Hydrol. Earth Syst. Sci. Discuss., 9, 10877–10916, 2012
www.hydrol-earth-syst-sci-discuss.net/9/10877/2012/
doi:10.5194/hessd-9-10877-2012

Hydrology and Earth System Sciences Discussions

Modeling postfire water erosion mitigation strategies

M. C. Rulli[1], L. Offeddu[1], and M. Santini[2]

[1]Politecnico di Milano, Piazza L. Da Vinci, 32, Milano, 20133 Italy
[2]Centro euroMediterraneo sui Cambiamenti Climatici, Lecce, Italy

Received: 4 September 2012 – Accepted: 17 September 2012 – Published: 27 September 2012

Correspondence to: M. C. Rulli (cristina.rulli@polimi.it)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Severe wildfires are often followed by significant increase in runoff and erosion, due to vegetation damages and changes in physical and chemical soil properties. Peak flows and sediment yields can increase up to two orders of magnitude becoming dangerous for human lives and ecosystem, especially in the wildland-urban interface. Watershed post fire rehabilitation measures are usually used to mitigate the effects of fire on runoff and erosion, by protecting soil from splash and shear stress detachment and enhancing its infiltration capacity. Modeling post fire erosion and erosion mitigation strategies can be useful in selecting the effectiveness of rehabilitation method. In this paper a distributed model based on Revised Universal Soil Loss Equation (RUSLE), properly parameterized for a Mediterranean basin located in Sardinia, is used to determine soil losses for six different scenarios describing both natural and post-fire basin condition, the last accounting also for the single and combined effect of different erosion mitigation measures. Fire effect on vegetation and soil properties have been mimed by changing soil drainage capacity and organic matter content, and RUSLE factors related to soil cover and protection measures.

Model results show for the analyzed rehabilitation treatments their effect in reducing the amount of soil losses with the peculiar characteristics of the spatial distribution of such changes.

1 Introduction

Forest fires in Mediterranean area are natural processes due to the mutual interactions between climate and vegetation forging the biodiversity typical of this ecosystem (e.g. Ursino and Rulli, 2011; Pausas and Paula, 2012). During the last decades the number, extent and severity of forest fires in the Mediterranean countries increased as a result of abandonment of agricultural lands, inadequate forest management, long seasonal droughts, environmental disturbances, human activities (e.g. Soulis et al., 2010; Rulli

HESSD

9, 10877–10916, 2012

Modeling postfire water erosion mitigation strategies

M. C. Rulli et al.

et al., 2006; Shakesby, 2011) leading to the alteration of natural fire regime. Follows that areas usually experiencing frequent low severity fires, are now hit by less frequent high severity fires and other areas, adapted to high severity fire, are now subjected to an increase in fire frequency (Fulé et al., 2008). As a results, mediterranean ecosystem is reducing its resilience to fire. Appropriate mitigation strategies can reduce the negative consequences of fire through a deep comprehension of fire effects and sustainable coexistence with forest fires, in terms of both human security and ecological processes (Pausas and Verdù, 2008).

Fire effects consist on direct damage of vegetation and alteration of physical and chemical soil properties which affect in turn the hydrological response and sediment erosion and transport (e.g. Moody et al., 2008; Andreu et al., 2001). In particular, both runoff and even more erosion in the first year after fire occurrence are often increased several times compared to natural condition (Rulli and Rosso, 2005). Measurements taken in the Sila Massif in Calabria (Italy) showed an 87 % increase in runoff on areas recently burned compared to non burned areas (Terranova et al., 2009), and rainfall simulations in Liguria (Italy) showed post-fire overland flow and sediment yield, respectively one and two orders of magnitude higher in a recently burnt site than in a long unburned site (Rulli et al., 2006).

Although the association among wildfire, flooding, increase in erosion and sedimentation has been observed all over the world (e.g. Benavides-Solorio and Mac Donald, 2005; Cerdà, 1998; Emmerich and Cox, 1994; Shakesby, 2011; Terranova et al. 2009) post wildfire research, especially regarding fire induced erosion enhancement, has a relatively brief history in the Mediterranean, starting from about the early 1980s (corresponding to the dramatic increase in fire activity) (Shakesby, 2011).

Burn severity has been identified as one of the most important variables affecting post fire changes in runoff response and soil losses (e.g. Fox et al., 2008). From low to high burn severity, the effect on erosion may vary from more than two orders of magnitude to only sevenfold, or no difference (Shakesby, 2011). Besides burn severity, many other factors concur in controlling post-fire runoff and erosion. Among these, are loss of organic matter (e.g. Soto and Diaz-Ferros, 1998), increase of bulk density (Neary et al., 2005), reduction of soil porosity and infiltration capacity (Robichaud et al., 2010), increase of soil water repellency (e.g. De Bano, 2000; Doerr et al., 2009). Other important factors, are rainfall intensity, slope and aspect, antecedent soil moisture (Wischmeyer and Smith, 1978), soil aggregate stability (Fox et al., 2008) grade of soil water repellency (Keizer et al., 2008), and the time interval between the fire episode and the occurrence of rainfall (Rulli et al., 2006). Univariate analysis conduced on sediment yields in Colorado Front Range burned hillslopes showed that about 77 % of the variability in post fire erosion rates is explained by five main factors: fire severity, bare soil percent cover, rainfall erosivity, soil water repellency and texture. Among these, bare soil percentage and rainfall erosivity alone explained 66 % of variability in soil loss measurements (Benavides-Solorio and Mac Donald, 2005).

Strategies for watershed post fire rehabilitation are mainly aimed to soil cover and infiltration capacity restoration, and sediment detachment and downslope sediment transport reduction (e.g. Fernàndez et al., 2010; Myronidis et al., 2009; Neary et al., 2005; Robichaud et al., 2010; Wohlgemuth et al., 2009) so acting mostly on soil characteristics like soil vegetation cover, erodibility, permeability or infiltration capacity.

There are many different mitigation strategies, which are suitable for diverse situations, and whose results depend on when, how and where they are applied (Wohlgemuth et al., 2009). Post fire treatments may be applied to hillslopes, channels and roadways. Treatments used on hillslopes can be divided in three main types: mulch treatments, erosion barriers and chemical treatments (Neary et al., 2005; Robichaud and Elliot, 2006). Hillslope treatments are designed to avoid sediment delivery to downstream water bodies and they are considered the most useful (Robichaud, 2009). Wagenbrenner et al. (2007) observed ground cover greatly influencing sediment production, meaning that the better performing treatments will be those immediately increasing the amount of ground cover and facilitating vegetative regrowth. Among these, mulch treatment is considered one of the most effective watershed rehabilitation treatment, consisting in spreading mulch on burned slopes, to provide soil surface cover prior

HESSD
9, 10877–10916, 2012

of vegetation regrowth. It produces soil protection from rain splash detachment and soil stabilization (Robichaud et al., 2007b; Wohlgemuth et al., 2009). For this purpose, several materials can be used: dry straw or wood-based mulches, wet mulches (hydro-mulch) mixed with water to form a slurry (Neary et al., 2005). Post-fire mulching needs to provide 60–80 % ground cover to reduce hillslope erosion (Robichaud et al., 2010). Some problems can arise by using this technique consisting in mulches slopes slipping down, aerially spread mulches residual vegetation interception, so reducing the actual ground cover and potential effectiveness (Neary et al., 2005; Robichaud et al., 2010).

Erosion barriers are commonly placed in a way to capture sediments and interrupt long flow paths, so decreasing downslope shear stress soil erosion and sediment transport on hillslopes and into streams. Erosion barriers can be contour-felled logs, straw wattles, contour trenches, straw bales (Neary et al., 2005). A barrier treatment performance can be defined as the ratio of dry weight of sediment stored by the barrier and dry weight of collected sediment below the barrier. Erosion barriers present some weakness reducing runoff and soil loss for low intensity rain events, but do not achieve significant results for high intensity events. In addition, the capacity of barriers can be overtopped soon after the first rain events, so determining the uselessness of not cleaned off barriers (Robichaud et al., 2010).

Rehabilitation treatments like ploughing or tilling on croplands burned areas are usually used to decrease soil aggregation and to break up the fire-induced water repellent soil layer to restore drainage capacity (Keizer et al., 2008).

Channel rehabilitation after fire is primarily done by cleaning channel beds and preventing obstruction of streams. The main treatments for these purposes are check dams or debris basins, debris clearing and streambank armoring (Neary et al., 2005).

Even if fire does not directly affect road drainage system, the increased overland flow can overwhelm its capacity. Mitigation measures as waterbars and bypasses, culvert improvements, ditch cleaning and armouring can enhance road drainage system functionality.

HESSD
9, 10877–10916, 2012

Despite the observation of large post fire increase in soil losses in the Mediterranean area (e.g. Shakesby, 2011 and the references herein) analysis of the efficiency of post-fire erosion mitigation strategies are very scarce. Field studies assessing the effectiveness of mulching and barriers were carried out in Spain (e.g. Badia and Martì, 2000; Bautista et al., 2009; Fernàndez et al., 2011) and in Portugal (Ferreira et al., 2009), but a systematic analysis at basin scale for the Mediterranean area is still lacking.

