**Post-fire erosion and sediment yield in a Mediterranean forest catchment in Italy**

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**Abstract**

Wildfires are an increasingly alarming phenomenon that affects forests and agro-ecosystems, generating several cascade effects among which soil erosion is one of the most deleterious. A robust body of data-based evidence on post-fire soil erosion and sediment yield at watershed scale is thus required, especially dealing with areas where wildfires are particularly frequent, such as the Mediterranean Basin. This study analyses the impact of the first rains after a large wildfire in terms of soil erosion and sediment yield at watershed scale in a Mediterranean area, the Pisan Mountains, Central Italy. Here about 1,000 ha of olive groves, maquis, maritime pine and chestnut forests burned.

Fire severity was mapped by remote sensing and checked by a field survey. Sediment yield was assessed by sampling the earthy material deposited upstream a check dam at the outlet of the watershed. Finally, a hydrological model was developed in HEC-HMS environment for exploring the relationship between the erosion-deposition events observed in the watershed and the rainfall-induced hydrological processes. The first two post-fire rainy events relocated a high amount of sediments, mostly non-organic, perhaps already in the stream before the fire, while the subsequent four rains deposited materials rich in pyrogenic organic matter. Overall, the soil erosion caused by such six main post-fire rains – the larger of which had a return time of one year – was estimated to amount to 7.85 t ha-1, corresponding to 42% of the watershed average annual potential erosion rate in normal conditions. This value is lower than expected and, overall, moderate if compared to other Mediterranean case studies, possibly because of the nature of soils in the studied watershed, i.e. shallow and quite stony, thus poor in fines prone to erosion.

**Keywords:** Wildfire, Check dams, Post-fire hydrological modelling, Soil loss, Sediment yield, HEC-HMS

1. **Introduction**

Wildfires are a major concern of our times, with huge amounts of biomass burned and the global average carbon emissions into the atmosphere being estimated to be 2.2 Pg C yr-1 (Van Der Werf et al., 2017). Post-fire soil erosion is a negative indirect outcome of wildfires, which make them a hydrological and geomorphological agent (Shakesby and Doerr, 2006; Rulli and Rosso, 2007; Greenbaum et al, 2021; Robinne et al., 2021). Burned areas are prone to soil erosion because of decreased vegetation and litter covers, which would otherwise protect the soil against wind and splash erosion by interception and slow down the surface runoff (Fernandez et al., 2016; Ebel, 2020; Vega et al., 2020). The latter is instead encouraged by fire, which increases topsoil clogging and hydrophobicity, so preventing water infiltration (Rulli et al., 2006; Larsen et al., 2009). Erosion implies a net loss in soil fertility, which is generally greater in the uppermost layers (Thompson et al., 1991; Shakesby, 2011). Furthermore, topsoil erosion implies a net loss of soil organic matter and a reduced potential for soils to act as carbon sinks, which is functional for contrasting the climate change (Powlson et al., 2011). Last, once transported downstream the eroded soil can also cause major hydraulic problems (Stavi, 2019; Robinne et al, 2021). It impacts surface waters with sediments and possible contaminants (Granath et al., 2016; Abraham et al., 2017), and often needs to be collected and disposed in landfills (Köthe, 2003).

Relatively few studies have been carried out to account for the consequences of wildfires in terms of soil erosion and sediment yield at the catchment scale compared to the plot, slope and swale scales, perhaps because of practical and/or economic issues (Shakesby, 2011; Mayor et al., 2011; Robichaud et al., 2016; Basso et al., 2019; Weninger et al., 2019; Wu et al., 2021). However, geomorphic and hydrological processes are highly affected by the spatial scale and, therefore, erosion rates at larger scale should not be inferred from plot-scale studies (Parsons et al., 2006). Indeed, plot- and hillslope-scale studies often overestimate hydrological and erosion processes, thus making difficult to assess the real fire impact at larger scale (Mayor et al., 2011; Wagenbrenner and Robichaud, 2014; Wilson et al., 2021). In a synthesis of several field studies on post-fire sediment erosion and deposition measurement across the western United States, Moody and Martin (2009) found significantly different results according to the spatial scale, although opposite to the above-mentioned trend, i.e. lower sediment yield at the plot scale. In fact, keeping into account a certain variability depending on the measurement method, the annual post-fire sediment yield measured by various authors at catchment scale using dams, check dams, debris basins, alluvial fan deposition, and channel erosion was between 14 and 300 t ha-1, with a mean of 240 t ha-1 (Moody and Martin, 2009). On the other hand, the annual sediment yield measured at hillslope scale by erosion pin, erosion bridge, survey transect, or grid measurements ranged between 37 and 160 t ha-1, with a mean of 110 t ha-1, or between 6 and 200 t ha-1, with a mean of 62 t ha-1, when sediment yield was measured by bounded hillslope plots, unbounded hillslope plots, and silt fences (Moody and Martin, 2009).

