LONG TERM ASSESSMENT OF FOREST FIRE IMPACTS AS A CRUCIAL KNOWLEDGE TO DESIGN AFTER-FIRE MANAGEMENT POLICIES

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Abstract
Forest fires have become of great concern at a world-wide level during the last decades, being alarming in the Mediterranean areas. The development of new policies on fire management and ecosystems restoration would be impossible without a sound basis of knowledge about fire effects on the land and their response to those impacts. The most effective way to reach this objective is with the study and treatment of long temporal data series obtained by the scientific assessment of the different parameters involved in this phenomenon. The study and application of experimental fires performed in Permanent Experimental Field Stations is one of the better sources to reach this information. With this objective, two permanent field stations were established on typical Mediterranean forest areas: Porta-Coeli (Serra) and La Concordia (Lliria), both located in Valencia (Spain). The first of them is in function since 1988 and the station of La Concordia since 1995.

In these stations, several experimental fires have been performed, to study the impact of different fire intensities on soil erosion processes and the ecosystems recovery. Experimental fires were performed in 1995 and 1996 in the station of Porta-Coeli and La Concordia, respectively. In this last one, other experimental fires were performed in 2003 to study the effect of repeated fires on the recovery processes of soil and vegetation.

Additional Keywords: soil characteristics, water erosion, fire intensity, repeated fires, field stations, soil loss, runoff generation.

Introduction
Forest fires, during centuries have played an important role in the ecosystems configuration of the world, but in the Mediterranean areas (Australia, California, the Mediterranean basin, Chile, Anatolia, etc.) has become a key phenomenon in the ecosystems survival and in the advance of Desertification. This phenomenon becomes extremely important in these areas where the continuous and repeated impact of fires, reducing progressively the recovery periods for the ecosystems, together with the incidence of torrential rains immediately after the fire season (Summer) that are characteristic of this zones, favours the intensification of the erosive processes (Giovannini *et al.* 1990; Andreu *et al*. 1996).

There is an important lack of knowledge about the course of the ecosystems and their response to the water erosion processes during long data periods, mainly after forest fires, which makes necessary the achievement of long temporal data series under natural conditions to understand the soil, ecosystems or climatic trends and their response to the erosive processes. This information is essential in the development of reliable mathematical models, to know and predict the incidence and evolution of the different fire impacts, and in the development of effective after-fire policies and strategies to relieve the ecosystem degradation processes and reach its recovery. In this sense, the establishment of permanent experimental field stations is an important tool to the continuous study and monitoring the impact of fire on water erosion, and to obtain long temporal series of data. By the other hand, to obtain a deeper knowledge on fire course and effects, the use of experimental fires allows controlling the main environmental parameters and fire characteristics before, during and after the fire event.

This work reflects some results in the study of the temporal evolution of soil and vegetation after the impact of fires of different intensities, and the incidence of water erosion processes, on a typical Mediterranean forest area by means of the use of two permanent field stations (Porta-Coeli and La Concordia) joined with the performance of experimental fires. In La Concordia station the incidence of repeated fires was also studied.

Materials and Methods
Field sites description
Porta-Coeli Experimental Station
The experimental station located near Porta-Coeli (Valencia, Spain) on a SW-facing forest hillside with scrub cover developed after a fire, which had occurred 14 years previously. It is characterized by shallow soils of Rendzic

Leptosol type according to the FAO Classification (1988). On the study slope there are frequent outcrops of highly variable consolidated conglomerate material with around 40% of stoniness. Annual precipitation of the zone is around 425 mm, and the mean annual temperature is 17 ºC. The dominant vegetation type corresponds to the *Rosmarinus-ericion* association with *Rosmarinus officinalis L., Thymus vulgaris L., Stipa tenacissima L.* and *Chamaerops humilis L.* as the most abundant species

The set up consists of four plots of 40 x 8 m in a slightly concave hillside located at 220 m a.s.l., with a mean slope of 20%. The plots were located on a slope with soil, vegetation and landscape characteristic of a typical Mediterranean forest. Each plot is limited by long bricks with hydrophobic cover, following the direction of the slope in a rectangular pattern, finishing at their bases in 2m-wide collectors which run into a 2000 l tank to collect all the runoff and sediment produced in the rain events.