Given the complexity of fire-related issues, and the importance of fire effects on watershed response and erosion dynamics, accurate predictions of post-fire runoff and sediment yields are needed to guide management decisions, mitigate post-fire soil loss and land degradation and for post-fire rehabilitation planning (Fernàndez et al., 2010). Land use changes impact on soil losses prediction has been carried out by using different kind of modeling depending on study area extent, data availability and output degree of accuracy required. The Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing, 1995) and the disturbed-WEPP (Elliott et al., 2001) are process-based erosion prediction models evaluating mean erosion rate in natural and disturbed condition. ERMiT (Robichaud et al., 2007a) is a probability-based erosion prediction model using multiple runs of WEPP model and developed to predict surface erosion from postfire hillslopes, and to evaluate the potential effectiveness of various erosion mitigation practices. Empirical models based on the Revised Universal Soil Loss Equation (RUSLE) were used by several authors (e.g. Terranova et al., 2009; Fernández et al., 2010; Ranzi et al., 2011) to account for forest fire and land use changes effect on erosion in large scales basins. Fully distributed hydro-geomorphological model was developed by Rulli and Rosso (2005, 2007) for analyzing the both hydrological and erosion and deposition process dynamic for both natural and disturbed basin condition.

This paper investigates first year post fire erosion mitigation strategies effectiveness through a distributed model based on the Revised Universal Soil Loss Equation properly parameterized and validated, by using field measurements and literature data, for a Mediterranean basin located in Sardinia, Italy. Soil losses corresponding to six different scenarios are analyzed through appropriate RUSLE parameters changes so

HESSD
9, 10877–10916, 2012

describing the particular soil treatment to which the study area is subjected. In detail, the amount and spatial distribution of soil losses under natural condition, burned, after tilling/ploughing treatment, after mulching treatment, with barriers and after a combination of the all treatments are examined.

2 Study area

The study area is the Rio Mannu river basin, located in North Sardinia, Italy (Fig. 1).

Basin area is about 650 km^2, mean elevation 252 m a.s.l. (minimum and maximum elevation, respectively 0 m a.s.l. and 755 m a.s.l.), mean slope 8.5° (minimum and maximum slope, respectively 0° and 63°). Rio Mannu is located in the so-called Fossa Sarda, an area repeatedly interested in the past by marine transgressions, regressions and volcanic activity, when the territory has been invaded by the sea and covered with thick sediment layers forming a big tableland. Geology consists of limestone, granites, volcanic substrates, carbonate deposits. Climate is typically Mediterranean, with hot and dry summers and mild and rainy winters. Precipitation occurs mostly in November and December. Sudden floods may happen in winter, while the summer is usually droughty.

Crops cover 60 % of the basin area with main cultivation represented by olive groves and vineyards, which are 77 % and 10 % of total area, while 10 % are cork tree plantations (Regione Autonoma della Sardegna, 2000). Shrub and herbaceous vegetation cover 28.4 % of the basin, with 11 % natural pasture, 10 % typical Mediterranean sclerophyllous vegetation. Urban area is about 4.4 %, with Sassari and Porto Torres representing the main urban sites.

Sardinia region is one of the most fire prone area in the Mediterranean basin experiencing on average 850 fires per year burning about 19 000 ha. During year 2009, 684 fires occurred in the island burning 37 104 ha, most of them (17 000 ha) in the same province of the study area, the Rio Mannu basin itself was burned for about 4700 ha suffering both damages to vegetation (crops and forest) and considerable increase in soil loss (Regione Sardegna, 2010).

3 Materials and methods

Soil loss in the six different scenarios, that is natural, burned and after application of single and combined mitigation practices are analyzed, by using a spatially distributed model based on the Revised Universal Loss Equation (RUSLE) (Renard et al., 1997; McCool et al., 1995), parameterized for a Sardinian river basin. RUSLE is commonly adopted in erosion analysis for the simplicity of its structure and inputs and it is recognized to be appropriate for studies as the present one, where different erosion scenarios are analyzed and compared one with each other (e.g. Terranova et al., 2009; Ranzi et al., 2012), despite its application can produce an overprediction of low sediment fluxes, and underprediction of very high erosion (e.g. Terranova et al., 2009; Solorio and Mac Donald, 2005; Mac Donald, 2007).

Digital elevation model (DEM) at 25 m resolution, previously depitted following the physically based procedure introduced by Grimaldi et al. (2007), has been used to subdivide the study area in square cells of 25 by 25 m. Soil loss is then evaluated for each cell through RUSLE equation.

RUSLE quantifies soil losses ($\mathrm{t\,ha^{-1}\,yr^{-1}}$) as

$$A = R \cdot K \cdot \mathrm{LS} \cdot C \cdot P$$

where:

- *R* factor

  R is the rainfall-runoff erosivity factor ($\mathrm{MJ\,mm\,ha^{-1}\,h^{-1}\,yr^{-1}}$), calculated on the basis of average monthly cumulated rainfall; the R factor has been determined using the Fournier method, from mean cumulated yearly precipitation P_{year} and monthly precipitations P_i.

HESSD
9, 10877–10916, 2012

Given the Fournier index

$$F = \frac{\sum_{i=1}^{12} P_i^2}{P_{\text{year}}}$$

the R factor is calculated as

$$R = 4.17 \cdot F - 152$$

In the present study R is obtained for seven raingauge stations based on monthly rainfall dataset over a period of 15 yr (1982–2007) (APAT, 2009). Spatially distributed R factor has been obtained by applying Thiessen's polygon method.

R factor ranges from $161\,\text{MJ}\,\text{mm}\,\text{ha}^{-1}\,\text{h}^{-1}\,\text{yr}^{-1}$ in Porto Torres to $293\,\text{MJ}\,\text{mm}\,\text{ha}^{-1}\,\text{h}^{-1}\,\text{yr}^{-1}$ in Thiesi (Fig. 2a).

– K factor

K is the soil erodibility factor ($\text{t}\,\text{h}\,\text{MJ}^{-1}\,\text{mm}^{-1}$) (Fig. 2e), determined after Renard et al. (1997), i.e. calculated as

$$K = (k_0 \cdot k_t + k_s + k_d)/759.4$$

where k_0, k_t, k_s and k_d are subfactors depending on different soil characteristics, as texture, drainage capacity, structure (soil percentage of silt, sand and clay), and organic matter content (Fig. 2b–d):

$$\begin{array}{lll}
k_0 = 12 - \text{co} \cdot 1.7 & & (\text{co} = \text{soil organic carbon class}) \\
k_d = 2.5 \cdot (\text{cd} - 3) & & (\text{cd} = \text{soil drainage class}) \\
k_s = (2 - \text{cs}) \cdot 3.25 & & (\text{cs} = \text{soil structure class}) \\
\text{if } v_{fs} + \%_{\text{silt}} \leq 68 & k_t = \text{ct} & (\text{ct} = \text{soil texture class}) \\
\text{if } v_{fs} + \%_{\text{silt}} > 68 & k_t = \text{ct} - 0.67 \cdot (\text{ct} - 2.1 \cdot (6800(1 - \%_{\text{clay}})^{1.14})/10\,000)^{0.82} & \\
v_{fs} = 0.74 \cdot \%_{\text{sand}} - 0.62 \cdot \%_{\text{sand}}{}^2 & & v_{fs} = \text{percentage of very fine sand}
\end{array}$$

HESSD
9, 10877–10916, 2012
Modeling postfire water erosion mitigation strategies
M. C. Rulli et al.

The pedological map of Sardinia has been used for K factor determination. Table 1 reports RUSLE input value classification after pedological map of Sardinia.

- *C* factor

  C is the unitless cover and management factor. In this study C (Fig. 2f) has been determined on the base of CORINE Land Cover 2006 (Table 2), as described by Cebecauer et al., 2004.

- LS factor

  LS is the unitless slope length and steepness factor (Fig. 2g), which is mainly based on the cell's slope and contributing area; LS factor has been calculated using data from basin DEM. The calibration of model parameters has led to the use of the equation proposed by Moore and Burch (1986), where A_S is the area of plot cell per unit width (25 m), and β is the cell slope, computed from the basin DEM.

- *P* factor

  P is the support practice factor, accounting for the effect of rehabilitation treatments as well as for other features, like roads, streams or railways, or also changes in soil use hampering natural runoff and erosion path. The P factor is unitless and ranges from 0 to 1, depending on the type of erosion soil protection strategy. P factor has been properly determined in each one scenario.

4 Study scenarios

The influence of soil use (natural and burned) and three rehabilitation practices and their combination on soil losses have been analyzed referring to six scenarios which are described in the following.

HESSD
9, 10877–10916, 2012

1. The first scenario assesses soil loss at basin scale in natural (unburned) conditions. In this scenario the conservation practices factor *P* was set equal to 1 all over the basin, except for paved roads, railways and bare surface where *P* factor is set to 0, due to the lack of information on particular conservation practices for the study basin, the other RUSLE parameters have been evaluated as described in materials and methods section.

2. The second scenario analyzes fire effect on soil losses. During the summer 2009 a forest fire burned about 47 km^2 of the study area, Fig. 1 reports.

   In burned area fire effects on soil characteristics have been mimed by changing the C factor, soil drainage capacity, and soil organic matter content. Fire, in fact, induces both a increase in soil aggregation leading to an increase in bulk density and soil compaction and a decrease of soil cohesiveness (Andreu et al., 2001). Moreover, the combustion of the organic matter can lead to the formation of a soil hydrophobic layer affecting soil hydrologic properties (De Bano, 2000).