In the Mediterranean Basin, the watershed-scale field studies on post-fire soil erosion and sediment yield are relatively less than in other geographic regions (Nunes et al., 2020; Greenbaum et al., 2021; Wu et al., 2021), in spite of some worrying aspects, such as the high frequency and severity of wildfires or the often thin, steep and highly erodible soils (Poesen and Hooke, 1997; Pausas et al., 2008). Moderate post-fire erosional events seem to be prevalent in the Mediterranean Basin (Shakesby, 2011); however, as highlighted by Esposito et al. (2017), most of the case studies in this region are from experimental plot in Spain and Portugal. The need of larger and more representative datasets is pressing also considering that these are necessary for developing erosion models, which are more and more tested at plot and hillslope scales, but not as much at catchment or landscape scales (Basso et al, 2019; Thomas et al., 2021).

In this work we dealt with one of the most devastating recent fires in Italy in terms of rate of spread (up to 500 m h-1), natural damages and structural/infrastructural damages. It occurred in September 2018 and affected an area of about 1,000 ha on Pisan Mountains, Tuscany. We evaluated the short-term impact of this fire in terms of soil erosion and sediment yield, focusing on the first rains after the fire – usually the most problematic ones (Greenbaum et al, 2021). The study was carried out on a single watershed, where post-fire precipitation and the characteristics (soil organic matter and granulometry) of the sediments accumulated at the catchment outlet were investigated. The aim of the study was to provide a valid contribution to the knowledge and measured data of post-fire rainfall-induced runoff processes at the catchment scale in a typical Mediterranean bio-geo-physical setting characterized by stony and shallow soils. With respect to the usually moderate post-fire erosion values reported for Mediterranean soils evaluated from plot studies (Shakesby, 2011), we hypothesize higher degree of soil erosion and sediment yield because of some predisposing factors of the study area (e.g., high rainfall erosivity and steep topography). Indeed, the average annual potential erosion rate of the investigated watershed, estimated with the USLE method in normal conditions, is 18.8 t ha-1 y-1 (Regione Toscana, 2020), a value much higher than 4.6 t ha-1 y-1, the overall erosion mean value of the Mediterranean climatic zone (Panagos et al., 2015) and closer to the highest values of sediment yield (i.e. 23.8 t ha-1 y-1) simulated by De Girolamo et al. (2022) in natural degraded areas of Southern Italy on steep slopes and a low vegetation rate. Our study is based on a methodology that takes into account multiple environmental factors (e.g., burn severity, slope, soil characteristics, pre-fire land use, rainfall-runoff transformation, etc.) and takes advantage of a hydrological model for exploring the relationship between the erosion-deposition events and the rainfall-induced hydrological processes.

1. **Material and methods** 
   1. *Study area*

The Pisan Mountains are a 15,000-ha wide ridge (maximum height 917 m a.s.l.) made of Triassic Verrucano metasediments consisting of ferriferous quartzites undergone relatively high pressure and low temperature metamorphism (Franceschelli et al., 1986; Giorgetti et al., 1998), located in Central Italy, 5 km north-east of Pisa (Fig. 1). It is a fire-prone environment, having been involved by over 75 large wildfires since 1970, mainly occurring in summertime and linked to the high anthropization of the area, as usual in Mediterranean coastal areas (Pausas et al., 2008). The slope of the area ranges between 30% and 60% and the vegetation is typically Mediterranean, with olive groves and maquis in the basal belt and forests of maritime pine or chestnut above (Fig. 1). The climate is Mediterranean (Csa – “Hot-summer Mediterranean climate” in the Köppen climate classification), i.e. characterized by hot and dry summers, and relatively cold and rainy falls and winters. The mean annual temperature is 14.4 °C and the mean annual precipitation is 883 mm (data source: Climate-Data.org, 2021).

