
ab
a
a
a
a
a
a
a
23 Aug 95
31 Aug 95
18 Sep(I)
18 Sep(II)
4 Oct 95
6 May 96
6 Dec 96
Rainfall events
I 30
High
Moderate
Control

Fig. 2

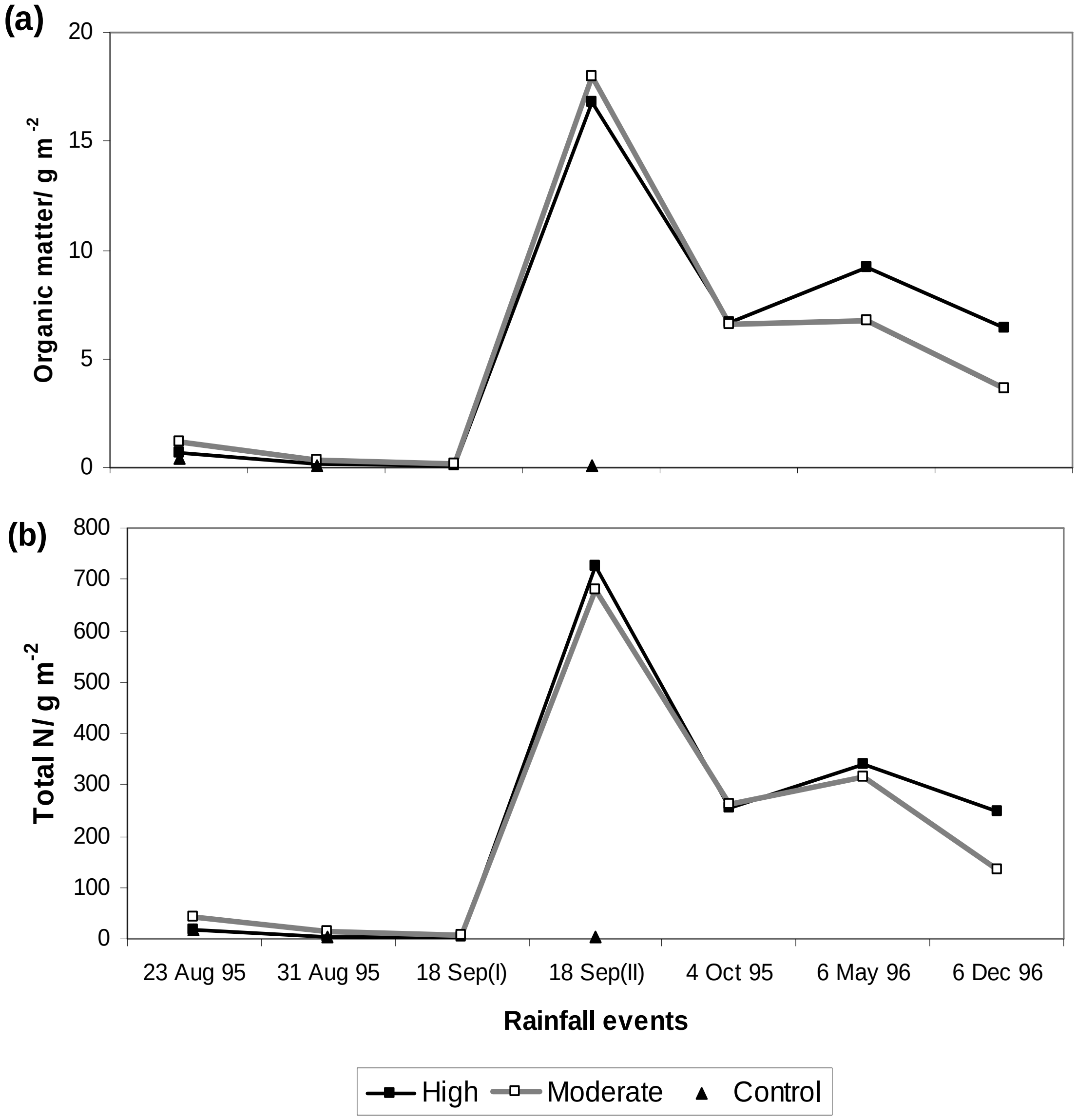
(a)
20
15
10
5
0
Organic matter/ g m $^{-2}$
(b)
800
700
600
500
400
300
200
100
0
Total N/ g m $^{-2}$
23 Aug 95
31 Aug 95
18 Sep(I)
18 Sep(II)
4 Oct 95
6 May 96
6 Dec 96
Rainfall events
High
Moderate
Control