   Changing of conservation factor *C* in burned areas has been suggested by several authors. Terranova et al. (2009) assumed *C* equal to 0.2, 0.05, 0.01 corresponding to high, medium or low burn severity for burned area in Calabria region (Italy) having Mediterranean characteristics like the Rio Mannu basin. Another usually adopted hypothesis is to set *C* equal to 1 for areas with a percentage cover lower than 15 %. In Slovakia, a study on soil erosion assessment set *C* factor ranging 0.35–0.55 to areas classified as "burnt areas" in Corine Land Cover map (Cebecauer et al., 2004). Larsen et al. (2007) assigned to *C* factor on burned areas having maximum of 0.33 and mean of 0.2.

   For Rio Mannu basin burned area C factor was set equal to 0.2.

   Post fire organic matter decrease has been simulated by considering burned areas having fertility class one level lower than in natural condition and soil water repellency layer formation has been accounted by reducing soil drainage capacity which was set to drainage class "very slow".

HESSD
9, 10877–10916, 2012

3. The third scenario analyses the effects of rehabilitation treatments like ploughing or tilling on crop burned areas. The partial restoration of soils drainage capacity due to ploughing or tilling has been reproduced by assigning to under treatment burned area a one level lower drainage class then natural condition drainage class.

4. The fourth scenario studies the mulching rehabilitation practice. Straw mulch is considered one of the more cost-effective stabilization treatments in reducing post-fire erosion. Besides, wood mulches provide greater resistance to wind erosion than straw mulch and also they are more decay resistant than hydromulch (Robichaud et al., 2010).

   In this study, both straw and wood mulching on burned forested areas have been considered. In particular gentle slopes (slope < 30°) have been treated with straw mulching and steeper slopes (30–50 %) with wood chip mulching. The treatment has been applied on about 45 % of the burned slopes. Mulching effect on soil has been mimed by changing RUSLE parameters P and C. According to Fernàndez et al. (2010) $P = 0.343$ has been used for straw mulching on slopes < 30 % and $P = 0.943$ for wood chip mulch on slopes up to 50 % (Fig. 3a). In addition, the effect of seeding and regrowth of vegetation on soil erosion have been described through C factor. It was set equal to 0.13 corresponding to the mean value of C on the burned area prior the fire occurrence (Fig. 3b).

5. The fifth scenario analyses the effectiveness in capturing soil losses by erosion barriers or trenches on arable land. Barriers at the distance of 50 m along the contour lines were placed on crop land. This treatment is applied to a share of 35 % of the burned area. Barriers application as rehabilitation treatments is usually modeled by modifying RUSLE P factor. Wischmeier and Smith (1978) and later Terranova et al. (2009) propose a P factor of 0.2 for reverse bench terraces. Myronidis et al. (2009) distinguished P factor for treatments and slope. They set $P = 0.85$ for branch piles and woodboards on gentle slopes (< 30 %), $P = 0.75$ for

HESSD
9, 10877–10916, 2012

branch piles and woodboards or log terraces on steeper slopes (30 % to 50 %), and $P = 1$ for slopes greater than 50 %.

In this study, the P factor values introduced by Myronidis et al. (2009) were used (Fig. 3c).

6. The sixth scenario considers the combination of all rehabilitation practices described in the previous scenarios 3, 4 and 5. In particular the effectiveness of the treatments combination is tested by assuming the following pattern: tilling all over the burned area, mulching on woodland and erosion barriers or trenches on arable land. The P factor has been set accordingly as showed in Fig. 3d, and the C factor is the same as in scenario 4 (Fig. 2f).

5 Results

Table 3 shows the summary of results where simulated soil loss main statistics, corresponding to the six studied scenarios, are reported. In particular, the statistical analysis of erosion in natural condition (scenario 1) has been reported both for Rio Mannu basin and for the sub-area subjected to treatments (47 km^2). Soil losses corresponding to basin sub-area under treatments have been analyzed for scenarios 2–6.

5.1 Scenario 1: pre-fire estimated erosion

Mean soil loss calculated over the whole basin amounts to 1.9 $t\,ha^{-1}\,yr^{-1}$. Zonal statistic underlines significant differences in soil losses among areas having different soil use. Mean soil loss ranges from 0.12 $t\,ha^{-1}\,yr^{-1}$ on land classified as pasture, to 4.5–5.6 $t\,ha^{-1}\,yr^{-1}$ on areas cultivated with vines or olive trees, up to 20.5 $t\,ha^{-1}\,yr^{-1}$ in areas with little or no vegetation cover. In these areas, maximum soil loss estimations is 69 $t\,ha^{-1}\,yr^{-1}$, which is a quite high value due to the combination of the steepest slope very high values of RUSLE factors, The analysis shows values greater than 30 $t\,ha^{-1}\,yr^{-1}$ occurring in very few cells of the basin (0.24 %). In addition, the 99th

HESSD
9, 10877–10916, 2012
Modeling postfire water erosion mitigation strategies
M. C. Rulli et al.

percentile of the whole area soil loss is 19.4 $t ha^{-1} yr^{-1}$, and 90 % is 5.05 $t ha^{-1} yr^{-1}$ (Fig. 4).

5.2 Scenario 2: fire effect on erosion

Soil losses in the burned areas are considerably higher then in not fire affected condition being the mean soil loss 7.18 $t ha^{-1} yr^{-1}$, while maximum value is 45.1 $t ha^{-1} yr^{-1}$. The 99th percentile lies at 24.4 $t ha^{-1} yr^{-1}$, and 90th percentile at 16.4 $t ha^{-1} yr^{-1}$. In the first scenario, soil loss within the same area reach a mean value of only 2.01 $t ha^{-1} yr^{-1}$, and a maximum of 41.5 $t ha^{-1} yr^{-1}$. These values show that fire affect erosion by increasing mean soil loss by more than 150 % (Fig. 5a). Again, only a very small percentage of cells (0.20 %) have extremely high erosion values, above 30 $t ha^{-1} yr^{-1}$.

5.3 Scenario 3: soil loss after tilling/ploughing

Amelioration of the burned soil drainage capacity by ploughing or tilling is modeled to achieve some mitigation of erosion. Nevertheless, on burned areas, after treatment maximum soil loss is around 47 $t ha^{-1} yr^{-1}$, mean value decreases to 6.15 $t ha^{-1} yr^{-1}$, while 99 % of soil loss lies under 21.2 $t ha^{-1} yr^{-1}$, and 90 % under 14.1 $t ha^{-1} yr^{-1}$ (Fig. 5b).

5.4 Scenario 4: soil loss after mulching on woodland areas

The mulching treatment reduces soil loss considerably more than the previous treatment: although maximum soil loss calculated is 60.1 $t ha^{-1} yr^{-1}$, 99 % of cells show soil loss lesser than 18.0 $t ha^{-1} yr^{-1}$, and 90 % lesser than 5.4 $t ha^{-1} yr^{-1}$; mean value is 1.78 $t ha^{-1} yr^{-1}$ (Fig. 5c).

HESSD
9, 10877–10916, 2012

5.5 Scenario 5: soil loss with barriers on crops land

Barriers on arable land reduce soil loss less than mulching, but a little bit more than ploughing. Maximum soil loss on burned areas states at 45.1 $\mathrm{t\,ha^{-1}\,yr^{-1}}$, and mean value is 6.71 $\mathrm{t\,ha^{-1}\,yr^{-1}}$, 99 % lies under 24.1 $\mathrm{t\,ha^{-1}\,yr^{-1}}$, 90 % under 15.9 $\mathrm{t\,ha^{-1}\,yr^{-1}}$. All these values are very close to those obtained in scenario 3 (Fig. 5d).

5.6 Scenario 6: soil loss with application of all rehabilitation treatments on burned areas

Combination of three different rehabilitation treatments on burned area further improves soil losses' reduction. Mean soil loss estimated over the Rio Mannu basin is 1.50 $\mathrm{t\,ha^{-1}\,yr^{-1}}$, maximum soil loss is 52.7 $\mathrm{t\,ha^{-1}\,yr^{-1}}$; 99 % of cells have soil lesser tahn 15.1 $\mathrm{t\,ha^{-1}\,yr^{-1}}$, 90 % lesser than 4.5 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ (Fig. 5e).

6 Discussion

Measured mean erosion in Mediterranean Europe amounts to 1.3 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ (Cerdan et al., 2010). In Italy forty reservoirs sediment deposition dataset, acquired by direct sonar sub-bottom profiler measurements or derived from estimates and measures carried by Italian Electricity Power Company during reservoirs dredging (Van Rompaey et al., 2005), reports mean erosion of about 2.3 $\mathrm{t\,ha^{-1}\,yr^{-1}}$. Concerning Sardinia region, these measurements show mean erosion of about 4.0 $\mathrm{t\,ha^{-1}\,yr^{-1}}$. Measurements in Mulargia and Flumendosa basins, located south of island, show a mean erosion of 5.56 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ (respectively 10.3 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ and 0.9 $\mathrm{t\,ha^{-1}\,yr^{-1}}$) (Van Rompaey et al., 2003). Lower values are also recorded in Bonassai (SS), south-west of the studied area, where mean erosion rates lie around 0.025 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ (Acutis et al., 1996), and a field study carried out in Pattada (SS) reports a mean soil loss of 0.034 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ (0.049 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ on ploughed land, 0.048 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ on grassland, 0.033 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ on natural pasture, 0.014 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ on burned pasture, 0.025 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ on slashed

HESSD
9, 10877–10916, 2012
Modeling postfire water erosion mitigation strategies
M. C. Rulli et al.

bushland) (Rivoira et al., 1989); the authors themselves, though, note that these values have to be considered quite low for Sardinian conditions. Two field campaigns were carried out in Ottava (SS), a field site in the northern part of the Rio Mannu basin (Porqueddu and Roggero, 1994; Porqueddu et al., 2001). During first experiment, lasted from 1989 to 1991, soil loss on several soil uses (permanent pasture, annual forage crop, and continuously ploughed soil) were measured. The second experiment took place from 1994 to 1997, assessing soil loss data for four common crops of the Sardinian hilly areas which are natural pasture, improved pasture, annual forage crop and winter cereal. During the two experimental campaigns mean soil loss of, respectively 2.55 and 0.86 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ were measured. Table 4 reports soil losses for each soil use and for each experiment.

