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Modelling sediment yield in burned areas

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Abstract The effects of forest fires on runoff and soil erosion were investigated by means of field experiments and model simulations. A set of rainfall simulation experiments were carried out on two plots with different fire histories in a typical Mediterranean area. A distributed soil erosion and sedimentation model, calibrated based on plot experiments, was used to investigate hillslope and channel erosion in a 1.5-ha drainage basin. The comparison between simulated runs, and observed data, indicate that the model is capable of accurately estimating sediment yields for the basin. The current approach provided good results in driving the transition from the plot scale, at which field rainfall simulator experiments are usually carried out, to the larger watershed scale, where hydrological models are more suitable for developing appropriate post-fire catchment rehabilitation plans.

Key words erosion; fire; hydrological models; rainfall simulator

INTRODUCTION

Over the past few years, Mediterranean countries have had to face a large increase in the number of wildfires; currently there are twice as many as during the 1970s, with an annual accumulated burn area of 600 000 ha (Alexandrian *et al.*, 1999). This has led to a new awareness about the effects of forest fires, not only for the loss of vegetation, but also to the possible loss of life and property, as well as to changes in the hydrological and sedimentological response of the once vegetated areas. Several studies have pointed out the effects of fire, including reduced infiltration rates, and increased overland flow (De Bano, 1981), accelerated soil erosion (Wilson, 1999), increased soil nutrient losses (Thomas *et al.*, 1999), modifications in soil physicochemical properties (Giovannini & Lucchesi, 1997), and changes in vegetation dynamics (Trabaud, 1996). Particularly, increases in post-fire runoff and erosion rates, by at least one or two orders of magnitude, as compared with unburned areas, were observed in many Mediterranean countries (Inbar *et al.*, 1998; Soto & Diaz-Fierros, 1998).

The present study aims to contribute to the understanding of the processes and responses associated with wildfires, focusing mainly on post-fire erosion at the basin scale. In fact, in spite of the relative abundance of plot-scale field experiments, a comprehensive knowledge of fire effects at the catchment scale still is lacking, and further research should focus on the issue of upscaling rainfall simulation experiments. As the factors influencing erosion are scale dependent, the predictions of a basin-scale model, in term of soil losses, cannot easily be compared to those observed at the plot (small) scale. In fact, although plot-scale studies eventually allow the assessment of erosion by raindrops, overland flow and rills, they do not provide information on gully erosion, soil slides, nor debris flows. Further, at the plot scale, the effect of depositional zones is excluded. Knowledge of the impacts of these factors can help explain the differences between erosive soil losses *vs* what actually reaches a river network.

Some previous studies have attempted to evaluate the impact of basin erosion, using plot scale data (Hamed *et al.*, 2002), or to simulate post-fire plot erosion with models such as the Water Erosion Prediction Project (Soto & Diaz, 1998). Even so, a thorough analysis of the hydrological and sedimentological response of a burned basin, coupling distributed models and plot data, is still lacking.

The analysis presented herein consists of two principal steps. First, a set of rainfall simulation experiments were carried out on two 30-m^2 plots; the results were used in the model calibration and validation procedure. Second, a distributed erosion and sedimentation model, consisting of a partitioning module (Menduni *et al.*, 2000), a rainfall–runoff module (Vertessy & Elsenbeer, 1999), and an erosive module (Sun *et al.*, 2002), was applied to a 1.5-ha drainage basin. Due to the physical basis of the erosion equations, the model has many advantages when compared to empirical lumped models. In fact, it can quantitatively evaluate the role of different factors causing sediment production; albeit as a result of catchment size and the magnitude of the simulated events, mass movements in the form of landslides and debris flows were not considered. Therefore, it should be capable of predicting the spatial location of the main sources and sinks of sediment and, at the very least, it could permit immediate application without extensive calibration.