Our study was focused on the Santo Pietro (hereafter SP) watershed, which extends on the west side of the ridge (Fig. 1) and covers an area of 0.408 km2 with a length of the main stream of 1.12 km and maximum, average and outlet altitudes of 409, 205 and 66 m a.s.l., respectively. According to the 1:250,000 soil map by Regione Toscana (<http://sit.lamma.rete.toscana.it/websuoli/>) – which refers to the ninth edition of the U.S. Soil Taxonomy (Soil Survey Staff, 2003) – the soils of the area are *Ultic Haplustalfs* (fine-silty, siliceous, mesic) or *Typic Dystrustepts* (loamy-skeletal, siliceous, mesic) near the river bed, and *Lithic Haplustepts* (loamy-skeletal, siliceous, mesic) or *Typic Dystrustepts*at higher elevations*.* A wooden check dam built right after the fire at the outlet (Figs. 2 and 3), near the small-town of Calci, induced the deposition of the eroded soil transported by the stream, so allowing its quantification and reconstruction of its depositional history (cfr. Par 2.6, Fig. 3).

* 1. *Fire description and burn severity assessment*

Following several relatively dry days, a fire started at 10 pm of September 24th, 2018. Classified as a strong wind-driven crown-fire with a slope-driven ground component, it burned a total area of 1,148 ha in over three days. Wind blew with gusts of 14 m s-1 (50 km h-1), first from North-North-East, then, in the morning of September 25th from East. Wind speed peaks were locally measured at 22 m s-1 (80 km h-1) by forest firefighters. Combination of slopes with wind speed and dense forest stand structure, as well as a low relative humidity (40% at 9 pm on September 24th), determined a maximum spread rate of 500 m h-1, generating several spot fires up to 8 km away from the main fire front.

Wildfire spread and intensity were dictated by the combination of several ground fires started from spot events, favored by local topography and a main crown fire front driven by the wind. Fire control was initially restricted to property protection and perimeter containment involving 580 firefighter crews (each one composed by 2-5 operators) and 12 aircrafts.

The assessment of burn severity was carried out using remote sensed data from Sentinel-2 images (spatial resolution scaled at 20 m) recorded at the end of August and the beginning of October, calculating the Relativized Burn Ratio (RBR) index. This index indicates a relative measure of fire severity based on the difference in radiometric response between the near infrared (NIR) and short-wave infrared (SWIR) wavelengths, measured before and after the fire (Parks et al., 2014). To improve readability of burn severity distribution, we applied the United States Geological Survey (USGS) classification to RBR index (Table 1).

* 1. *Field investigation and soil sampling*

Fire severity was also checked by a field survey (Fig. 4), done right after the fire on the whole Pisan Mountains range area, according to the visual scale of fire severity proposed by Parsons et al. (2010). During this campaign we randomly selected 20 circular areas, 30 m in diameter, five areas each vegetation stand, i.e. maquis, pine forest, chestnut forest, and olive orchards. Sixteen of these plots were burned, the other four ones unburned (control plots), all located on the two main soil types of the area (i.e. *Typic Dystrustepts*and*Lithic Haplustepts*). At each plot, the following variables were measured in the field:

1. *Stoniness* (presence of rock fragments >1 cm and outcrops on the ground surface, % of the area), estimated by eye on eight circular mini-plots, with a diameter of 0.3 m, spaced 2 m each other on an alignment;
2. *Soil depth*, down to the bedrock, determined by a steel auger on nine randomly selected spots.

One soil sample was collected from each plot, bulking together three soil samples taken with a shovel to a depth of 1 cm (ca. 300 g each), for determining the soil texture.

* 1. *Post-fire rainfall events*

We focused our analysis to the first rains after the fire. Rainfall data of interest for our study (Fig. 5) were recorded by a station around 2.5 km from the catchment, at an altitude of 705 m a.s.l (Latitude 43.731°, Longitude 10.553°) and managed by the Hydrologic Regional Service (SIR) of the Tuscany Region. The first precipitation (October 28th to November 3rd, 2018; Fig. 5) occurred about one month after the wildfire, when five distinct intense rainy events were recorded.

We analyzed the return period (Rt) of these events by considering the specific rainfall intensity (h) - duration (t) curve in the form:

[Eq. 1]

The parameters of this relationship (a’; m; n) are available from the AlTo database of the Tuscany region (Regione Toscana, 2007; Preti, 2013; Preti et al., 2011). For the specific study case, they were a’ = 24.08, m = 0.19, n= 0.31.