Fig. 3

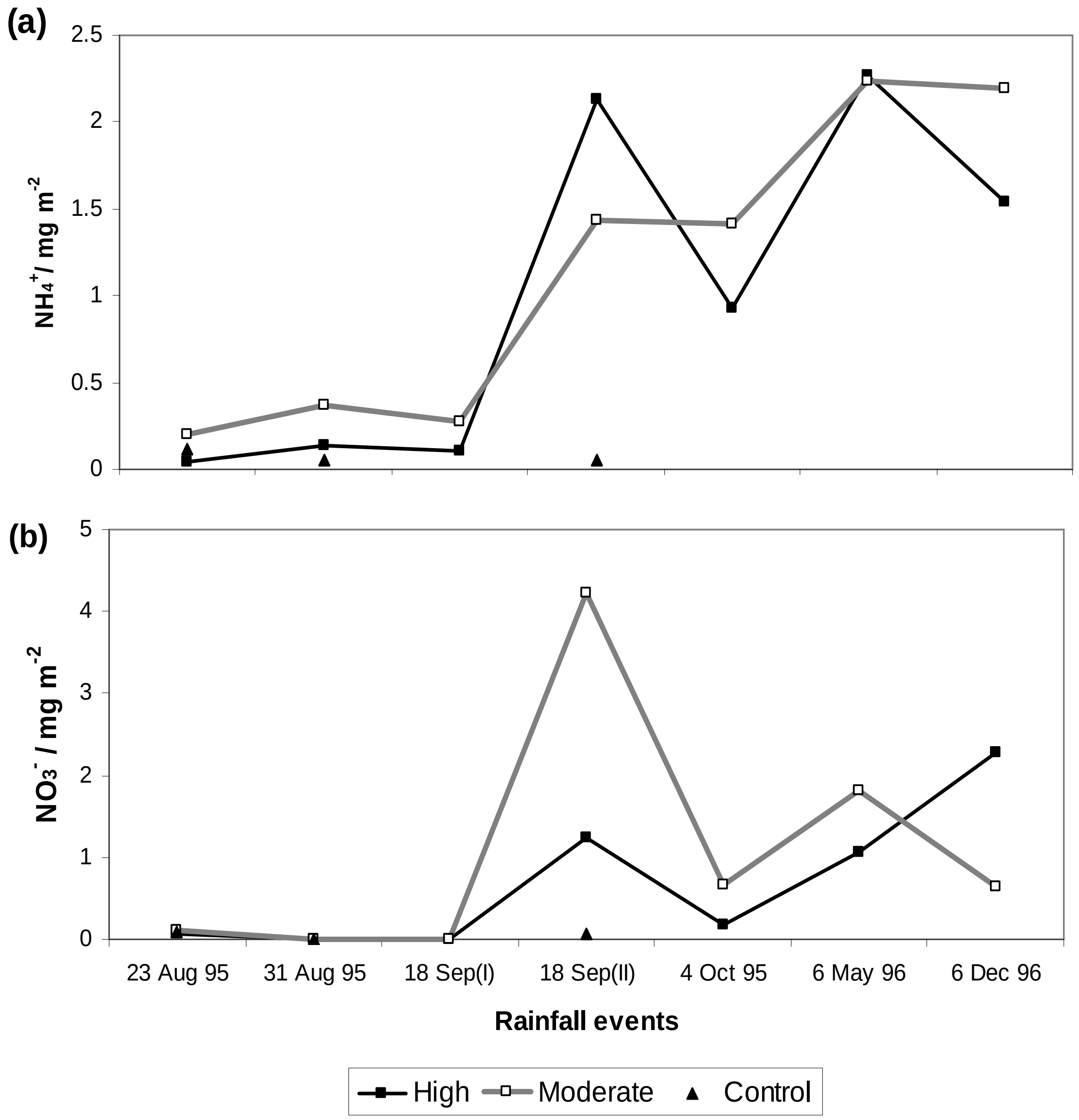
(a)
2.5
2
1.5
1
0.5
0
NH4+/ mg m-2
(b)
5
4
3
2
1
0
NO3- / mg m-2
23 Aug 95
31 Aug 95
18 Sep(I)
18 Sep(II)
4 Oct 95
6 May 96
6 Dec 96
Rainfall events
High
Moderate
Control

