NATURAL DISASTER RESEARCH, PREDICTION AND MITIGATION

WILDFIRES

PERSPECTIVES, ISSUES AND CHALLENGES OF THE 21ST CENTURY

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Chapter 10

Assessing Performance of Post-Fire Hillslope Erosion Control Measures Designed for Different Implementation Scenarios in NE Portugal: Simulations Applying USLE

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Abstract

Wildfires are common in NE Portugal, annually affecting large areas and contributing to increase soil degradation in a territory under severe erosion risk. Wildfires dominantly occur in forests and scrubland that cover mountain areas all over the region. Post-fire measures, required for erosion control in such hillslopes, if applied, currently lack background design.

The research aimed at assessing performance of erosion control measures in hillslopes representing different implementation scenarios in Bragança District, NE Portugal (6608 km^2).

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Methodology applied involved building up regional scenarios for simulated application of common post-fire measures (seeding and contour barriers), using USLE procedures. Variability of precipitation, soil and slope gradient across the region was represented by 14 simulation scenarios, for which potential erosion was calculated with USLE R, K and S factors, regionally assessed in previous work by the authors. Scenarios correspond to a range of susceptibility of burnt areas across the region, represented by potential erosion. Different sediment retention degrees and spacing of contour barriers (made with burnt vegetation residues) were simulated, exploring USLE L factor to estimate their effectiveness in reducing erosion. Seeding herbaceous vegetation as a post fire measure was simulated applying USLE C factor and considering vegetation growth rates typical of each scenario. Post-fire measures were classified according to their performance in reducing potential erosion to tolerable rates in the different implementation scenarios: low, moderate, and high performance with, respectively, erosion rates > 10 Mg ha^{-1} y^{-1}, 10 – 2 Mg ha^{-1} y^{-1}, and < 2 Mg ha^{-1} y^{-1}.

Seeding is a low performance measure and re-seeding next post-fire year is recommended. Contour barriers show generally high performance, yet dependent on design parameters. In fact, increasing barrier retention degree is more effective than reducing spacing between barriers, a result that highlights the need of well built contour barriers. The combination of the two measures has a high performance in most scenarios, thus recommending its wide application across the region. These results point out the importance of adequately designed post-fire measures, adapted to the regional diversity of potential erosion conditions, in order to mitigate impacts and accelerate recovery of NE Portugal burnt areas.

Keywords: hillslope erosion, burnt areas, post-fire recovery, USLE, NE Portugal

INTRODUCTION

Wildfires are common in NE Portugal, annually affecting large tracts of this mountain territory, following the pattern prevailing along the Mediterranean basin (Pausas et al. 2008). Burnt surfaces are exposed to accelerated erosion and soil loss is a major damage to fragile environments as mountain areas (Korner & Ohsawa, 2005; Price, 2015). Rehabilitation of burnt areas is key to mitigate off-site impacts of soil erosion and to reestablish soil functions as vegetation support, hydrological processes regulation and nutrient cycling (Alexandre, 2015).

Post-fire erosion control measures are meant to control runoff, limit soil loss and accelerate restoration of soil functions in burnt areas (Shakesby, 2011). Post-fire measures comprise a set of solutions to meet these purposes. Furthermore, cost effectiveness is the main driver of post-fire erosion control measures, meaning that performance must comply with feasibility. Measures applied in hillslopes may be based on revegetation, mulching, soil conditioners or contour barriers (Vega et al. 2013).

Contour barriers are regularly spaced along the hillslope to control runoff development and promote retention of eroded soil particles coming from the upslope contributing area, and may be mechanically built and consist on furrow-like retention ditches or vegetation based. In the latter, building materials are either external inputs, as it is the case of straw barriers, or burnt and unburnt vegetation debris assembled in the area, which is actually the lower cost measure. Results of experiments with burnt vegetation contour barriers by Badía et al. (2015) are not consistent with those of Fernández & Vega (2016), erosion control performance was high in the first case and low in the second one. Experimental design of both studies, however, indicates that results correspond to barriers retention degree (dependent on building quality), and barriers spacing was not tested.