One of the plots maintained the natural vegetation recovered after the fire that took place 14 years before. This shrub cover showed a vigorous growth with 65% coverage of the soil surface, because of that it was selected to perform the experimental fire. The aim was to obtain a forest fire as similar as possible to that occurred in natural conditions. In other two plots the protective effect of restraining runoff and soil removal was tested on two foraging shrub species: *Medicago arborea L.* and *Psoralea bituminosa L*., and the remainder plot was left bare of vegetation.

La Concordia Experimental Station

It is located at 50 km NW of Valencia city. It is 575 m above the sea level (Figure 1), 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, abundant stoniness (≅ 40%) and good drainage. The main physical and chemical characteristics of the soils of both experimental stations are recorded in Table 1.

The station consists on a set of nine erosion plots, 4 m wide x 20 m long each, with similar characteristics such as soil morphology, slope gradient, rock outcrops and vegetation cover. The selection of each plot location was made after intensive surveys of the vegetation, soil and the morphology pattern, based on across slope transects every 2 m. 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 record all the runoff and sediment produced during each rainfall event. Inside them there is a 30 l tank to concentrate the sediments produced facilitating its collection. A random design of three different fire intensity treatments (with three plots each) was used. Two sets of three plots each were burned reaching high and moderate fire intensities, and the remainder three plots were maintained unburnt to be used as control treatment.

The experimental fires

In all plots on both experimental stations, an intensive survey of the presence and distribution of vegetation was made, in a 1 m x 1 m grid basis. It was used to calculate the spatial distribution of vegetation and the dry biomass present in each plot. This last parameter was estimated by using a non-destructive method (Etiene and Legrand, 1994). The existing biomass on the plot of Porta-Coeli selected to be burned was 21.2 t/ha, and in the plots of La Concordia it ranged from 5 to 8 t/ha.

In the station of La Concordia, a random design of two different fire intensity treatments, with three plots each, was used. One treatment corresponds to a high intensity fire; the second treatment was a fire of moderate intensity, and a third set of three unburned plots was used as a control. Contrasting amounts of fuel load, obtained from the surrounding shrub vegetation, were added to obtain the two fire intensity levels (40 t/ha for high intensity and 20 t/ha for moderate). The quantity of dry biomass necessary to obtain these two fire intensities was calculated considering the type of vegetation present in the plots.

Table 1. Soil characteristics of the studied sites.

	Porta-Coeli	La Concordia
Water retention capacity (%)[a]	30.00	30.83
Aggregate stability (%)[b]	30.75	32.95
pH	8.10	7.17
Electric Conductivity (dS/m)[c]	0.55	0.71
Total Carbonate Content (%)	33.85	43.01
Organic Matter (%)[e]	5.94	9.81
Clay (%)	7.40	7.52
Silt (%)	48.36	27.88
Sand (%)	44.24	60.84
Gravels (%)	38.95	30.45
Vegetation	Shrubs, Pine	Shrubs
Fire Intensity	Medium	Medium/High

Experimental fires were carried out on 20 and 21 June 1995 in La Concordia, and on 4 of December 1996 in Porta-Coeli. Immediately before and after fires, four soil samples were taken randomly in each plot of La Concordia and eight in those of Porta-Coeli. The mean soil surface temperatures reached in La Concordia station during the fires were 439ºC for high fire intensity plots and 232ºC for the moderate intensity ones (Gimeno-Garcia 2000). In the experimental fire of Porta-Coeli (1996) the average temperature reached on soil surface was around 121 ºC. In this case, 60% of the burned plot suffered temperatures between 60 and 172 ºC, which could be considered as a moderate-low intensity fire.