Our simulation results for the scenario 1, reported in detail in Table 5, show for Rio Mannu basin mean soil losses of 1.9 $\mathrm{t\,ha^{-1}\,yr^{-1}}$, that lies in the range of measured erosion data in Sardinia, South Italy and the Mediterranean Europe. Model results have been further compared with measurements of Ottava, the field site in the northern part of the Rio Mannu basin. Peak simulated soil losses in Rio Mannu basin corresponds to areas with spare vegetation, olive groves or vineyards. For these land use classes, zonal statistics provide soil losses of 55.4 $\mathrm{t\,ha^{-1}\,yr^{-1}}$, 13.72 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ and 10.9 $\mathrm{t\,ha^{-1}\,yr^{-1}}$, respectively. Indeed, peak values of 55.4 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ occur in very few cells (0.2 %) where the combination of steep slopes, high LS factor and C factor lead to such maxima. Cerdan et al. (2010), during their field experiments in Mediterranean environment, observed erosion on bare soil of 9.05 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ and on vineyards of 8.62 $\mathrm{t\,ha^{-1}\,yr^{-1}}$. Model performances in reproducing soil losses in selected soil uses as pasture, forage crops, cereals have been assessed by comparison with Ottava field campaigns measurements. Model simulations have been carried out both for a sub area located in the proximity of Ottava study site and for the whole Rio Mannu basin by using rainfall input being the measured rainfall in the same time period of when the experiment took place. Data coming from Sassari raingauge, the closest to Ottava, were used for sub area simulation, while for Rio Mannu 7 raingauges data properly spatialized formed the model input. Results, reported in detail in Table 6, show a good agreement with measurements especially among sub area simulations and second experiment results reporting mean erosion of 1.08 and 0.86 $t\,ha^{-1}\,yr^{-1}$, respectively. The model, despite its simplicity, adequately reproduces observed soil loss for the different land uses.

Scenario 2 results, assuming post-fire conditions, show mean soil loss of 7.18 $t\,ha^{-1}\,yr^{-1}$ on the burned area corresponding to an increase of almost +260 % compared to pre fire condition on the same area (mean soil losses equal to 2.01 $t\,ha^{-1}\,yr^{-1}$).

Before commenting this increase, it should be kept in mind that the variability of measured data concerning post fire erosion is unavoidable, depending on several factors, such as, among others, site specific characteristics, fire severity, rainfall intensity and total.

The few measured data on burned plots in Sardinia are those from Rio S. Lucia (Vacca et al., 2001), from Pattada (Rivoira et al., 1989) and from Ottava (Porqueddu and Roggero, 1994). Field experiments in S. Lucia basin report mean yearly soil loss on burned pasture lands of 0.06 $t\,ha^{-1}$, less than soil loss on slopes covered with shrub (0.11 $t\,ha^{-1}$) and with Eucalyptus (0.23 $t\,ha^{-1}$); in Pattada, the erosion on burned slope is 0.014 $t\,ha^{-1}\,yr^{-1}$, less than on ploughed land (0.049 $t\,ha^{-1}\,yr^{-1}$), grassland (0.048 $t\,ha^{-1}\,yr^{-1}$), natural pasture (0.033 $t\,ha^{-1}\,yr^{-1}$) and shrub (0.025 $t\,ha^{-1}\,yr^{-1}$); in Ottava, soil losses of 0.23 $t\,ha^{-1}\,yr^{-1}$ have been observed on burned plot, as shown in Table 4. In all three cases, the erosion values on burned soil do not significantly differ from values on unburned slopes. The authors themselves underline that such low values are probably not representing of the not controlled wild fire impact on soil losses and they are probably due to the very low severity of fire.

Some more useful evidence of fire forcing on erosion can be inferred from other studies, most of them carried out in Mediterranean environment, pointing out how most of the fire effect on soil loss depends on fire severity. Soto and Diaz-Ferros (1998) measured, in the first year after fire in Monte Pedroso (Galicia, Spain), soil loss of

HESSD
9, 10877–10916, 2012

12.4 t ha^{-1} on high severity burned plot, and on average 4.9 t ha^{-1} on two low severity burned plots, whereas the control plot erosion in the same year was 1.96 t ha^{-1}. These values show an increase in erosion of 150 % passing from unburned to low severity burned, and of 530 % from unburned to high severity burned plots. Moreover, measurements after several wildfires in the Colorado Front Range showed soil losses of 0.05 t ha^{-1} yr^{-1}, of 2 t ha^{-1} yr^{-1} and of 2–10 t ha^{-1} yr^{-1}, respectively in areas burnt by low, medium and high severity fire (Benavides-Solorio and Mac Donald, 2005), so representing an increase of more than two orders of magnitude from low severity to high severity fire. Further, mean post-fire erosion estimations in Greece report an increase of 570 % (Vafeidis et al., 2006) in post fire erosion, and plot scale erosion rates after rainfall simulations in the Branega catchment in Liguria (Italy) show ratios of 143 to 162 between a recently burned plot and a long unburned one, depending on soil moisture conditions before rainfall (Rulli et al., 2006).

According, simulation results in this study highlight the impact of fire in enhancing soil losses so showing the increase of maximum and mean erosion in the burned areas, as well as the increasing of the percentage of basin area affected by large soil losses (high level of erosion) (Tables 3 and 7).

The successive three scenarios investigate the effect of some post fire erosion mitigation treatments.

Scenario 3 mimics the breaking up of the hydrophobic layer by acting on the soil's drainage capacity. This treatment does not achieve significant reduction on soil erosion: mean soil loss on burned area is only 14 % less than in the scenario with burned soils (Table 3).

Mulching rehabilitation treatment on woodland (Scenario 4) shows a decreasing of 75 % in mean soil loss calculated over the whole burned area. The decrease in erosion is such that estimated soil loss becomes slightly lower than in the first scenario (Table 3).

Robichaud (2006) measured effectiveness for mulching treatments ranging from 63 % to 68 % for wood and straw mulch, while for hydromulch it ranged from 19 %

HESSD
9, 10877–10916, 2012

Modeling postfire water erosion mitigation strategies

M. C. Rulli et al.

to 27 %. During the first year after a fire in Galicia Fernàndez et al. (2011) measured that straw mulch application with 80 % soil cover produced a reduction of sediment production of 66 % compared with the control plots, while chip mulch application with 45 % soil cover produced almost no reduction of sediment yield (33 $\mathrm{Mg\,ha^{-1}}$ after treatment, 35 $\mathrm{Mg\,ha^{-1}}$ in the control plot). In our exercise rehabilitation treatment has been applied on about 45 % of the burned slopes, so that our results agree with the literature measured data.

Scenario 5, consisting on applying barriers on crop land, leads to a decrease of only 6.5 % in mean soil losses on the whole burned area, by applying the treatment to a share of 35 %. Robichaud (2006) found a reduction in soil losses due to the presence of barriers (contour felled logs) of about 20–50 % for mid- to high-intensity rainfall events. Accordingly, Fernàndez et al. (2011) observed that the initial mean efficiency of cut-shrub barriers in retaining sediment (58 %) decreased to 15 % four months after treatment. Measurements in burned plots treated with different barrier types (Robichaud et al., 2007) showed better performance for contour-felled logs and straw wattle treatment while contour trench showed no significant erosion mitigation effect.

Finally, scenario 6, studying the effects of the combination of the three different rehabilitation treatments, shows mean soil loss lower than the post fire scenario (79 %) and also the natural scenario (20 %) (Table 3).

Besides mean and maximum estimated soil losses, an interesting feature to observe for the six scenarios is the erosion levels distribution on the study area. In the present study four erosion levels have been defined: low, medium, high, very high having, respectively soil loss lesser than 0.5 $\mathrm{t\,ha^{-1}\,yr^{-1}}$; comprised between 0.5 and 2 $\mathrm{t\,ha^{-1}\,yr^{-1}}$; comprised between 2 and 8 $\mathrm{t\,ha^{-1}\,yr^{-1}}$; greater than 8 $\mathrm{t\,ha^{-1}\,yr^{-1}}$.

In the first scenario, the area of the Rio Mannu basin classified at very high erosion level is 5 % of total area, while 53 % of the basin presents low erosion level. High and moderate erosion levels cover 20 % and 22 % of the area, respectively.

Regarding the sub-area, 63 % shows low erosion level, 10.3 % moderate, 16.6 % high and 10.1 % very high (Fig. 6a).

In scenario 2, the area having very high level raises to 37 %, while low erosion level decreases to 11 % of the area. Also high level shows a considerable increase to 41 % of the total burned area, while moderate class remains around 12 % (Fig. 6b).