DESCRIPTION OF THE STUDY AREA

The field experiments at both the plot and the basin scale were carried out in an area of the Branega catchment, that was subjected to a fire in early August 2003 (Fig. 1). During the last 30 years, this catchment, located in the Ligurian region (northwestern Italy), has been subjected to a large number of fires of different intensities that, together with changes in land use, caused relevant alterations in plant community dynamics and soil properties, exposing some areas to potential desertification (Regione Liguria, 2002). The climate of the Branega catchment is typically Mediterranean. The

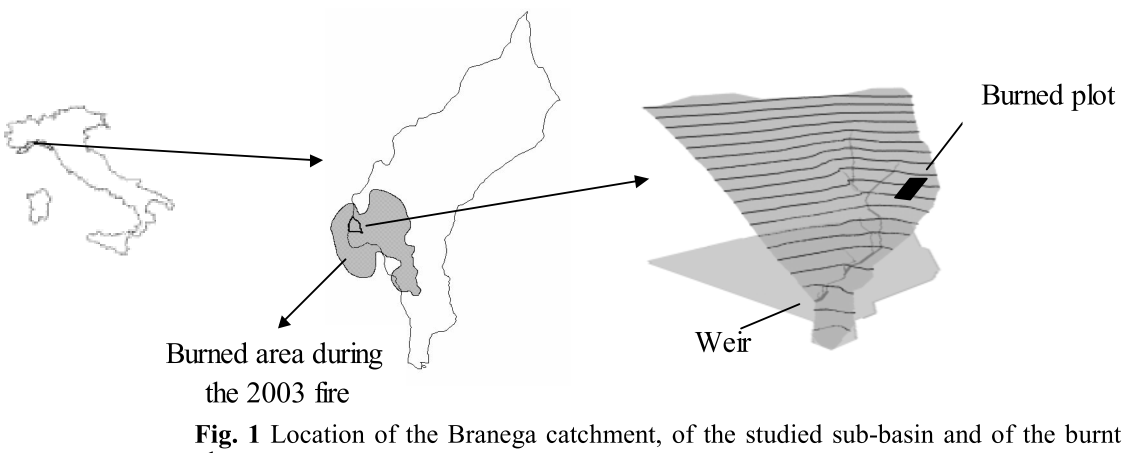

Fig. 1 Location of the Branega catchment, of the studied sub-basin and of the burnt plot.

average annual rainfall is about 1400 mm, and intensity–duration–frequency curves for this area show that hourly rainfall, with an intensity of 100 mm h^{-1}, has a return period of 20 years. The catchment features steep hillslopes (mean of 52%), with an easterly/ southeasterly aspect (Regione Liguria, 2002).

The Branega catchment has a typical matorral cover, characterized by the presence of pinewood forests and evergreen shrubs, including *Erica arborea* L., *Erica scoparia* L., *Arbutus unedo* L., *Myrtus communis* L. and *Cistus salvifolious* L. In the catchment areas subjected to frequent wildfires, a reduction in the number of species, and a prevalence of the most resilient ones, as well as an increase in shrubland, has been observed. The existing ecosystem can be classified as garrigue (i.e. a degraded Mediterranean habitat), which has evolved in acid soils with low nutrient concentrations.

PLOT-SCALE EXPERIMENTS

The plot-scale experiments were carried out on two 32-m^2 plots, 4 m × 8 m. The study plots had a different fire history: one was established in an area burned during a 2003 fire and the other was located in a different area that was not subject to that fire. However, both plots were burned in 1985 and 1997. Therefore, this study compares an area recently burned for the third time, with one previously burned twice, but not for the last six years (see Rulli *et al*., 2003).

The experiments were carried out six weeks after the forest fire, using a rainfall simulator consisting of nine nozzles that generated a 76 mm h^{-1} rainfall intensity. Each simulation consisted of a single 60-min rainfall application at a constant intensity. The actual rainfall intensity, and its spatial distribution, was assessed by means of 10 rain gauges placed in and around the plot.