After the fires, the plots were left untouched allowing the natural regeneration of the vegetation cover, although continuing the monitoring of climatic and erosion parameters. Eight years later, in July 2003, the plots correspondent to the fire treatments of La Concordia station were burnt again but, in this case, all the plots in the same conditions. It was done in this way trying to reflect the actual situation, common in the Mediterranean countries, of the repeated incidence of fires on zones in recovering from previous ones. Only a constant quantity of biomass (2.5 T/ha) was added to each one of the plots to obtain continuity on the vegetation mass and thus favour the advance of the fire front. The average of the temperatures obtained in the surface of the plots reached around 160 ºC.

Analyses
Soil samples were air-dried, sieved to remove the fraction higher than 2 mm diameter and stored in plastic boxes until analysis. The standard laboratory methods for analysis were used to measure the main chemical and physical parameters of soil. The sediments and runoff generated in each rain event were quantified in all plots and analysed using the same methodology. Fire parameters, as temperatures, residence time, and their distribution, were measured by means of sensors (thermocouples) and thermo-sensitive paints.

Climatic parameters and the intrinsic characteristics of the different rainfall events were monitored by a logging system of sensors with GSM transmission of data, placed close to the plots. The complete runoff generation and sediment produced in the different plots in each rain event, during the studied periods, were collected. Statistical analysis of the data was done using classical statistics as ANOVA, Tukey's test, multiple correlations, etc.

Results and Discussion
From 1995, where the first experimental fire took place, until 2003 have been monitored in the stations of La Concordia and Porta-Coeli 557 and 772 rain events, respectively. The number of erosive rains, events with runoff production, has been higher in La Concordia, with 100 erosive rains relative to the 72 at Porta-Coeli. The characteristics of the erosive events recorded on it were less aggressive than for Porta-Coeli, being of lower average intensity and volume (Figure 1), but of longer duration.

Although, the differences in rain volume between stations were not statistically significant (< 3%), they remained almost constant during all the studied period. Maximum intensities of rain (I_{30}) correspond to Porta-Coeli (Figure 1) with 78.40 mm/h (31st July, 2002) with 34 episodes of more than 10 mm/h, while in the other station did not rise above 65.40 mm/h and only 27 were of intensities of more than 10mm/h. Other important factor is the duration of rains; those monitored in La Concordia were, generally, longer than in Porta-Coeli with average values of 9 h 42' and 7 h 29', respectively. In this case 33 erosive events showed more than ten hours of duration, but in Porta-Coeli, only 21 were registered. It could indicate a more permanent state of soil humidity in La Concordia soil, which would favor a quicker runoff development. This fact has been more patent during 2002 and 2003 where rains had a mean duration of 18 h 41' in La Concordia and only 7 h 28' in Porta-Coeli, reaching maximums of 90 h 50' (17th/21st April, 2003) and 23 h 18' (7th/8th October, 2002), respectively. Differences on rain characteristics and distribution have been translated in the response to the incidence of water erosion processes and in the recovery of the burned soils.