In the third scenario, where no significant reduction in term of mean or maximum soil loss estimations have been observed compared with scenario 2, there is nevertheless a remarkable decrease in the percentage of area affected by very high soil loss, which is 30 %, while high, moderate, and low are, respectively the 41 %, 12 % and 11 % (Fig. 6c).

Scenario 4, already reporting a significant contribution for soil loss mitigation in term of mean or maximum soil loss at treated area scale, shows that the effect of treatment in reducing soil loss is made more evident by the distribution of erosion levels over the area: only 6 % of area presents very high erosion level, 15 % high, 21 % moderate and as much as 58 % low (Fig. 6d).

In the fifth scenario, very high erosion affects 39 % of the area, and 16 % of it is classified as low in erosion level. This means an increase in low erosion zones and a decrease in very high erosion zones, while high or moderate erosion affects the same percentage of area as in the second scenario. As noticed before, the erosion barriers performance would be more appreciable if studied with a model for sediment propagation (Fig. 6e).

The last scenario shows that the area presenting low erosion is 62 %, whereas very high erosion occurs on just 4 % of it (Fig. 6f).

A summary of the erosion levels corresponding to the analyzed treatments is reported in Table 7.

7 Conclusions

In this paper a simple distributed model based on RUSLE equation has been presented and the analysis of several post erosion mitigation strategies has been carried out for the Rio Mannu basin. Modeling watershed response to erosion rehabilitation

HESSD
9, 10877–10916, 2012

treatments can be useful to choose the better soil losses mitigation methods, particularly in the Mediterranean area experiencing every year a large number of wildfires most of them at the interface with urban area.

Model results compared with the available field measurements and the detailed analysis of the treatments scenarios show distributed RUSLE capacity to be a simple and useful model for correctly reproduce soil losses in Rio Mannu basin and also for selecting the most appropriate treatment related to site characteristics. Nevertheless, a distributed model capable of representing sediment dynamic could better assess the efficiency of mitigation strategies, especially for erosion barriers.

Results showing changes both in soil losses total and on erosion levels among the six scenarios demonstrates the effectiveness of mitigation treatments on the Rio Mannu basin burned area, as well as the importance of choosing the most appropriate erosion mitigation strategies related to site characteristics. Choosing how to restore channels and slopes after a wildfire is an important issue, which could be properly dealt with, if more effort would be spent for the collection of field data before and after fires. In fact, most of the existing models, as the RUSLE based model used in this study, try to describe and quantify post-fire erosion considering variables like fire severity, percentage bare soil, rainfall erosivity, soil repellency, despite measures of these are not always available.

In the USA, Burned Area Emergency Rehabilitation (BAER) activities have been established for assessing the need and implementation of post-fire treatments so providing choice of treatments and essential protection (Neary, 2005; Robichaud, 2006). Since any treatment recommendation has to be matched to the specific environmental and climatic conditions of the area, models and parameterizations based on measurements made in the USA do not necessarily apply to Sardinian conditions. The choice of which treatment to apply, if any, should be based on careful scenario analysis and this can be only done if watershed characteristics and response to rehabilitation practices are well assessed through modeling based on field data parameterization.

HESSD
9, 10877–10916, 2012

Further efforts should therefore be directed to collect field data for the Mediterranean environment.

Accurate estimation of potential soil losses, coupled with evaluation of watershed rehabilitation effectiveness can useful to maintain soil loss and soil renewal rate at equilibrium, which is a critical issue for successful land management. Mitigation strategies of forest fires effects in the Mediterranean areas should be aimed toward sustainable coexistence with forest fires, in terms of both human security and ecological processes.

Acknowledgements. The financial support provided for this work by Regione Sardegna through the project named "methodology and indicators for fire risk assessment in rural-urban interface of Mediterranean environment" (MIUR CRP 2_565) is gratefully acknowledged.

References

Acutis, M., Argenti, G., Bersani, L., Bullitta, P., Caredda, S., Cavallero, A., Giordani, C., Grignani, C., Pardini, A., Porqueddu, C., Reyneri, A., Roggero, P. P., Sulas, L., Talamucci, P., and Zanchi, C.: Effetti di tipologie di suolo e colture foraggere sulle perdite per ruscellamento di azoto, fosforo e potassio in differenti areali italiani, Riv. Agron., 30, 329–338, 1996.

Andreu, V., Imeson, A. C., and Rubio, J. L.: Temporal changes in soil aggregates and water erosion after a wildfire in a Mediterranean pine forest, Catena, 44, 69–84, 2001.

Badia, D. and Marti, C.: Seeding and mulching treatments as conservation measures of two burned soils in the Central Ebro valley, NE Spain, Arid Soil Res. Rehabil., 13, 219–232, 2000.

Bautista, S., Robichaud, P. R., and Bladé, C.: Post-fire mulching, in: Fire Effects on Soils and Restoration Strategies, edited by: Cerdà, A. and Robichaud, P. R., Science Publishers, Enfield, NH, 353–372, 2009.

Benavides-Solorio, J. D. and Mac Donald, L. H.: Measurement and prediction of postfire erosion at the hillslope scale, Colorado Front Range, Int. J. Wildland Fire, 14, 1–18, 2005.

Campo, J., Andreu, V., Gimeno-García, E., González, O., and Rubio, J. L.: Occurrence of soil erosion after repeated experimental fires in a Mediterranean environment, Geomorphology, 82, 376–387, 2006.

Cebecauer, T., Súri, M., Hofierka, J., and Fulajtár, E.: Corine Land Cover in the context of soil erosion assessment at a regional scale, in: Workshop CORINE Land Cover 2000 in Germany and Europe and its use for environmental applications, 20–21 January 2004, Berlin, UBA Texte 04/04, ISSN 0722-186X, 131–137, 2004.
Cerdà, A.: Changes in overland flow and infiltration after a rangeland fire in Mediterranean scrubland, Hydrol. Process., 12, 1031–1042, 1998.
Cerdan, O., Govers, G., Le Bissonnais, Y., Van Oost, K., Poesen, J., Saby, N., Gobin, A., Vacca, A., Quinton, J., Auerswald, K., Klik, A., Kwaad, F. J. P. M., Raclot, D., Ionita, I., Rejman, J., Rousseva, S., Muxart, T., Roxo, M. J., and Dostal, T.: Rates and spatial variations of soil erosion in Europe: a study based on erosion plot data, Geomorphology, 122, 167–177, 2010.
DeBano, L. F.: The role of fire and soil heating on water repellency in wildland environments: a review, J. Hydrol., 231, 195– 206, 2000.
Doerr, S. H., Shakesby, R. A., and MacDonald, L. H.: Soil water repellency: a key factor in post-fire erosion, in: Fire Effects on Soils and Restoration Strategies, edited by: Cerdà, A. and Robichaud, P. R., Science Publishers, Enfield, NH, 197–223, 2009.
Elliot, W. J., Hall, D. E., and Graves, S. R., Disturbed WEPP: Forest Service interfaces for the Water Erosion Prediction Project (WEPP) computer model, Moscow, ID, US Department of Agriculture, Forest Service, Rocky Mountain Research Station, available at: http://forest.moscowfsl.wsu.edu/fswepp (last access: August 2012), 2009.
Emmerich, W. E. and Cox, J. R.: Changes of surface runoff and sediment production after a repeated rangeland burns', Soil Sci. Soc. Am. J., 58, 199–203, 1994.
Ferreira, A. J. D., Sande Silva, J., Coelho, C., Boulet, A. K., and Keizer, J. J.: The Portuguese experience in managing fire effects, in: Fire Effects on Soils and Restoration Strategies, edited by: Cerdà, A. and Robichaud, P. R., Science Publishers, Enfield, NH, 353–372, 2009.
Fernández, C., Vega, J. A., and Vieira, D. C. S.: Assessing soil erosion after fire and rehabilitation treatments in NW Spain: Performance of RUSLE and revised Morgan-Morgan-Finney models, Land Degrad. Dev., 21, 58–67, doi:10.1002/ldr.965, 2010.
Fernández, C., Vega, J. A., Jiménez, E., and Fonturbel, M. T.: Effectiveness of three post-fire treatments at reducing soil erosion in Galicia (NW Spain), Int. J. Wildland Fire, 20, 104–114, 2011.

HESSD
9, 10877–10916, 2012

Modeling postfire water erosion mitigation strategies

M. C. Rulli et al.

Flanagan, D. C. and Nearing, M. A.: USDA-Water Erosion Prediction Project: hillslope profile and watershed model documentation, NSERL Report No. 10, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, 1995.

Fox, D. M., Maselli, F., and Carrega, P.: Using SPOT images and field sampling to map burn severity and vegetation factors affecting post forest fire erosion risk, Catena, 75, 326–335, 2008.

Fulé, P. Z., Ribas, M., Gutiérrez, E., Vallejo, R., and Kaye, M. W.: Forest structure and fire history in an old Pinus nigra forest, Eastern Spain, Forest Ecol. Manag., 255, 1234–1242, 2008.

García Rodríguez, J. L. and Giménez Suárez, M. C.: Historical review of topographical factor, LS, of water erosion models, Aqua-LAC, 2, 56–61, 2010.

Grimaldi, S., Nardi, F., Benedetto, F. D., Istanbulluoglu, E., and Bras, R. L.: A physically-based method for removing pits in digital elevation models, Adv. Water. Resour., 30, 2151–2158, doi:10.1016/j.advwatres.2006.11.016, 2007.