* 1. *Rainfall-runoff model*

To explore the relationship between the erosion-deposition events monitored in the watershed and the hydrological processes induced by the rains occurred from October 28th to November 3rd, 2018, we implemented a hydrological model of the SP watershed to simulate the discharges at the basin outlet.

A simplified model based on the Hydrologic Modeling System (HEC-HMS, see Scharffenberg et al., 2018) was built starting from static data (land use and soil maps) and dynamics inputs (rainfall). HEC-HMS is a simple, globally available and widely used software that is a well-established standard in hydrology. It simulates a basin-wide dynamic by sub-basins interconnected through a channel network, where rainfall-runoff generation is calculated independently for each sub-basin. The modeling of these hydrological phenomena is obtained by the simulation of the different hydrological processes, such as the rainfall partitioning between runoff, interception and deep basin losses, the successive rainfall-runoff transformation, and the routing of river discharges in schematized flow channels.

In this study, the SP watershed was modeled with a parsimonious strategy, using a single sub-basin scheme and without involving any river channel modelling, given also the small extent of the area. The model was built starting from the rainfall data. Rainfall partitioning and the sub-basin loss, “Loss Method” section in the HEC-HMS interface, were calculated by the application of the SCS Curve Number (CN) method (United States Department of Agriculture, 1986).

For each time interval considered, the CN method calculates the instant runoff generated (Q) with the following equation:

Eq. 2

where:

* P is the rainfall height for the calculation interval (mm)
* S is the potential maximum soil moisture retention after the runoff starts (mm), and is calculated as:

Eq. 3

* Ia is the initial abstraction, namely the depth of water retained by the landscape before the runoff starts, by infiltration or by rainfall interception by vegetation (mm). Ia is generally assumed to be 0.2 S.

The method is based on the CN adimensional parameter that accounts for the physical response of a landscape unit to rainfall, and ranges from 30 to 100. It depends upon the soil type and the land cover, and the higher the CN, the lower the basin losses and, consequently, the larger the runoff generation. Combining data on soil and land cover, an initial CN value, namely CNII, valid for average soil moisture conditions, is calculated. Each CNII value corresponds to a CNI (lower) value, to be used for dry soil conditions, and to a CNIII (higher) value for wet conditions (see United States Department of Agriculture, 1986, for the complete method and CN value parametrization).

In our case, the overall average CN for the SP watershed in post-fire conditions was obtained by an area-weighted average of the CN of all landscape units falling within the watershed, which were extrapolated from the CN map of Tuscany (Castelli, 2014). Since no significant rain was recorded right after the wildfire and before the simulation date, values for CN in dry soil conditions (CNI) were used.

Several CN-based methods are available for the modeling of burned landscape conditions. One of these is BAER (Burned Area Emergency Response, USDA Forest Service, 2006), which prescribes increases in CNII of 15, 10 and 5 for areas affected by high, medium and low severity, respectively. Instead, Coschignano et al. (2019) adopted increases of CN varying from 5 and 20 for growing fire severities. In our case, most of the burned area in SP watershed was characterized by a moderate severity. However, aiming at investigating the short-term effect of fire, therefore with the maximum alteration of CN, we followed Soulis (2018), who assumed an increase of 25 units in CN for burned areas in a catchment in Greece. We made this choice because of the similarities between the Soulis’ study site and ours in terms of environment, vegetation and fire impact.

The SCS Unit Hydrograph method (United States Department of Agriculture, 1986) was used as rainfall-runoff transformation method (“Transform Method”). Hence, at each calculation time, the instant runoff generated by the watershed was transformed in a standard hydrograph with peak time 0.6 times that of the basin concentration time, which meant 27 minutes for the SP watershed. The overall sub-basin response was calculated as the convolution of all hydrographs.

The HEC-HMS version 4.3 was used for the modeling process, and no baseflow and evapotranspiration processes simulation were considered, since the model was replicating a peak flow event. The model was not calibrated nor validated, since burned catchments in the area were not gauged at the time of the analysis, while performing a validation of the model some months after the fire would have led to different catchment conditions due to vegetation regrowth.