Revegetation implies seeding mixtures of herbaceous species, selected to combine different growth rates and resistance to very limiting soil conditions. Seeds are directly spread onto the ground with no prior operation, commonly in the Autumn following wilfires, in order to provide the adequate soil cover during the wet season, thought to be reached faster than with natural recovery based on soil seed bank. In their experiment, Vega et al. (2014) found slow cover development in the first year after seeding, actually similar of that of native vegetation.

Mulches cover the ground with materials as straw or forest residues in order to prevent direct rainfall impact on soil surface. Results by Vega et al. (2014) and Fernández & Vega (2016) show that the application of 1.5 Mg ha^{-1} was able to reduce erosion to 38% of the untreated soil, in the first 3 years after fire, qualifying this performance as low. Prats et al. (2012) applied forest residue mulches in two forest plantations (eucalyptus and pine) and results were sharply different as in the eucaliptus forest the technique was highly performing in reducing erosion, while in the pine forest it had no significant effect. Hydromulching was also applied by Prats et al. (2016) to burnt areas and the technique was high performing, reducing soil loss by 80%, besides improving soil physical properties. Smets et al. (2008b) stress that mulching performance assessments is much affected by the spatial scale, which may explain differences in results from the above cited experiments, especially plot length (Smets et al. 2008a).

Soil conditioners are synthetic compounds applied to soil surface to increase aggregate stability and improve soil resistance to erosion processes. Prats et al. (2012) tested polyacrylamid as a so called emergency measure in burnt areas, yet with no significant effects in reducing soil loss.

Experimental results reported above show that consistent information on post-fire measure performance is still scarce so as to allow reliable design and selection of measures to be implemented. Model-based approaches to estimate measures performance were carried out by Vieira et al. (2016) obtained encouraging results with the modified M-M-F model. Fernández & Vega (2016) found RUSLE to yield better results than PESERA, the two erosion models applied in their study. In any case, research developments on measures performance assessment are still required to better design and guide well grounded selection of post-fire erosion control measures.

In Bragança District, an administrative division of NE Portugal, environmental threat chain associates desertification, soil degradation by water erosion and fire hazard, in mutual feedbacks. Moderate and severe desertification susceptibility affects near 3/4 of the territory. Soil degradation status is severe in 38% of Bragança District, mainly caused by inadequate land use and land management practices, and by wildfires, whereby fire hazard is high and very high in 62% of the area. Main land uses affected by wildfires, as forests and scrubland, cover 76% of Bragança District, with an increasing proportion in scrublands due to land abandonment (Figueiredo et al. 2014).

Total area burnt in the last 15 years (2005 – 2014) summed up 808 km^2, or 12% of Bragança District, meaning an average annual generation of ca. 60 km^2 burnt areas, where vegetation potentially providing soil protection is lost, and thereby the soil (calculations based on official statistic by the Portuguese Institute for Nature Conservation and Forest, ICNF, www.icnf.pt). Post-fire erosion control measures were part of emergency plans, following ICNF (2006) rules, to protect and recover burnt areas after a large wildfire in Picões, July 2013, affecting 130 km^2 (ICNF 2013). Yet, this is not a procedure applied in most of burnt areas in Bragança District. As a costly operation, and following Picões experience, recovery plans should be prepared for application scenarios across the region and a model approach to guide recommendations is seemingly adequate to such purpose and to the regional scale.

Research presented in this paper aimed at assessing performance of simulated post-fire erosion control measures applied in hillslopes representing different implementation scenarios in Bragança District, NE Portugal, using USLE erosion model.

METHODS

Study Area

The study focused in Bragança District, an administrative unit that covers an area of about 6608 km^2 in the most northeastern corner of Continental Portugal, stretching approximately from 41° N to 42° N and from 6° 11' W to 7° 26' W (Figure 1). The area is geographically bounded by the Douro River at south and east, and borders Spain at north and east.

Mediteranean climate prevails in the Region (Csb according to Koppen classification; Köppen 1936; Peel et al., 2007), with less than 10% annual rainfall occuring in the Summer months. This general pattern is combined with an increasing continental influence eastwards, due to the effect of mountain ranges located west of the region, aligned NNW-SSE and rising above 1500 m, that limit the atlantic influence common in at this latitude and therefore decreases rainfall and increases temperature range eastwards. Also, as a mountain area, the region depicts sharp climatic contrasts due to altitude, and this helps defining the main regional climatic domains, labelled as "Terra Fria" (Cold Land), mostly above 700 m elevation with average annual temperature, T, lower than 12ºC, and "Terra Quente" (Warm Land) mostly below 400 m elevation with T > 14ºC. Futhermore, above 1200 m elevation, mean annual precipitation (P) is higher than 1400 mm, while in the deep valleys below 200 m elevation, P < 600 mm (reaching less than 400 mm) (Agroconsultores & Coba, 1991).