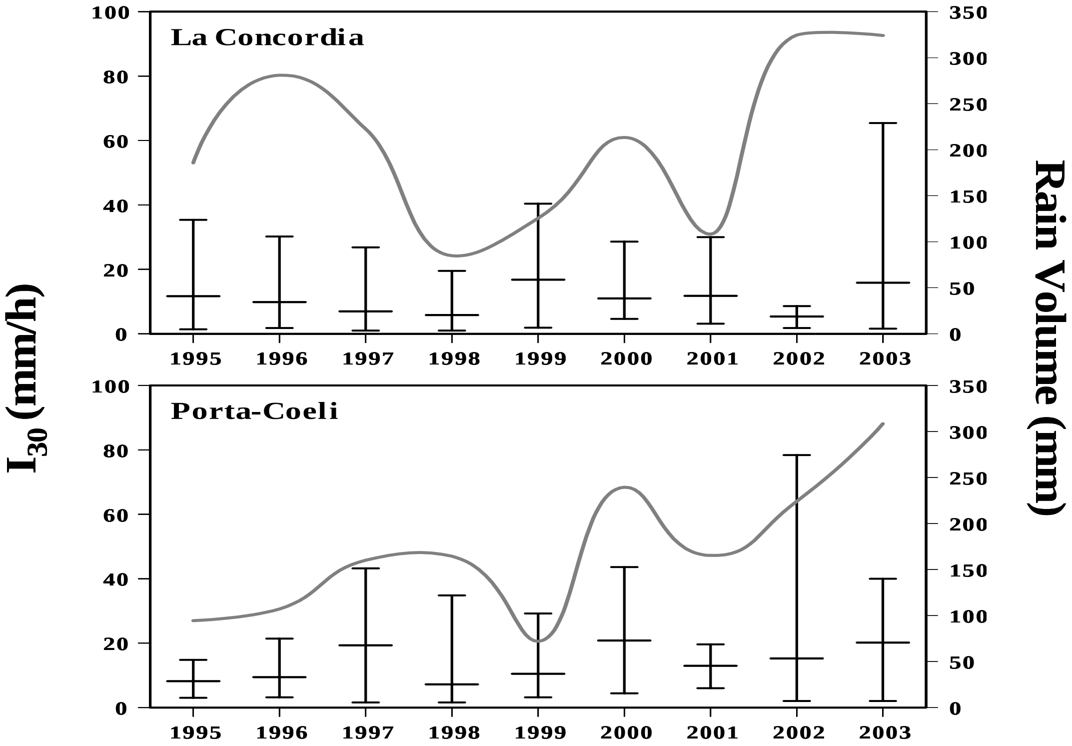

Figure 1. Annual volume and mean, maximum and minimum intensities of the erosive rains recorded in the experimental stations during 1995-2003.

In the station of La Concordia, immediately after the fire, was generated a 65.57% less runoff than in the same period of 2003 (Figure 2). The highest values for 1995 and 2003 were of 4.41 L/m^2 (plot 4, high intensity, 18th September) and 12.48 L/m^2 (plot 7, moderate intensity, 30th July), respectively. The lower intensity and volume of rains in 2003, with the circumstance that the first erosive rain after the fire of 1995 occurred almost two months later, allowing the soil some kind of stabilization. By the contrary, in 2003, the first erosive event was 10 days after fire and showed the highest intensity (65.40 mm/h). These facts could be responsible of this great variation on runoff production.

Differences between burned plots and the control ones, not burned, increase likewise from an average of 85.62 % after the fire in 1995 to 95.27 % in 2003. Although the dissimilarities among plots burned in 1995 with high intensity and those burnt with moderate one have not been statistically significant they increased in the five months after the fires from 5.22 % in 1995 to 12.74 % in 2003. It has been reflected in the values of infiltration rate that are lower in the moderate intensity plots (average of 9.34 mm/h) than in the others (10.11 mm/h on the high intensity treatment and 12.23 in the moderate one). Values of runoff coefficient reflected also this tendency, but in this case the differences were still lower.

The evolution of the hydrological response in the fire treatments during the studied period, after the incidence of fires, in 1995 and 2003, become more evident for soil losses. The great aggressiveness of rains observed in 2003, together with the earlier incidence of important erosive rains, have been translated in a global soil loss after the fire in that year almost double (88.56% higher) than in 1995 (Figure 2). Maximum values on sediment yield in 1995 and 2003 were of 293.51 g m^{-2} (plot 4, 18th September) and 367.019 g m^{-2} (plot 7, 30th July), respectively.