* 1. *Stream sediments quantification and sampling*

A few days after the fire, a large wooden check dam was built to act as a sediment trap at the SP watershed outlet, just before the small town of Calci, to prevent streambed aggradation in the urban area in case of post-fire floods (Fig. 2). No rainfall occurred between the fire and the setting up of the structure, while the whole volume of the latter was filled by sediment just after the significant rainfall events described in par. 2.4. Therefore, the sediment volume trapped upstream the check dam corresponded to the sediment produced by the rains occurred from 28.10 to 03.11.2018.

Soon after that time lapse, a detailed topographic survey was carried out to measure location and elevation of a 32-point grid at the surface of the sediment deposit and at the level of the streambed by digging small trenches upstream the check dam. This allowed determining the shape and volume of the deposit (Fig. 3), which was then sampled by metal pipes 12 cm in diameter, driven as deep as possible. The individuation of the boundary between the post-fire sediments and the pre-existing streambed based on the assumption that, due to the relatively high slope of the stream, the original streambed was mainly composed by gravel, which prevented the sampling pipes to be driven deeper. Further discussion on the analysis of the sedimentation dynamics is reported in par. 3.3.

Five deposit cores were taken at five different points and three cores were kept for further analysis (see Fig. 3): one close to the check dam (E), another almost at the opposite extreme of the sedimentation area (B), and the third (A) approximately in between. Core A was the thickest and the one used for the calculation of the volume of the sediment. For each layer individuated in this core, the relative deposited volume was determined with a geometric procedure, considering the widening of the trapezoid section and, at the cut-off length, adjusted layer by layer (Fig. 3). For each layer the respective mass deposited at the check dam site (MDi) was calculated multiplying the estimated volume by the related bulk density measured in the core (see par. 2.7 for the bulk density calculation).

The total mass of soil eroded at the catchment scale (MEi), namely the one flowed up to the check dam site (either deposited before or flowed past it through the overflowing water), was calculated from MDi by the means of the Sediment Trap Efficiency of the check dam at the time of deposition of the uppermost layer of core A (STEi):

Eq. 4

where STEi was estimated according to Brown (1943), by the following equation:

Eq. 5

where Ci is the volume capacity upstream the check dam before the deposition of the uppermost layer of core A in m3, W is the extension of the watershed upstream the check dam, and D is a coefficient assumed to be 1 for watersheds with variable and limited runoff.

By analysing the outputs of the HEC-HMS model (par. 2.5), each sedimentation event (i.e., each layer in the core) was related to a peak flow event during the modelled period, and the sediment concentration was calculated dividing MEi by the total volume of the flow. Finally, the average post-fire erosion rate was calculated dividing the total sediment eroded by the area of the SP watershed.

*2.7. Soil and sediments analysis*

The disturbed soil and sediment samples were air-dried and then sieved to 2 mm. The lone fine earth, the smaller than 2-mm fraction, underwent further analysis.

Particle size analysis was performed according to the hydrometer method. The bulk density of collected sediments was determined dividing their weight after oven-drying at 105 °C to constant weight by the known volume of the sediment cores. The organic matter content was measured as Loss On Ignition (LOI) at 480 °C for eight hours.

1. **Results**
   1. *Burn severity*

The burn severity, as registered by remote sensed data from Sentinel-2 images, is shown in Fig. 6. Most of the SP watershed underwent moderately severe fire, as in the other Pisan Mountains catchments involved in the same wildfire. About 12% of the Pisan Mountains area burned with high severity, while just 2% did so in the SP catchment, perhaps because of its proximity to the smalltown of Calci, where fire suppression efforts were greater than elsewhere. Possibly for the same reason, the unburned surface amounted to over 16% in the SP watershed versus less than 9% in the whole Pisan Mountains area.

Field investigation mostly confirmed the remote-sensed data. In the areas where burn severity was recorded as moderate, most of the litter had completely burned, leaving a mixture of gray ash and black char on the soil surface, while in the understory the shrub skeletons remained. In the areas where fire severity was recorded as high, most of the above ground biomass, including finer fuels and the shrub layer < 2‒3 cm, was consumed and turned into a gray or white ash covering the ground, while most of the tree stems were still standing although scorched (Fig. 4). The ash layer, however, did not last for long and was flushed away after the first rains.