Fig. 4

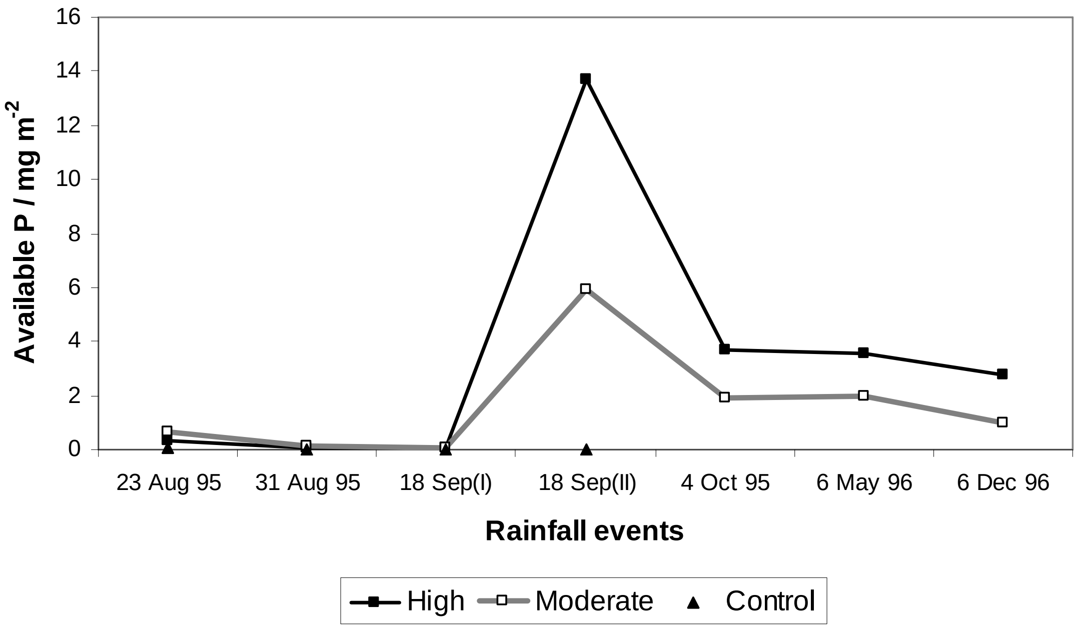
16
14
12
10
8
6
4
2
0
Available P / mg m^{-2}
23 Aug 95
31 Aug 95
18 Sep(I)
18 Sep(II)
4 Oct 95
6 May 96
6 Dec 96
Rainfall events
High
Moderate
Control