The experiments were designed to analyse the hydrological and sedimentological responses under three different antecedent soil moisture conditions. Each plot underwent three rainfall events: Event 1 (dry) was carried out under existing soil moisture conditions, Event 2 (wet) was carried out a few days after Event 1, and Event 3 (very wet) was conducted about 2 h after Event 2. Before the experiments, four soil samples were collected in each plot, at different depths, to determine antecedent soil moisture conditions; these were determined gravimetrically after drying.

The runoff ratio (i.e. the fraction of the precipitation converted to runoff) of the burned plot ranged from 21 to 41%, whereas in the unburned plot, it ranged from 0 to 2%. When comparing the results from simulated events with the same antecedent soil moisture conditions, the runoff ratio from the burned plot was 60 times higher than from the unburned one for the wet run, and 20 times higher for the very wet run (Table 1). The overall shapes of the runoff hydrographs were consistently related to the antecedent soil moisture conditions The time to runoff initiation decreased with soil moisture, with the slope of the rising limb of the hydrograph becoming steeper and steeper as the soil moisture increased (Fig. 2).

Substantial increases in sediment yields were measured from the burned plot relative to the unburned one. At the burned site, the average erosion rate, that encompasses total sediment yield per unit area and per hour, was about 17 g m^{-2} h^{-1} during the first two simulations, and twice as much during the third one. Conversely, the unburned

Table 1 Summary of the results of the field experiments.

	Burned: Event 1	Event 2	Event 3	Unburned: Event 1	Event 2	Event 3
Plot area (m^2)	13	26	26	30	30	30
Average rainfall intensity ($mm\ h^{-1}$)	74	68	76	58	74	74
Duration (min)	60	55	60	42	61	71
Runoff ratio	0.21	0.24	0.41	0	0.004	0.02
Peak runoff ($mm\ h^{-1}$)	33.5	25.3	41.3	0	0.7	2.2
Average erosion rate ($g\ m^{-2}\ h^{-1}$)	16.8	17.8	32.9	0	0.1	0.2