* 1. *Soil characteristics*

In general, the Pisan mountains’ soils were shallow and quite rich in rock fragments. The median depth of soils we measured was 0.4 m, with a minimum value of 0.1 m and a maximum value of over 1.2 m, the latter just in one plot in the maquis stand. The median value of stoniness, estimated by eye on the soil surface, was 16%, with a minimum value of <1% and a maximum value of over 34%. As a reference, a stone cover of 30% has shown to imply a consistent reduction of post-fire soil erosion (Prats et al., 2018). Soil texture was quite uniform in the investigated plots and ranged from sandy loam to loam, being composed by half sand and a third of total by silt on a weight basis.

* 1. *Analysis of the sediments*

The collected cores of sediments retained by the wooden check dam are shown in Fig. 7, while the organic matter content and particle size distribution of the different layers – confidently corresponding to the main episodes of deposition – are reported in Table 2. The maximum thickness of the sediment deposit, 71.5 cm, was individuated 13 m upstream of the dam. None of the cores contained rock fragments, i.e. larger than 2 mm, or coarse charcoal pieces, which were instead abundant in the ash layer covering the burned soils (Mastrolonardo et al., 2017).

The thickest core, core A, showed six distinct layers (A1 to A6, from the surface downwards). The A1‒A4 layers, overall 40.6 cm thick, were clearly made of post-fire eroded soil, as revealed by the blackish colour imposed by the abundant charred material (Table 2). The A4 was much richer in organic matter than all the overlying material, which was of course brought in by subsequent rainfall. The A5‒A6 layers, i.e. the bottom of the whole deposit (i.e. the first ones that settled), were much different from the upper ones, i.e. lighter, brownish in colour and poorer in organic matter. However, they differed each other in their organic matter content, the deeper one being poorer. In terms of particle size distribution, there was no clear discontinuity between the A1‒A4 and A5-A6 sediment layers (Table 2). Nevertheless, with the subsequent rainy events the deposited eroded soil tended to become increasingly coarser from base upward, i.e. richer in sand and poorer in silt (whereas clay was almost constant and amounting to around 10 %).

Core B was taken several meters upstream of Core A, where the sediment deposit was much thinner. The layers of which it was composed approximately corresponded to the ones in the uppermost 20 cm of core A. However, there were some discrepancies between the two cores, such as the much higher organic matter and sand contents in the deepest layer in core B compared to the relative layer in core A, most probably due to progressive selective deposition of particles on a weight basis.

Core E comprised four layers, including a brownish layer at the bottom, which is a similar material described at the base of core A in terms of thickness, organic matter content and particle size distribution. The blackish material, assumed to be from the burned area, had a more homogeneous appearance than in the other two cores, although still showing three distinct layers; actually, these latter were similar to each other in terms of both organic matter and particle size distribution. This homogeneity could be explained by the flow turbulences acting in the water close to the check dam, where the E core was from.

* 1. *Post-fire rainfall-runoff-erosion*

The average CNI calculated for the SP watershed was 71, considering the extent of the burned areas according to RBR map. Rainfall and runoff time series, together with the hypothesized deposition events for the SP watershed, are reported in Fig. 8, where the main flow events are associated with the six deposition events detected by the analysis of sediment core A. Coherently, layer A3 was assigned to the largest flow event.

Table 3 shows the overall results of the analysis, including the values used for STE calculation. The latter was performed considering the same Ci for events A4 and A3, and for events A2 and A1, since the two couples of events were very close in time.

By equation 1 and the available rainfall data, the Rt of the largest 30-minute event monitored was estimated to be 1 year. The main rainfall-runoff events recorded from October 28th to November 3rd, 2018, showed a significant correlation with the mass calculated for the deposition layers of Core A, when the six events are considered as a whole group (Fig. 9). However, a second interpretation of the results based on the separation of the A6‒A5 events from the A4‒A1 ones provided a better regression and additional insights. The sediment concentrations in the runoff events related to the A6 and A5 layers were similar (around 26 g l-1) and higher than the ones related to the events generating the A4 to A1 layers. Therefore, the two classes of events could represent two separated groups, both characterized by two linear relationships (forced to pass at 0) with R2 ~ 1 (Fig. 9). The values for the A4 to A1 layers were in line with those from other studies related to post-fire sedimentation (e.g., Ryan et al., 2011; García-Comendador et al., 2017), which amount to 10‒14 g l-1. Such relatively low sediment concentrations are due to the shallowness of soils in the study area and the abundance of outcrops and emerging rock fragments.