Fig. 5

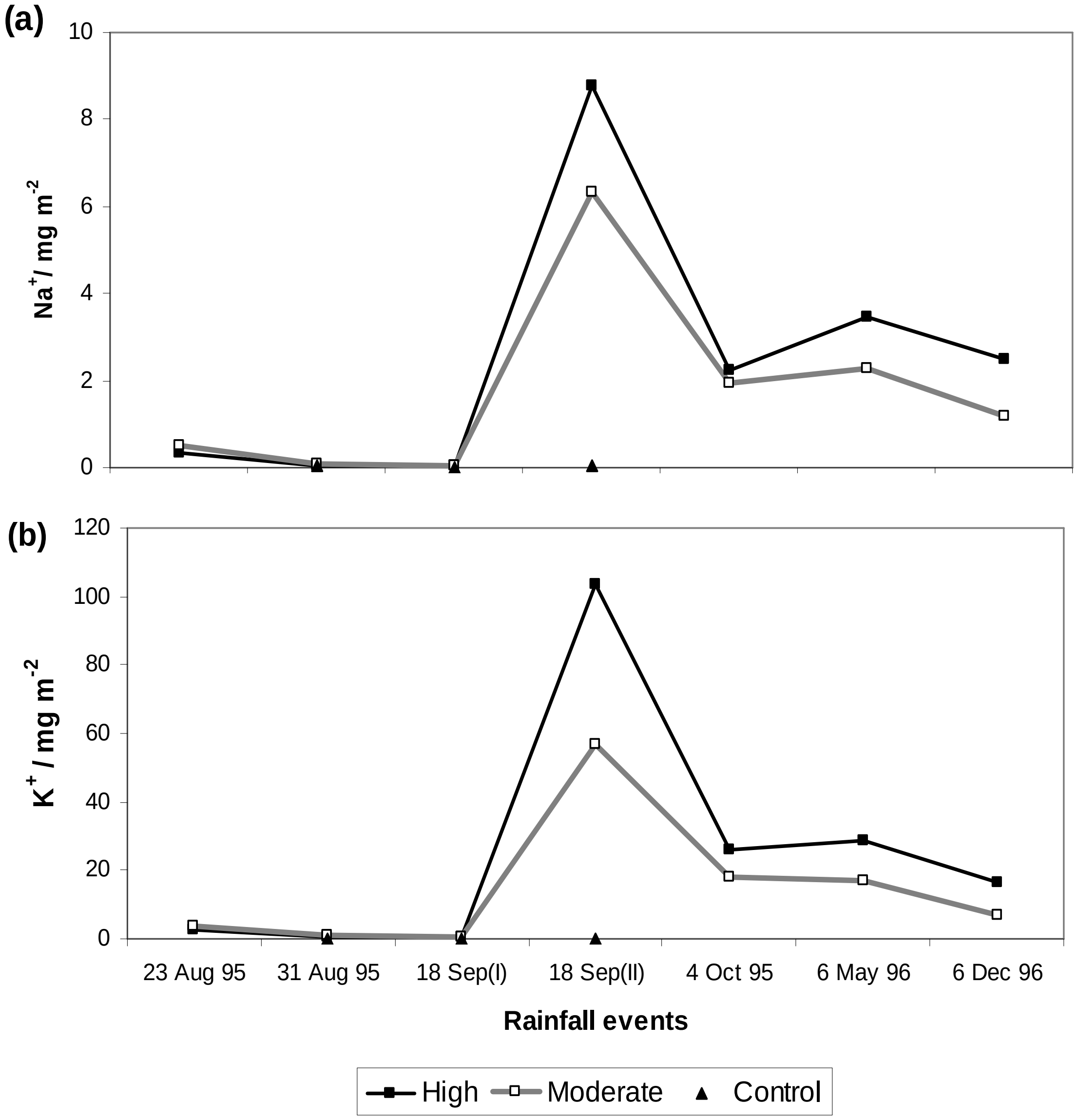
(a)
Na$^+$ / mg m^{-2}
0
2
4
6
8
10
(b)
K$^+$ / mg m^{-2}
0
20
40
60
80
100
120
23 Aug 95
31 Aug 95
18 Sep(I)
18 Sep(II)
4 Oct 95
6 May 96
6 Dec 96
Rainfall events
High
Moderate
Control