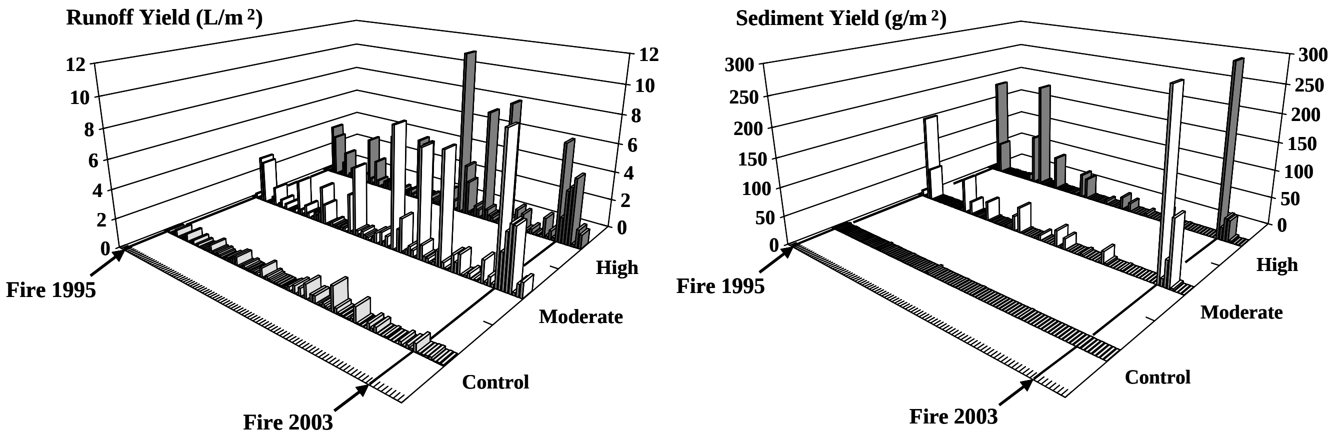

Figure 2. Runoff (L/m^2) and sediment (g/m^2) produced in each erosive event occurred in La Concordia experimental station.

Burned plots maintain in 2003 similar differences than those observed in the post-fire period of 1995, respect to the unburned ones, giving these lasts values around 99% lower. By the other hand, the differences between fire treatments increased and changed its tendency after the repeated fire. In 1995, during the five moths after the fire, plots burned with high intensity gave values 8.12 % higher than those burnt with moderate intensity, but in 2003 these values have been increased, giving the moderate intensity treatment until 26.81 % more sediment than the high intensity one. It has to be taken into account that the tendency to the equilibrium among the values corresponding to the plots of the different fire treatments, during the period previous to the fire in 2003, showed a difference of 11.53% but, after this they reached 21.19%.

Soil loss obtained for each treatment after the fire in 2003 reflects clearly the effect of repeated fires on soil erosion. It has been a total of 5.14 t ha^{-1} of soil loss in the moderate intensity plots and 4.05 t ha^{-1} in the high intensity ones, while in the control plots this loss only reached 0.007 t/ha. In 1995, after the fire, total soil losses in the moderate and in the high intensity treatments were 2.31 t/ha and 2.51 t/ha, respectively. In addition to that, the plots not affected by fire showed an important reduction on sediment yield (84.94 %) compared with its values of 1995. These values give an important indication of how adverse can be the incidence of repeated fires on zones in regeneration from a previous burning regards water erosion processes.

By the contrary, in the Porta-Coeli experimental station a fast recovery after the fire was observed. The incidence of a moderate-low intensity fire had a limited impact on soil characteristics and allowed the accumulation of residues of vegetation partially burned that helped to protect the soil surface against water erosion and provided an additional input of organic matter to soil, which is reflected in the values of runoff and soil losses of the burned plot in relation to the other plots, mainly respect to the bare one. Even after the fire this plot has continued giving lower values on runoff generation and soil loss that the control plot bare of vegetation (Figure 3). This degree of recovery has been favoured also by the fact that there were no very intense rain events in this zone until almost a year after the fire.