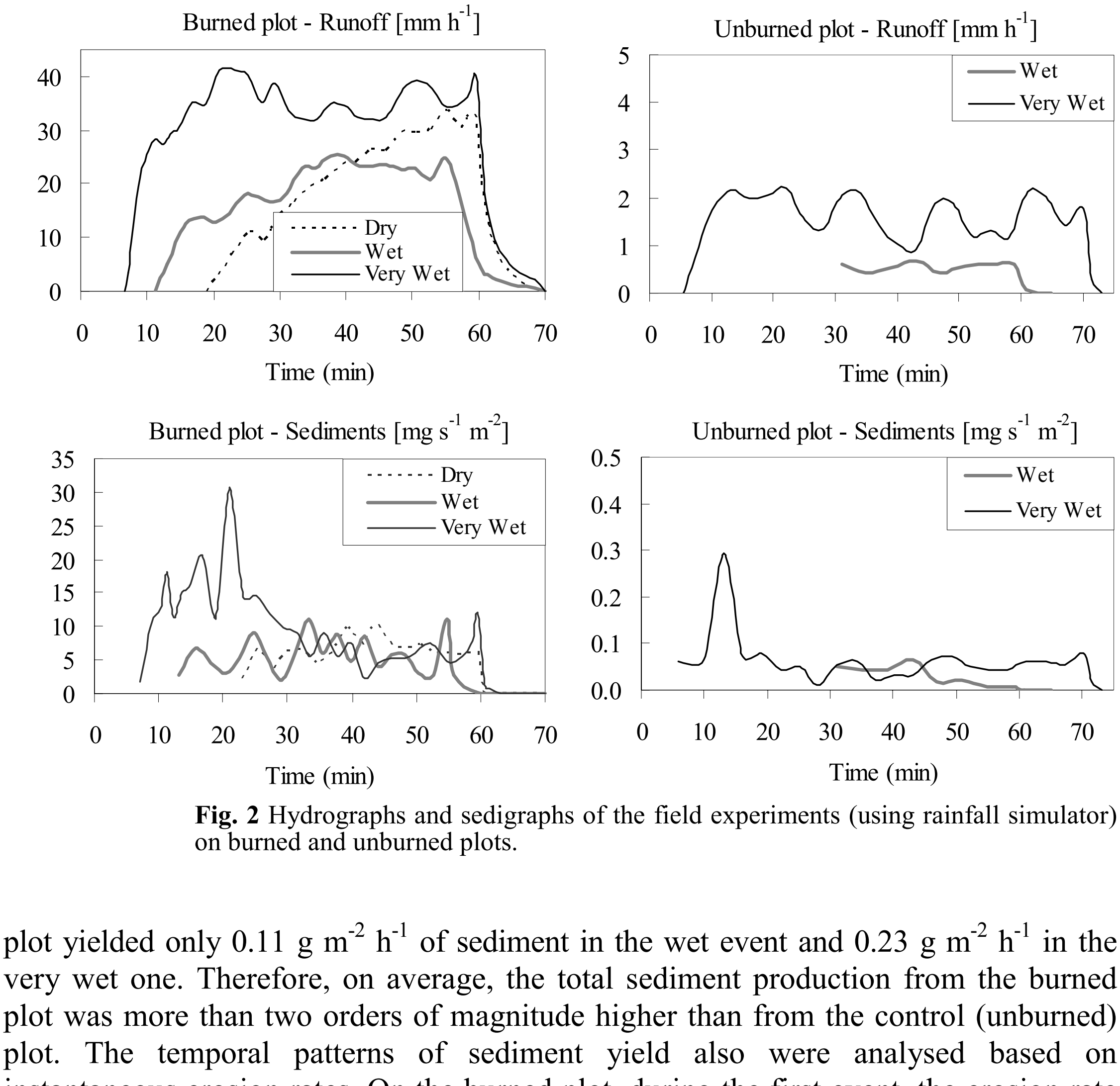

Fig. 2 Hydrographs and sedigraphs of the field experiments (using rainfall simulator) on burned and unburned plots.

plot yielded only 0.11 $g\ m^{-2}\ h^{-1}$ of sediment in the wet event and 0.23 $g\ m^{-2}\ h^{-1}$ in the very wet one. Therefore, on average, the total sediment production from the burned plot was more than two orders of magnitude higher than from the control (unburned) plot. The temporal patterns of sediment yield also were analysed based on instantaneous erosion rates. On the burned plot, during the first event, the erosion rate fluctuated, but then became steady when runoff reached the maximum observed value, whereas during the second event, it varied throughout the simulation period, without ever reaching a steady-state condition. The sedigraph of the third event on the burned plot was the most consistent: it featured an initial peak, followed by a flat or slightly declining trend (Fig. 2).

PLOT- AND BASIN-SCALE MODEL SIMULATIONS

The field experiments on the burned plot were simulated through the application of a distributed erosion and sedimentation model. These simulations were adopted to calibrate the appropriate model parameters in order to successively investigate fire effects on soil erosion at a larger scale. In fact, after calibration, the model was applied to a small (1.5-ha) sub-basin of the Branega catchment where the burned plot was located. An instream weir was located at the outlet to the watershed. This facilitated a measure of the sediment production from the recently burned area. Three months after the fire, the accumulated sediments upstream of the weir were collected and weighed. The total amount of accumulated sediment was 2000 kg. During this 98-day period, there were several intense rainfall events; the total accumulated rainfall was 1037 mm.