Metamorphic rocks are the dominant soil parent material (Silurian and Ordovician schists), representing about 50% of he area, Variscan granites raking second in area (40%) while metabasic rocks cover about 6% of the region. Other geological formations outcropping in the region include, recent alluvial deposits in larger valley bottoms, Tertiary sedimentary deposits in patches as relicts of the ancient plain, dissected by a juvenile stream network, and ultramaphic rocks in two small outcrops (Agroconsultores & Coba, 1991).

Leptosols dominate in the region, covering ca. 70% of the area, followed by Cambisols, with 13%, the other soil units defined according to FAO/UNESCO (1987) being much less represented: Alisols, Luvisols, Regosols, Fluvisols, Anthrosols (Agroconsultores & Coba, 1991). As Leptosols and acid parent materials dominate, soils are, in extensive areas of the region, shallow, with high rock fragment content, and acid. Moreover, in the most represented dry environments, organic matter content is low, except in the colder and wetter highlands, where Umbric A horizons developed. Most soils are not suitable for agriculture (55% of the regional surface) or have marginal suitability (37%), and about 40% of the area is suitable for forestry (Agroconsultores & Coba, 1991).

Simulation Scenarios

Methodology applied involved building up regional scenarios for simulated application of post-fire measures. Severe fire hazard threatens 62% of the area (Figueiredo et al. 2014) and wildfires were recorded all over Bragança District (Figure 1). Scenarios correspond to the distinct conditions of occurrence of wildfires, and therefore represent those where post-fire measures for erosion control would be recommended. Variability of climatic conditions, namely of precipitation, soils and slope gradient across the region were represented by 14 simulation scenarios, for which potential erosion was calculated with USLE R, K ands factors. Scenarios correspond to a range of potential susceptibility to erosion of burnt areas, quantified by annual soil loss rates assessed by the product R K S.

In previous work by the authors, regional distribution of R estimates based on average annual precipitation was validated (Figueiredo & Gonçalves, 1990; Figueiredo, 2001; Figueiredo, 2015):

$$R = 3{,}0292\ P^{0{,}852}$$

where R is rainfall erosivity (MJ ha^{-1} mm h^{-1}) and P is mean annual precipitation (mm).

As a region susceptible to desertification, the main climatic domains considered as scenarios for simulations were those defined by the aridity index class (AI = precipitation /evapotranspiration, expressed as annual averages): semiarid (AI < 0.5), dry sub-humid (0.5 < AI < 0.65) and wet sub-humid and humid together (AI > 0.65). Based on the AI map of Continental Portugal (PANCD, 2014), estimated areas of those 3 classes represent 20%, 53% and 27%, respectively (Figueiredo et al. 2014). Moreover, these AI classes match with regionally defined precipitation classes (Agroconsultores & Coba, 1991), which allowed assigning, based on area dominance, a typical value to each one of them, as follows: semiarid with P = 550 mm, dry sub-humid with P = 700 mm, wet sub-humid and humid with P = 1100 mm. Following, R values were calculated with the above expression.

USLE erodibility factor, K, was calculated following the original procedure, with a correction to account for the effect of surface rock fragment cover (Wischmeier & Smith, 1978):

$$K_{rc} = K\ e^{-3.5\ RC}$$

where K_{rc} is the corrected K value due to the effect of rock cover, RC (0 – 1).