Hydrological Annals: Regione Autonoma della Sardegna, Istituto Idrografico di Cagliari, 2009.

Keizer, J. J., Doerr, S. H., Malvar, M. C., Prats, S. A., Ferreira, R. S. V., Oñate, M. G., Coelho, C. O. A., and Ferreira, A. J. D.: Temporal variation in topsoil water repellency in two recently burnt eucalypt stands in North-Central Portugal, Catena, 74, 192–204, 2008.

Larsen, I. J. and Mac Donald, L. H.: Predicting postfire sediment yields at the hillslope scale: testing RUSLE and disturbed WEPP, Water Resour. Res., 43, W11412, doi:10.1029/2006WR005560, 2007.

McCool, D. K., Foster, G. R., Renard, K. G., Yoder, D. C., and Weesies, G. A.: The Revised Universal Soil Loss Equation, Department of Defense/Interagency Workshop on Technologies to Address Soil Erosion on Department of Defense Lands, San Antonio, TX, 11–15 June 1995.

Moody, J. A., Martin, D. A., Haire, S. L., and Kinner, D. A.: Linking runoff response to burn severity after a wildfire, Hydrol. Process., 22, 2063–2074, doi:10.1002/hyp.6806, 2008.

Myronidis, D. I., Emmanouloudis, D. A., Mitsopoulos, I. A., and Riggos, E. E.: Soil erosion potential after fire and rehabilitation treatments in Greece, Environ. Model. Assess., 15, 239–250, doi:10.1007/s10666-009-9199-1, 2010.

Neary, D. G., Ryan, K. C., and DeBano, L. F. (eds).: Wildland fire in ecosystems: effects of fire on soils and water, Gen. Tech. Rep. RMRS-GTR-42-Vol. 4, Ogden, UT, US Department of Agriculture, Forest Service, Rocky Mountain Research Station, 2005 (revised 2008).

HESSD

9, 10877–10916, 2012

Modeling postfire water erosion mitigation strategies

M. C. Rulli et al.

Ollesch, G. and Vacca, A.: Influence of time on measurement results of erosion plot studies, Soil Till Res., 67, 23–39, 2002.
Pausas, J. G. and Paula, S.: Fuel shapes the fire-climate relationship: evidence from Mediterranean ecosystems, Global Ecol. Biogeogr., doi:10.1111/j.1466-8238.2012.00769.x, 2012.
Pausas, J. G. and Verdú, M.: Fire reduces morphospace occupation in plant communities, Ecology, 89, 2181–186, 2008.
Petroselli, A.: LIDAR data and hydrological applications at the basin scale, Gisci. Remote Sens., 49, 139–162, doi:10.2747/1548-1603.49.1.139, 2012.
Porqueddu, C. and Roggero, P. P.: Effect of the agronomic techniques for the improvement of forage production on soil erosion of slopes in a Mediterranean environment (in Italian), Riv. Agron., 28, 364–370, 1994.
Porqueddu, C., Caredda, S., Sulas, L., Farina, R., and Fara, G.: Impact of crop intensification on soil erosion in farming systems based on cereal – annual and permanent forage production in a Sardinian hilly region, Riv. Agron., 35, 45–50, 2001 (in Italian).
Ranzi, R., Than Hung, L., and Rulli, M. C.: A RUSLE approach to model suspended sediment load in the Lo river (Vietnam): effects of reservoirs and land use changes, J. Hydrol., 422, 17–29, 2012.
Regione Autonoma della Sardegna: Water Resources Report, 2006.
Regione Autonoma della Sardegna: Fire Service Statistics, 2009.
Robichaud, P. R. and Elliot, W. J.: Protection from erosion following wildfire, Presentation at the 2006 ASABE Annual International Meeting, ASABE Paper No. 068009, American Society of Agricultural and Biological Engineers, 2006.
Robichaud, P. R., Beyers, J. L., and Neary, D. G.: Evaluating the effectiveness of postfire rehabilitation treatments, Gen. Tech. Rep., RMRS-GTR-63, USDA Forest Service, 2000.
Robichaud, P. R., Elliott, W. J., Pierson, F. B., Hall, D. E., Moffet, C. A., and Ashmun, L. E.: Erosion Risk Management Tool (ERMiT) user manual (version 2006-01.18), Gen. Tech. Rep., RMRS-GTR188, USDA Forest Service, 2007a.
Robichaud, P. R., Pierson, F. B., Brown R. E., and Wagenbrenner, J. W.: Measuring effectiveness of three postfire hillslope erosion barrier treatments, Western Montana, USA, Hydrol. Process., 22, 159–170, 2007b.
Robichaud, P. R., Wagenbrenner, J. W., Brown, R. E., Wohlgemuth, P. M., and Beyers, J. L.: Evaluating the effectiveness of contour-felled log erosion barriers as a post-fire runoff and

erosion mitigation treatments in the Western United States, Int. J. Wildland Fire, 17, 255–273, 2008.
Robichaud, P. R., Ashmun, L. E., and Sims, B. D.: Post-Fire Treatment Effectiveness for Hillslope Stabilization, Gen. Tech. Rep., RMRSGTR-240, USDA Forest Service, Rocky Mountain Research Station, 2010.
Rivoira, G., Roggero, P. P., and Bullitta, S. M.: Improvement techniques and erosion of hillside pasturelands (in Italian), Riv. Agron., 23, 372–377, 1989.
Rulli, M. C. and Rosso, R.: Modeling catchment erosion after wildfires in the San Gabriel Mountains of Southern California, Geophys. Res. Lett., 32, 1–4, doi:10.1029/2005GL023635, 2005.
Rulli, M. C. and Rosso R.: Hydrologic response of upland catchments to wildfires, Adv. Water Resour., 30, 2072–2086, 2007.
Rulli, M. C., Spada, M., Bozzi, S., Bocchiola, D., and Rosso, R.: Rainfall simulations on a fire disturbed Mediterranean area, J. Hydrol., 327, 323–338, 2006.
Shakesby, R. A.: Post-wildfire soil erosion in the Mediterranean: review and future research directions, Earth Sci. Rev., 105, 71–100, 2011.
Soto, B. and Diaz-Fierros, F.: Runoff and soil erosion from areas of burnt scrub: comparison of experimental results with those predicted by the WEPP model, Catena, 31, 257–270, 1998.
Soulis, K., Valiantzas, J., and Dercas, N.: Modelling forest fires hydrological impact using spatio-temporal geographical data, in: International Congress on Environmental Modelling and Software, Modelling for Environment's Sake, Fifth Biennial Meeting (iEMSs), Ottawa, Canada, 2010.
Terranova, O., Antronico, L., Coscarelli, R., and Iaquinta, P.: Soil erosion risk scenarios in the Mediterranean environment using RUSLE and GIS: an application model for Calabria (Southern Italy), Geomorphology, 112, 228–245, 2009.
Ursino, N. and Rulli, M. C.: Hydrological minimal model for fire regime assessment in a Mediterranean ecosystem, Water Resour. Res., 47, W11526, doi:10.1029/2011WR010758, 2011.
Vacca, A., Loddo, S., Ollesch, G., Puddu, R., Serra, G., Tomasi, D., and Aru, A.: Measurement of runoff and soil erosion in three areas under different land use in Sardinia, Italy, Catena, 40, 69–92, 2000.
Vafeidis, A. T., Drake, N. A., and Wainwright, J.: A proposed method for modelling the hydrologic response of catchments to burning with the use of remote sensing and GIS, Catena, 70, 396–409, 2007.

HESSD
9, 10877–10916, 2012

Modeling postfire water erosion mitigation strategies

M. C. Rulli et al.

Van Rompaey, A. J. J., Bazzoffi, P., Jones, R. J. A., Montanarella, L., and Govers, G.: Validation of Soil Erosion Risk Assessments in Italy, in: European Soil Bureau Research Report No. 12, EUR 20676 EN, Office for Official Publications of the European Communities, Luxembourg, 2003.

Van Rompaey, A. J. J., Bazzoffi, P., Jones, R. J. A., and Montanarella, L.: Modeling sediment yields in Italian catchments, Geomorphology, 65, 157–169, 2005.

Wagenbrenner, J. W., Mac Donald, L. H., and Rough, D.: Effectiveness of three post-fire rehabilitation treatments in the Colorado Front Range, Hydrol. Process., 20, 2989–3006, doi:10.1002/HYP.6146, 2006.

Wohlgemuth, P. M., Beyers, J. L., and Hubbert, K. R.: Rehabilitation strategies after fire: the California, USA experience, in: Fire effects on soils and restoration strategies, edited by: Cerdà, A. and Robichaud, P. R., Science Publishers, Enfield, NH, 511–535, 2009.

Wischmeier, W. H. and Smith, D. D.: Predicting rainfall erosion losses, in: Agriculture Handbook, 537, Agriculture Research Service, US Department of Agriculture, Washington, DC, USA, 1978.

HESSD

9, 10877–10916, 2012

Modeling postfire water erosion mitigation strategies

M. C. Rulli et al.

Table 1. RUSLE input value classification after pedological map of Sardinia.