Model overview

The model presented here is modular and consists of: (a) a watershed partitioning module; (b) a rainfall–runoff module; and (c) an erosion and sedimentation module. The watershed partitioning procedure used in the model was developed by Menduni *et al.* (2000), and is based on a preliminary identification of an Ideal Drainage Network (IDN) based on contour lines through a variable mesh size, and on a further extraction of the Actual Drainage Network (AND) from the IDN, using land morphology. The model first derives the steepest slope lines starting from the highest contour and then proceeds downslope. Once extraction of the ideal drainage network is complete, the program identifies all the contributing areas draining to each link (sub-basin). The automatic drainage network delineation is straightforward, and the method provides physically consistent one-dimensional stream channels. Further, the procedure defines polygons bounded by the two steepest adjacent contour lines, orthogonal to the contour lines. Overland flow is routed through stream tubes, formed by pairs of stream lines constructed normal to the contour lines (equipotentials) of the watershed (Onstad & Brakensiek, 1968). The model can also automatically identify significant terrain characteristics (e.g. peaks and saddles) and account for their impact on streamflow. Using this type of discretization, the model divides the elements where the water flows into two classes: cells, that are polygons where the overland flow is modelled as sheet flow, and channels obtained by joining two or more stream tubes where surface runoff is channelized. This partitioning procedure makes it possible to solve the equations that describe the active hydrological processes in a quasi-mono-dimensional way.

Process-based storm-flow generation in the model is analysed via the Topog Soil Bucket Model (SBM), (Vertessy & Elsenbeer, 1999) where Topog contour-based watershed partitioning is replaced by the ADN described above. The Topog SBM structure consists of a simple bucket model for handling soil/water fluxes in each element of a one-dimensional kinematic subsurface wave flow module for simulating the movement of a soil/water mixture downslope along the stream tubes, and of a one-dimensional kinematic overland wave flow module for simulating surface runoff along the stream tubes.

The amount of sediment eroded and deposited is computed following the approach proposed by Sun *et al.* (2002). The model calculates, for each element and time step, the amount of sediment mobilized by raindrop splash in inter-rill areas, and by overland flow in channels. Inter-rill area detachment is calculated as a function of rainfall intensity, the USLE soil erodibility factor, the USLE cover and management factor, and a slope factor (Foster, 1982). Rill detachment is computed as a simple function of discharge, the slope gradient of the channel, and a calibration parameter α (Foster, 1982). Then the transport capacity of overland flow is computed, and used to determine the actual amount of sediment eroded or deposited.

Plot-scale simulations

The aim of these simulations was to reproduce the hydrological response of the plots observed during the field experiments described above. For this purpose, two rainfall simulations events (events 2 and 3) were modelled for the burned plot, after evaluating the required input parameters from field data and surveys.

An accurate topographic survey provided a high resolution elevation model of the study plot. Three soil samples (P1, P2 and P3) were collected throughout the studied basin, and were processed in the laboratory to determine soil depth, particle-size distribution, and organic matter content. Soil porosity and residual moisture content were taken from literature values for the local soil type, and set to 0.4 and 0.1, respectively (Clapp & Hornberger, 1978). The saturated hydraulic conductivity was measured at different locations using a Guelph permeameter; the mean value, around 57 mm h^{-1}, was used in the model simulations at the plot scale. The Manning roughness coefficients were set, equal to 0.02 for slope elements, because there was little ground cover remaining after the fire; values for channel elements ranged from 0.011 to 0.065.

To model the erosion processes based on the equations proposed by Sun *et al.* (2002), four more parameters had to be estimated: (a) the median grain size of the sediment; (b) and (c) the USLE parameters K and C_{slr}, respectively, the soil erodibility factor and the cover and management factor; and (d) one calibration parameter, α, used in the computation of soil detachment in channel elements. The USLE soil erodibility factor was estimated using the regression equation proposed by Wischmeier & Smith (1978), which depends on four parameters: (i) a texture factor (M); (ii) the percent organic matter (a); (iii) a soil structure code (b); and (iv) a soil permeability class (c). The first two parameters (M and a) were evaluated from actual soil sample analyses, whereas the permeability class was estimated from *in situ* measurements of hydraulic conductivity; the soil structure code was estimated in the field. The resulting soil erodibility factor was 0.024 kg h^{-1} N^{-1} m^{-2}. The cover and management factor, representing an estimate of the ratio of soil loss under actual conditions to losses experienced under continuous fallow conditions, was set to 1. This choice was made because the recently burned area was essentially devoid of vegetation, and hence, susceptible to the type of soil losses associated with fallow soil. In fact, in the study area, ground cover represented less than 5% due to rock fragments and plant residues, canopy cover was around 20%, and the organic matter content was substantially reduced by fire. The median grain size of the soil, based on several soil sample analyses, was set to 0.12 mm.