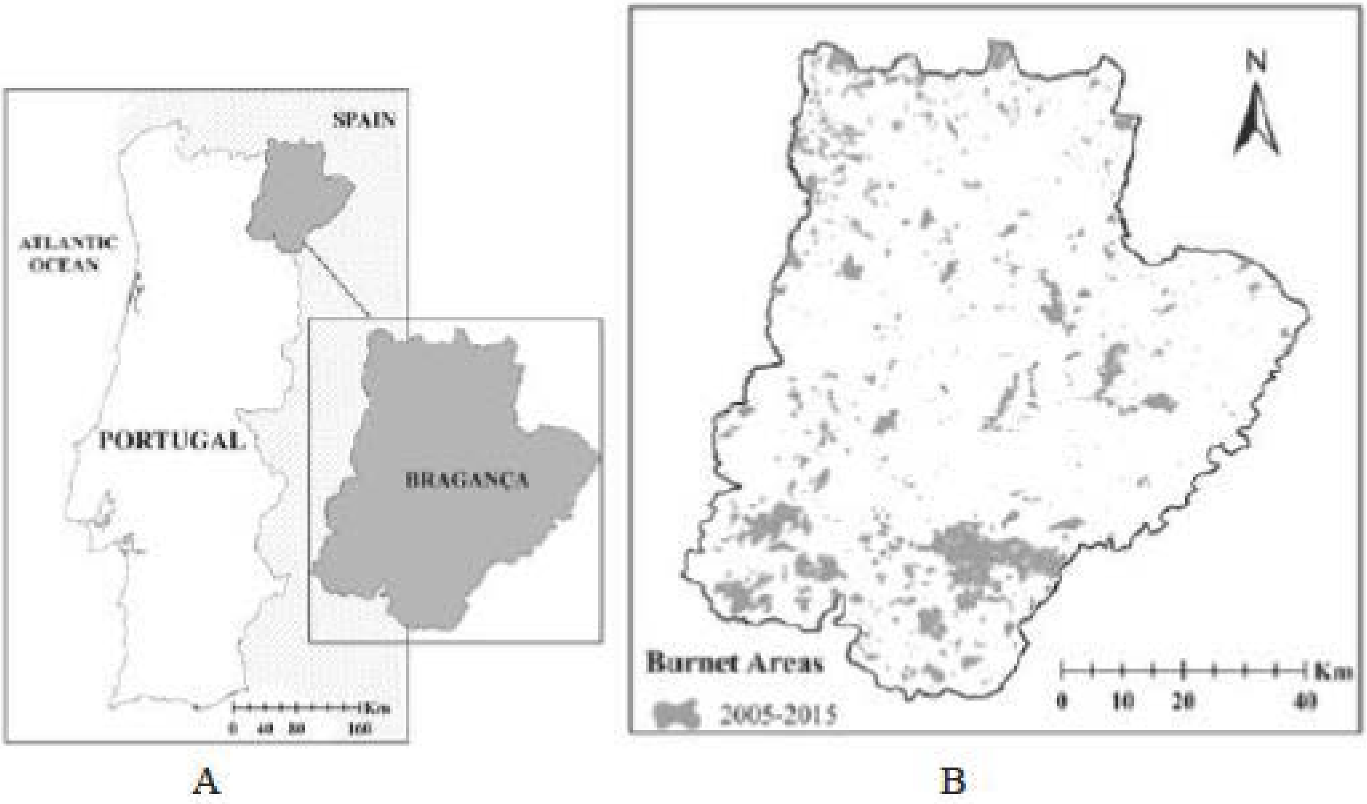


Figure 1. Bragança District, NE Portugal: (A) location and (B) burnt areas from 2005 to 2015 (Portuguese Institute for Nature Conservation and Forest – ICNF data).

K values were calculated with analytical data from soil profiles representing the main soil units occuring in the region (Agroconsultores & Coba, 1991). Soil units selected as simulation scenarios were those summing up 50% or more of each AI class area. In cases where the same soil unit occurs in more than one AI class, additional units were also selected. Following Figueiredo (2001) and Figueiredo (2012), each soil units has a typical soil stoniness class represented by topsoil rock fragments content, used to calculate K_{rc} as indicated above (Table 1).

USLE slope factor, S, was calculated with (McCool et al. 1987):

$$S = 16.8 \sin \theta - 0.50$$

where θ is the slope angle (°).

The Soil Map of NE Portugal (Agroconsultores & Coba, 1991) provides information on soil units typical slope gradient class. These were selected with the same criteria adopted for selecting soil units for simulation scenarios. Selected slope gradient classes sum up 50% or more of the respective AI class area. Average values of each slope gradient class were taken fors calculations (Table 1).