Comparing the precipitation and erosion events at the watershed scale, the soil erosion calculated for the SP basin in occasion of the rains immediately after the fire was 0.26 mm, corresponding to7.85 t ha-1. This value corresponded to 42% of the watershed average annual potential erosion rate in normal conditions (18.8 t ha-1 y-1) estimated with the USLE method (Regione Toscana, 2020).

1. **Discussion**
   1. *Sedimentation dynamics*

The sequence of sedimentary layers of Core A (Table 2 and Fig. 7) is quite counter-intuitive, since the bottom layers (A5-A6), which were deposited before layers A1-A4, are poor in charred residues, which are light and, consequently, more prone to be eroded. In this framework, we hypothesized that the first rainfall events and the subsequent peak flows initially transported to the sedimentation site those fire-unaffected sediments that were close or within the river stream, as found by Esposito et al. (2017) in a burned watershed in Southern Italy. Nunes et al. (2020) observed even very long delays in post-fire sediment transportation after evident soil erosion processes in a partially burned catchment in the north-western Iberian Peninsula. According to our above-mentioned hypothesis, the burned soil eroded from the watershed slopes reached the channel and was consequently trapped by the check dam after some hours from the beginning of the rain. This would explain the virtual lack of organic material in the A6 layer. Layer A5 was richer in organic matter than the underlying one, revealing that some of the burned sediments intermixed with the previously eroded material and reached the check dam site on the occasion of the second deposition event.

The increasing coarseness of texture from the bottom A6 layer to the A1 one could be a consequence of progressive depletion in silt-sized particles of the residual soil of the watershed. Shakesby et al. (2003), studying two small catchments in Australia on sandstone bedrock affected by fires of different severity, found that the sediments transported downstream were richer in organic matter, mostly charred, and contained more fines (<63 μm particles) than those deposited on slopes. Layer A3, the thickest one (20 cm), was rather homogenous and apparently put in place by a single runoff event, fast and uninterrupted. This is confirmed by the HMS model (Fig. 8), which shows that the A3 layer was generated by the largest runoff event, although it comprised two flow peaks induced by a bimodal rainfall pattern. On the contrary, the two overlying layers, A2 and A1, were finely stratified, suggesting a discontinuous deposition.

* 1. *Erosion rate and sediment yield*

The first two rains analyzed for the SP watershed – those that most plausibly originated the A6 and A5 layers – transported an overall higher concentration of sediments than the subsequent ones, which can be explained by one or both the following reasons: i) the first two floods have remobilized that C-poor material accumulated near the river bed or already in it (as explained in par. 3.3); and ii) the initial sediment yield has been fed by the operations for building some erosion control structures, including the check dams on the SP stream, as also found by other studies (e.g. Malvar et al., 2017). The second hypothesis is consistent with the lower presence of organic matter in the A6-A5 layers compared the overlying ones. Although the used model was not validated, leading to a relative uncertainty in the estimation of sediment concentrations, the differences between the first two events and the four following ones are consistent and can be considered representative of the overall sediment mobilization dynamics at catchment scale.

The estimated erosion rate in the SP watershed, 7.85 t ha-1, is comparable to that found in other studies, as, for instance, the one by Kampf et al. (2016), who measured an average loss of 5.9 t ha-1 after some summer storms, of comparable intensities than those described in this study, observed a couple of months after a fire that affected a forest stand composed predominantly by ponderosa pine on stony sandy loam soils in Colorado. On the other hand, our results are quite lower than those from other studies. For instance, Esposito et al. (2017) observed sediments yield ranging from 19.8 to 33.1 t ha-1 in a watershed 11 ha wide in Southern Italy on fresh volcanic deposits because of an intense rainstorm happened one month after a wildfire. Similarly, Robichaud et al. (2013) reported soil losses of 18.6 to 24.4 t ha-1 after two high-intensity rainstorms in a previously burned 4.6 ha wide watershed in Colorado. These studies, however, dealt with slightly higher intensity rainfalls than ours. On a longer term, again at the catchment scale, Mayor et al. (2007) measured 35 mm and 4.6 t ha-1 as total volume of runoff and sediments during 7 years (from 1999 to 2005) after a wildfire nearby Alicante, Spain. In a 72-km2 catchment in southern Italy, Grangeon et al. (2021) checked over an entire hydrological year including 21 flood events (from November 2010 to May 2011), finding that the mean sediment yield had increased by 5% and up to a maximum of 37% because of fire, ranging from 2.0 t ha−1yr−1 to 2.7 t ha−1yr−1 depending on the burned area. Simulating the fire sediment yield after a high-severity fire and post-fire logging activities using the SWAT model in two sub-basins ca. 2 km wide in southern Italy, De Girolamo et al. (2022) found values as high as 26‒54 t ha−1yr−1 (baseline values 9.5‒9.7 t ha−1yr−1), the variability strongly depending on the percentage of extension of the fire affected area. However, a comparison of our data with those from longer-term studies could be somewhat improper as we evaluated just the first rain events after the fire. Nonetheless, in the Mediterranean Basin the period of high susceptibility to erosion of burned soils is typically short as the maximum fire potential is during the dry summer (July-August), which is followed by a rainy autumn (Granged et al., 2011; Shakesby, 2011; Lucas-Borja et al., 2019).