The soil moisture content measured before each rainfall event simulation, was used as the initial soil condition, and the simulated rainfall intensities (68 mm h^{-1} for Event 2 and 76 mm h^{-1} for Event 3) were given as input, with a computational time step of 1 s.

Basin-scale simulations

A DEM with 5-m plane resolution was used for basin partitioning. The watershed in which the burned plot was located was partitioned into 217 elements; 30 were considered channel elements. The average element area was 78 m^2. For basin-scale simulations, the parameters mostly were based on field data, as described in the previous paragraph. In a few cases, where no field data were available (i.e. Manning roughness, porosity and residual moisture content), literature values were used. Based on the field surveys, two parameters were assumed to vary spatially: soil depth and saturated hydraulic conductivity. The former ranged from 0.35 to 1.1 m, and the latter from 20 to 140 mm h^{-1}. The parameter α was used as a calibration parameter, whereas the erosion equation parameters were set to the same values used in the plot scale simulations.

The computational time step was set at 100 s, and rainfall input was determined from three raingauge stations close to the basin that recorded rainfall at 5-min intervals. Nine rainfall events, representing 90% of the total accumulated rainfall, were simulated; then the total amount of sediment simulated by the model was compared with actual erosion data measured in the field.

RESULTS AND DISCUSSION

At the plot scale, model performance was assessed by comparing the results with the runoff hydrographs and sedigraphs calculated during the rainfall simulation experiments (Fig. 3). Total discharge was simulated with a reasonable accuracy in both events, although the model predicted higher peak runoffs, especially during Event 2. The shape of the hydrographs and the start time for runoff were reproduced satisfactorily, whereas the simulated rising limbs of the hydrographs rose more slowly than the observed ones. This may have been due to the use of a fixed value for the saturated conductivity of the soil, which would be unable to simulate the quick runoff production of the less permeable parts of the plot. For both events, the steady-state runoff was reached at the same time in the model simulations and field experiments: in Event 2 (wet) it was at the end of the simulation, whereas in Event 3 (even wetter) stable conditions were achieved only a few minutes after the initiation of runoff.

The simulated sedigraphs agreed with those obtained from direct observations, in terms of the total amount of soil loss, but the shape of the observed graphs was more irregular than the simulated ones. Also, the onset of sediment delivery was correctly simulated; however, the rising and falling limbs of the sedigraphs were less steep than in the field experiments. Regardless, despite some differences, the model was able to reproduce, with a good degree of accuracy, the processes observed in the field.