Fig. 6

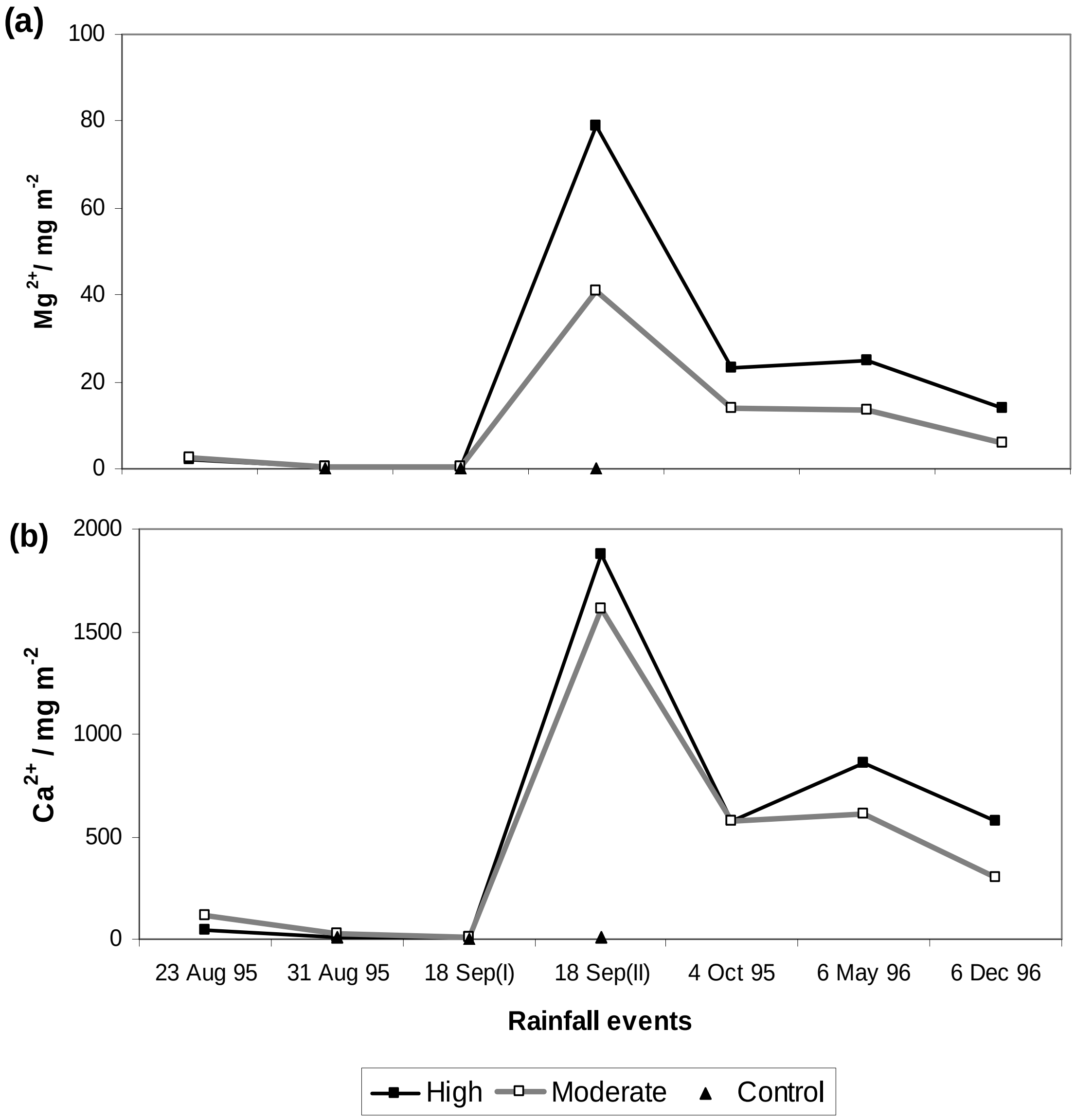
(a)
100
80
60
40
20
0
Mg2+/ mg m-2
(b)
2000
1500
1000
500
0
Ca2+ / mg m-2
23 Aug 95
31 Aug 95
18 Sep(I)
18 Sep(II)
4 Oct 95
6 May 96
6 Dec 96
Rainfall events
High
Moderate
Control

Fig. 7