Drainage class	Excessive	Good	Moderate	Imperfect	Slow	Very slow	Other
RUSLE input values	1	2	3	4	5	6	7

Fertility class	Low	Medium	High	Very high	Other
RUSLE input values	1	2	3	4	5

Texture class	Coarse	Medium	Medium fine	Fine	Very fine	Other
	RUSLE input values					
Texture	1	2	3	4	5	6
Clay %	0.079	0.176	0.170	0.460	0.733	0
Silt %	0.136	0.404	0.760	0.270	0.133	0
Sand %	0.786	0.420	0.070	0.270	0.133	0
Structure	1	1	1	1	2	0

HESSD
9, 10877–10916, 2012

Table 2. *C* factor assignment after CORINE Land Cover class 2006.

Soil use	*C* factor	CORINE Land Cover Class	Description
High	0.001–0.01	14 ×, 231, 31 ×, 32 ×, 41 ×	Artificial vegetated areas, pastures, forests, scrub and herbaceous associations, inland wetlands
Moderate	0.1	241, 243, 244	Annual crops with permanent crops, agricultural land with natural vegetation, agro-forestry areas
Low	0.165–0.0335	211, 212, 242	Arable land, complex cultivation patterns
Very low	0.350–0.550	22 ×, 333	Permanent crops, sparsely vegetated areas
Not classified	0	11 ×, 12 ×, 13 ×, 331, 332, 51 ×	Urban, industrial, transport units, sands, rocks, waters

HESSD
9, 10877–10916, 2012

Table 3. Simulated soil loss corresponding to the six studied scenarios. Erosion in natural condition (scenario 1) has been reported both for Rio Mannu basin and for the sub-area subjected to treatments in scenarios 2–6. Soil losses corresponding to basin sub-area under treatments are reported in scenarios 2–6.

Simulated soil loss ($t\,ha^{-1}\,yr^{-1}$)	Mean	99th percentile	90th percentile
Scenario 1 (basin area)	1.90	19.4	5.1
Scenario 1 (sub-area)	2.01	18.6	5.6
Scenario 2 (sub-area)	7.18	24.2	16.4
Scenario 3 (sub-area)	6.15	21.2	14.1
Scenario 4 (sub-area)	1.78	18.0	5.4
Scenario 5 (sub-area)	6.71	24.1	15.9
Scenario 6 (sub-area)	1.50	15.1	4.5

HESSD
9, 10877–10916, 2012

Table 4. Measured soil loss in Ottava at Rio Mannu basin.

Field campaigns	Mean yearly precipitation (mm)	Measured soil loss ($t\,ha^{-1}\,yr^{-1}$) in Ottava Soil use				
		Overall pasture	Burned pasture	Annual	Forage crop	Ploughed
1989–1990	435		0.09	0.05	0.59	1.04
1990–1991	702		0.08	0.06	2.86	8.38
1991–1992	569		0.6	0.57	3.83	5.45
Mean value	569	2.55	0.26	0.23	2.43	4.96
		Overall	Natural pasture	Improved pasture	Annual forage crop	Winter cereal
1994–1995	566		0.08	0.12	2.05	1.03
1995–1996	546		0.03	0.03	0.06	0.06
1996–1997	429		0.08	0.48	3.25	1.16
Mean value	514	0.86	0.06	0.21	1.78	0.75

HESSD
9, 10877–10916, 2012

Modeling postfire water erosion mitigation strategies

M. C. Rulli et al.

Table 5. Simulated soil losses in the area of Ottava.

Study area	Mean yearly precipitation (mm)	Land Cover	Area (km^2)	Simulated soil loss ($t\,ha^{-1}\,yr^{-1}$)	
				Mean	Max
Rio Mannu – around Ottava	530 (Sassari raingauge)	Olive groves	0.5	1.5	5.86
		Complex cultivation patterns	1.24	1.03	12.41
		Natural pasture	0.1	0.02	0.09
		Non-irrigated arable land	1.63	1.61	14.76
		Annual crops with permanent crops	0.02	0.3	0.48
		Broad-leaved forests	0.02	0.02	0.07
		Mediterranean maquis/ sclerophyllous vegetation	0.17	0.07	0.26
		Natural transitional woodland-shrub	0.09	0.03	0.23
		Other	1.17	0	0
Rio Mannu – whole basin	528 (7 raingauges)	Permanent crops	79.30	4.17	65.20
		Annual crops	10.00	1.27	20.47
		Forests	39.60	0.12	0.88
		Moors and heathland	55.50	0.14	0.83
		Arable land	330.30	2.15	35.19
		Pastures	67.80	0.15	0.91
		Spare vegetated areas	1.50	20.50	69.02
		Transitional woodland-shrub	14.10	0.14	0.77
		Agro-forestry areas	9.40	1.60	9.88
		Other	40.50	0.00	0.00

HESSD
9, 10877–10916, 2012

HESSD
9, 10877–10916, 2012

Table 6. Simulated soil losses vs. measured soil losses for the area of Ottava and for the Rio Mannu basin.

Observed precipitation ($mm\,yr^{-1}$) Soil use	Ottava 1989–1991	Ottava 1994–1997	Rio Mannu at Ottava	Rio Mannu whole basin
	569	514	530 (Sassari raingauge)	528 (7 Raingauges)
	Measured soil loss ($t\,ha^{-1}\,yr^{-1}$)		Simulated soil loss ($t\,ha^{-1}\,yr^{-1}$)	
Pasture	0.26	0.06	0.02	0.15
Annual forage crop/Annual crops	2.43	1.78	1.61	1.27
Ploughed/Cereal/Arable land	4.96	0.75	1.61	2.15
Average soil losses	2.55	0.86	1.08	1.19

HESSD
9, 10877–10916, 2012

Modeling postfire water erosion mitigation strategies

M. C. Rulli et al.

Table 7. Percentage of under treatment area (47 km^2) having different erosion levels.

	Erosion level			
Scenario	Low	Moderate	High	Very high
Scenario 1	56 %	14 %	25 %	5 %
Scenario 2	11 %	12 %	41 %	36 %
Scenario 3	11 %	15 %	44 %	30 %
Scenario 4	58 %	21 %	15 %	6 %
Scenario 5	16 %	11 %	39 %	34 %
Scenario 6	62 %	19 %	15 %	4 %

HESSD

9, 10877–10916, 2012

Modeling postfire water erosion mitigation strategies

M. C. Rulli et al.

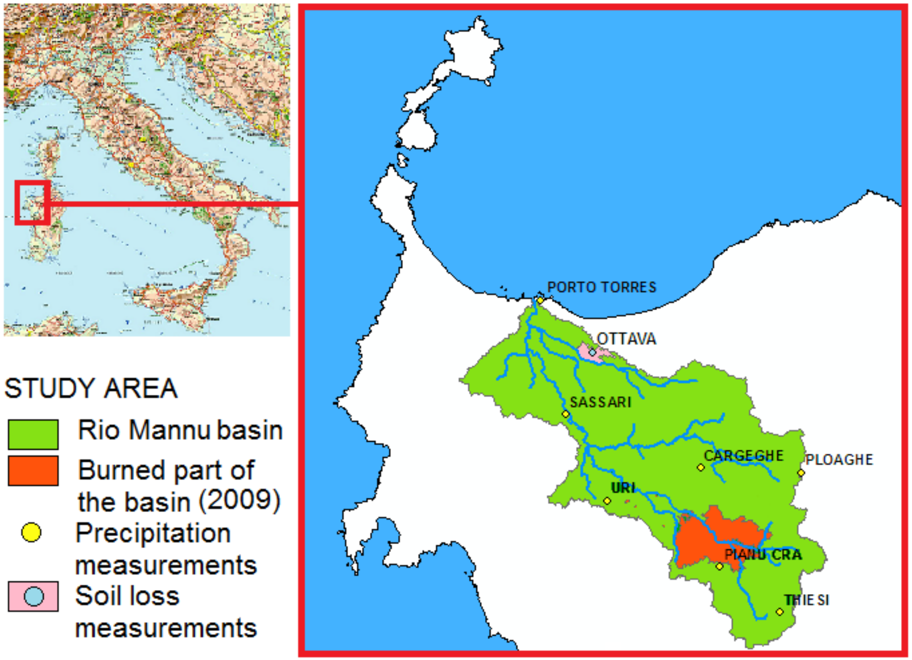

Fig. 1. Rio Mannu watershed, Northern Sardinia. The red colour represents the burned area following 2009 fire event. The pink area represents field campaigns sites (Porqueddu and Roggero, 1994; Porqueddu et al., 2001). Yellow circles denote raingauge positions.