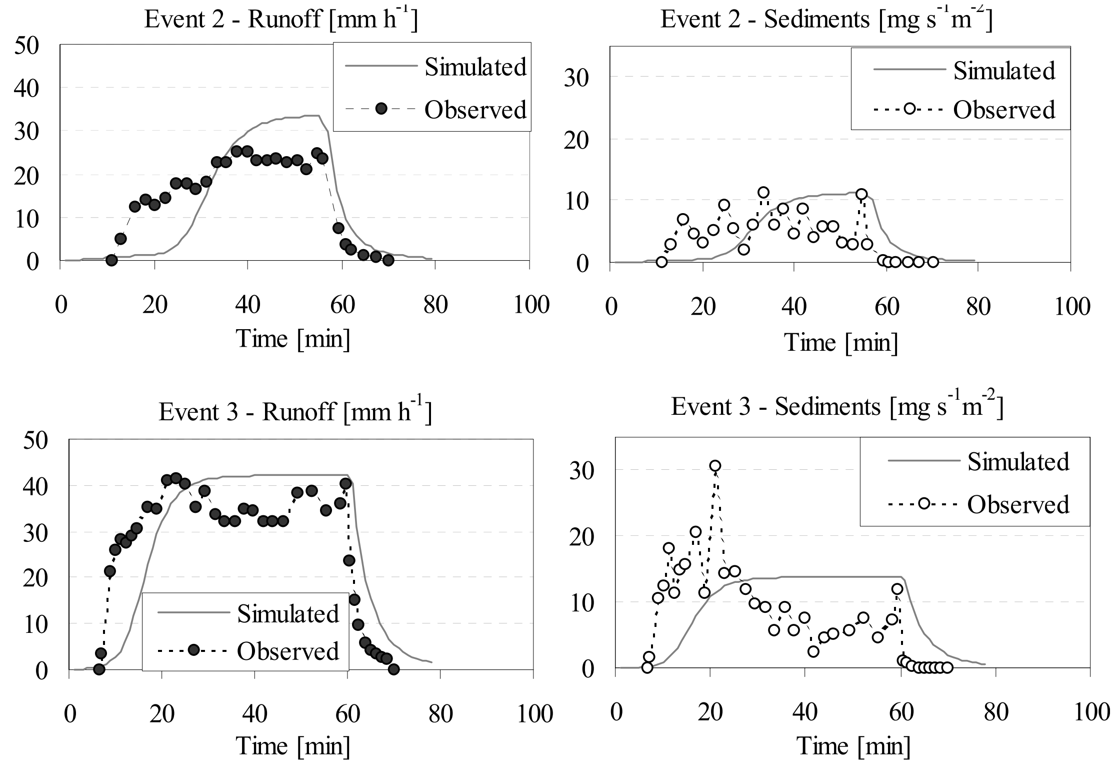

Fig. 3 Comparison between observed and simulated hydrographs and sedigraphs for events 2 (wet) and 3 (very wet) on the burned plot.

It should be noted that the simulated results were insensitive to changes in α (the parameter used in the computation of soil detachment in channel elements): different runs with α ranging from 1 to 4000, showed an increase in the simulated sediment yield of less than 5%. In fact, it can quantitatively evaluate the role of different factors causing sediment production; albeit, as a result of catchment size and the magnitude of the simulated events, mass movements in the form of landslides and debris flows were not considered. This was mainly due to the small number of elements with channelized flow resulting from the partition of the plot, and thus, to the greater importance of the interrill processes at the plot scale. However this also can suggest that in post-fire conditions, the erosion process is predominantly limited by the transport capacity of the overland flow, rather than by the availability of sediments.

Similar results were noted during the sub-basin scale simulations. Unfortunately, in these cases, model simulation only was compared with measured accumulated sediment yields, due to a lack of continuous water and sediment discharge data. The model satisfactorily predicted the sediment yield of the small catchment after nine major events; it estimated 2600 kg, compared to a measured value of 2000 kg.

The simulated model runs incorporated a wide range of rainfall intensities ranging from 3 to 77 mm h^{-1}. It was noted that, even during several weak rainfall events, the small amount of rainfall detachment did not limit the erosion process on the hillslopes; the limiting factor remained the transport capacity. Therefore, at both study scales, detachment by raindrop splash always was higher than the transport capacity. K and C_{slr} (the soil erodibility factor and the cover and management factor, respectively) played leading roles in the availability of erodible soil for post-fire conditions, at least at these spatial scales.

In conclusion, the adopted approach provided good results in driving the transition from the plot scale to the watershed scale, the latter being more useful for developing appropriate post-fire catchment rehabilitation plans.

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