The fire-induced impact on soil is the combination/interaction of various factors, in particular fire severity and extent, terrain slope, rainfall intensity and soil infiltrability (the “fire nexus” *sensu* Neary, 2019). The Pisan Mountains have steep slopes characterised by high erosion rates and the studied wildfire, whose severity was moderate to high, affected entire watersheds, theoretically triggering conditions for dramatic soil erosion even with relatively modest rainfall events. Nonetheless, this did not happen. Often, post-fire erosion rates in the Mediterranean area have been reported to be relatively modest, ranging from 0.016 to 13.1 t ha-1 year-1 (Shakesby, 2011), mainly because of the shallow, skeleton-rich soils that: i) provide limited amount of fines and: ii) are endowed of a stony pavement, which protects the underlying soil from erosion (Shakesby, 2011), encourages water infiltration and limits the formation of a continuous fire-induced water repellency layer (Urbanek and Shakesby, 2009; Wu et al., 2021). This could be the case for our study area, indeed.

A relatively moderate soil loss caused by a fire, however, does not necessarily correspond to an equally moderate negative impact on the ecosystem. In fact, most of the organic matter and nutrients are concentrated near the surface, so topsoil erosion negatively affects both soil fertility and water quality (Basso et al., 2019), especially in such already degraded, where even small soil losses are not sustainable and can have serious consequences in terms of land degradation (Verheijen et al., 2009; Shakesby et al., 2015). Here as elsewhere in the Mediterranean regions, the application of soil and water bioengineering solutions, such as cover and barrier treatments, can hinder the progression of erosion in a sustainable way (Florineth, 2012; Girona-García et al., 2021). Particularly in severely burned areas, targeted economically viable and effective measures are strongly requested to stabilize the slopes (Girona-García et al., 2021; Zaimes et al., 2020), as well as to drain and control runoff (Florineth, 2012).

1. **Conclusions**

This paper inspects the short-term hydrological impacts at watershed scale of a fire of moderate to high severity that involved the Pisan Mountains in central Italy. The high extent of the fire, the marked loss of vegetation cover, and the steep slopes would have suggested substantial post-fire soil erosion. Our watershed-scale investigation, carried out by a HEC-HMS model, and the sediment yields, inferred by sediment cores taken upstream the ultimate dam, allowed estimating the eroded soil through the dynamic calculation of STE. This amounted to 7.85 t ha-1, which is unexpectedly moderate considering the already high average annual potential erosion rate of the watershed.

The comparison of such findings with those from other studies in the Mediterranean area highlights that the post-fire hydrological response can be highly variable, even in comparable conditions of fire severity, wildfire scale, slope and post-fire rainfall. It supports the opportunity to rely on multiple studies targeting all the specific and diverse conditions for the prediction of hydrological and erosive risks and the management in fire-affected environments of Mediterranean regions. Even if characterised by some limitations, such as , the methodology implemented in our study is an example in this sense, taking into account burn severity, slope, soil characteristics, pre-fire land use, rainfall patterns etc., as well as other factors such as the potential downstream off-site damages to valuables. This methodology could be reproduced in all those cases where civil works aiming at retaining sediments are implemented but the available data are scarce. The results from such studies, if well integrated with watershed planning, are useful for indicating how quick check dams built for reducing the risk flood would fill, and if further infrastructures are needed.

**Declarations**

The authors have no relevant financial or non-financial interests to disclose.

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