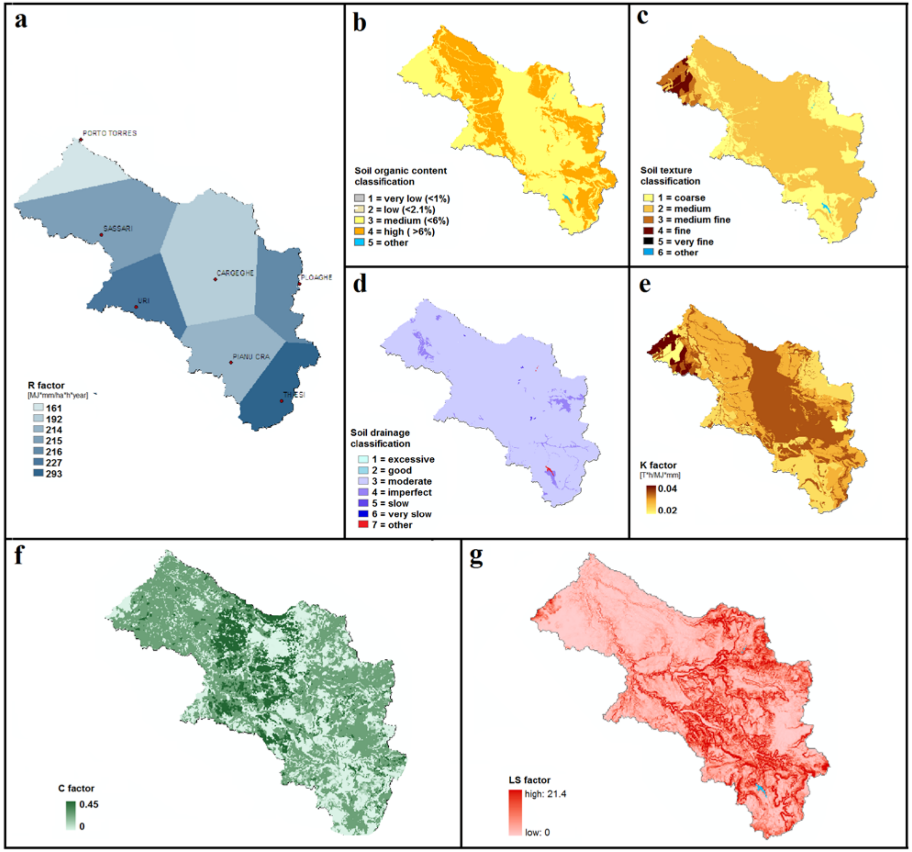

Fig. 2. RUSLE parameters for Rio Mannu basin.

HESSD

9, 10877–10916, 2012

Modeling postfire water erosion mitigation strategies

M. C. Rulli et al.

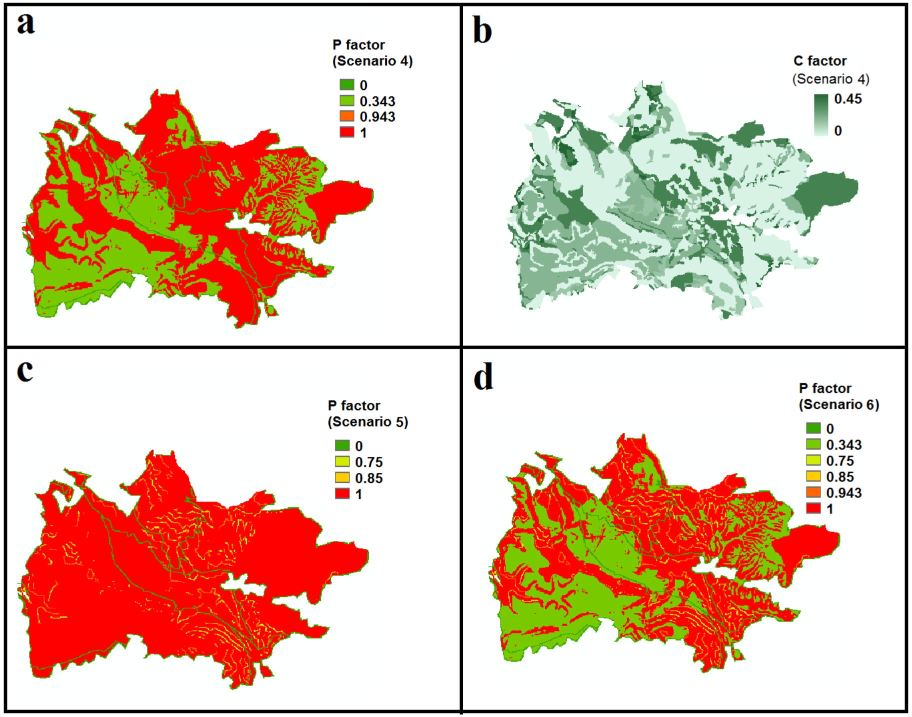

Fig. 3. RUSLE parameters after erosion mitigation strategies.

HESSD
9, 10877–10916, 2012

Modeling postfire water erosion mitigation strategies

M. C. Rulli et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

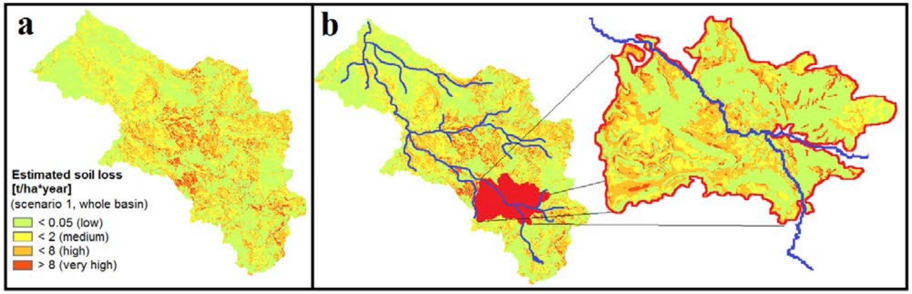

Fig. 4. Simulated soil losses under natural condition (Scenario 1).

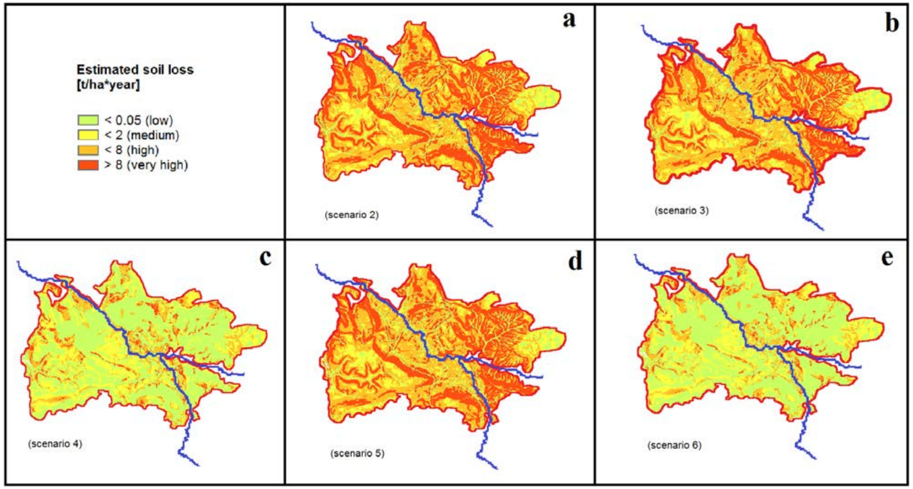

Fig. 5. Simulated soil losses under: **(a)** burned scenario (Scenario 2); **(b)** to **(d)** single soil erosion mitigation treatments (Scenario 3–5); and **(e)** combined mitigation treatments (Scenario 6).

HESSD
9, 10877–10916, 2012

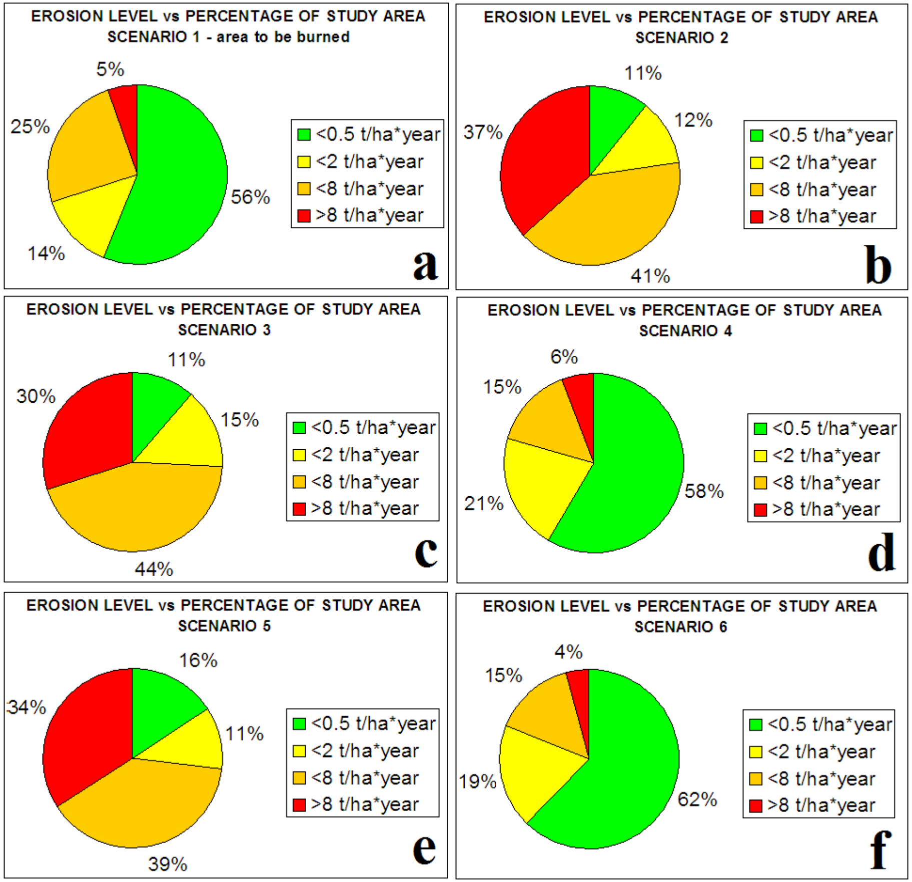

Fig. 6. Erosion level in the study area.

HESSD
9, 10877–10916, 2012

Modeling postfire water erosion mitigation strategies

M. C. Rulli et al.