Soil losses in the burned plot have been always lower during the studied period then in the other ones, but mainly respect to the control plot (Figure 3). In 1997 the burned plot already gave 87.86% less sediment than the bare one, increasing this difference to 94.39% in 2003. The maximum values of soil loss during the studied period correspond to the rain of April 26th of 1998, which were 0.05 T/ha in the burned plot and 0.81 T/ha in the bare one. But, is in the evolution of the hydrological parameters where the recovery of the burned plot is more clearly defined. The values of runoff yield (Figure 3), after the fire, do not reach its normal trends, being lower than the remainder vegetated plots and mainly as regards to the bare plot, until year 1999. From the fire (1996) to 1999 the burned plot gave higher values than that of *Medicago arborea*, but the differences were reduced gradually until

1999, where the tendency changes presenting the burned plot runoff values similar to those previous the experimental fire. This recovery was also confirmed by the values of infiltration rate and runoff coefficient.

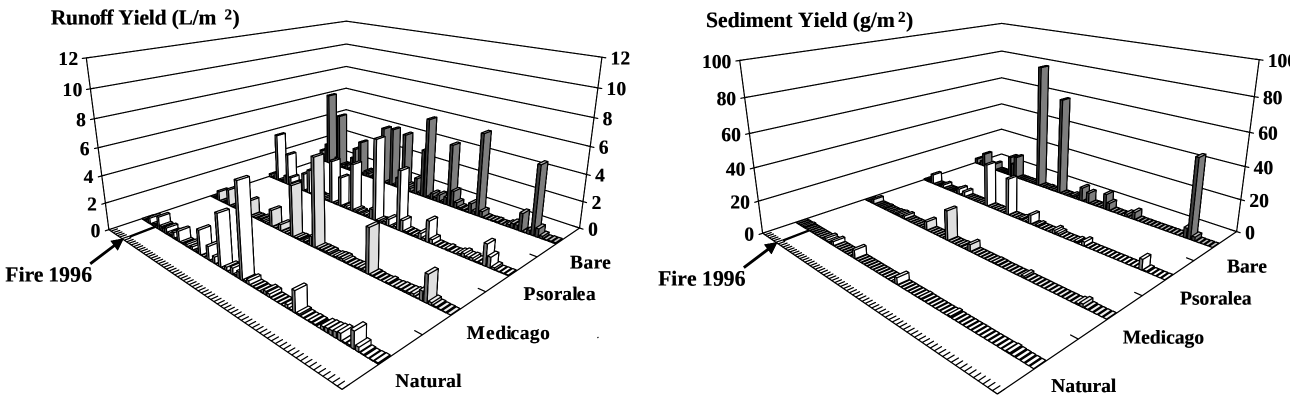

Figure 3. Runoff (L/m^2) and sediment (g/m^2) produced in each erosive event occurred in Porta-Coeli experimental station.

Conclusions

Erosion rates increase shortly after the fire in both experimental stations, depending of the fire intensity suffered. It has been observed that during the four to six month period after the fire the soil is most susceptible to water erosion, although this pattern is subjected to the incidence and timing of high intensity rain events. Fire intensity is a key factor that determines the possibilities of ecosystems recovery. The incidence of moderate-low intensity fires, usually, has little incidence on soil properties and can produce an increase of soil organic matter, due to the accumulation of partially burned remains of vegetation. It which could favor infiltration, reducing the effect of erosion processes. Other important factor is the time of apparition of high intensity rains after the fire. The longer the period without heavy rains after the fire the higher the capacity of soil to receive their impact.

Amounts of runoff and sediments produced after the fire tended to decrease and stabilize with time, depending of the damage suffered, returning to its original values. Porta-Coeli plot burned with moderate-low intensity returned to its previous conditions around five years after the fire. By the contrary, the plots of La Concordia station, which were burned with higher intensities than that of Porta-Coeli, seven years after the fire, still maintain important differences on erosion parameters with the unburned plots. The incidence of a repeated fire on an ecosystem not totally recovered from a previous burning, shortening its resilience time, can cause a severe damage on its properties and a strong increase on runoff generation and soil loss that could be higher than those observed after the previous fire. In Mediterranean ecosystems, where the maintenance of the fragile soil hydrological conditions allows their subsistence the increase in frequency of fires could produce a regression towards more degraded stages favoring the advance of desertification processes.

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