Simulated Post-Fire Measures

Contour barriers (made with burnt and unburnt local material) and revegetation were selected as simulation post-fire erosion control measures. These are among the set of measures recommended by ICNF (2006) and actually applied under the emergency plan for the recovery of the bunrt area left by Picões large wildfire, that occurred in the study area in July 2013. USLE procedures were applied to assess relative performance of these selected post-fire measures. For countour barriers, different spacing and sediment retention degrees were simulated, exploring USLE L factor to estimate their effectiveness in reducing erosion. Spacing, meaning the distance between two adjacent barriers, is input in L factor calculation (Wischmeier & Smith, 1978; Figueiredo, 2015):

$$L = a \, \lambda_b^{m}$$

where L is the USLE slope-length factor and λ_b is barrier spacing (meters). The above exprssion was applied with $m = 0.5$, because all simulated scenarios correspond to slope gradients steeper than 5%, and $a = 22.13^{-0.5} = 0.213$.

Retention degree is the fraction of sediment washed from the upslope contributing area that is trapped in a contour barrier, the remainder passing through the barrier to the adjacent downslope area contributing to the next barrier. The non-retained fraction is accounted for in the calculation of L factor for the next downslope barrier, as follows:

$$L0_i = RD\ L_{i-1}$$
$$\lambda 0_i = (L0_i/a)^2$$
$$L_i = a\ (\lambda 0_i + \lambda_b)^{0.5}$$

where i is the number a barrier in the downslope sequence of barriers (1 – n), RD is barrier retention degree (0 – 1), $\lambda 0$ is the virtual length upslope a barrier that contributes to the respective non-retained sediment, expressed in relative terms as L0, other symbols are as described above. $L0_i$ and L_i stand for, respectively, L factor calculated at the top and at the bottom edges of the upslope contributing area to barrier i.

Table 1. Simulation scenarios defined by climatic domain (AI class), soil type and slope gradient class

AI class[1] (% area Bragança District)	**Soil unit[2] (% area AI class)**	**Stoniness class[3]**	**Slope class[4] (% area AI class)**	**Scenario**
SAR (20%)	Ieox (53%)	High	STP (47%) VST (32%)	1. SAR_ Ieox_VST
				2. SAR_ Ieox_STP
DSH (53%)	Idox (41%)	Moderate	STP (31%) MOD (28%)	3. DSH_Idox_STP
				4. DSH_Idox_MOD
	Idbx (14%)	Moderate		5. DSH_Idbx_STP
				6. DSH_Idbx_MOD
	Idog (11%)	High		7. DSH_Idog_STP
				8. DSH_Idog_MOD
	Iug (6%)	Moderate		9. DSH_Iug_STP
				10. DSH_Iug_MOD
WSH (27%)	Idox (39%)	Moderate	MOD (59%)	11. WSH_Idox_MOD
	Iux (13%)	Moderate		12. WSH_Iux_MOD
	Idbx (12%)	Moderate		13. WSH_Idbx_MOD
	Iub (5%)	High		14. WSH_Iub_MOD

[1] AI (Aridity Index) classes: SAR, Semiarid, AI < 0.5; DSH, Dry Subhumid, AI 0.5 – 0.65; WSH, Wet Subhumid & Humid, AI > 0.65.

[2] Soil units: Ieox – Eutric Leptosols on schists; Idox – Dystric orthic Leptosols on schists; Idbx – Dystric cambic Leptosols on schists; Idog – Dystric orthic Leptosols on granites; Iug – Umbric Leptosols on granites; Iux – Umbric Leptosols on schists; Iub – Umbric Leptosols on basic rocks (Agroconsultores & Coba, 1991; FAO/UNESCO, 1987).

[3] Stoniness classes (% rock fragments, vol): Moderate, 15 – 30; High, 30 – 50 (Figueiredo, 2001).

[4] Slope gradient classes (%): MOD, Moderate, 12-15 to 25-30; STP, Steep, 25-30 to 45-50; VST, Very steep, > 45-50 (Agroconsultores & Coba, 1991).

L_b, calculated for the last barrier (n) in the sequence, quantifies the relative soil loss from the entire upslope protected area.

$$L_b = RD\ L_n$$

Expressed as a relative value, L_{brel}, as follows, it quantifies barrier erosion control performance for any slope length:

$$L_{brel} = L_b / L$$

Figure 2 illustrates the application of these L factor calculation procedures.

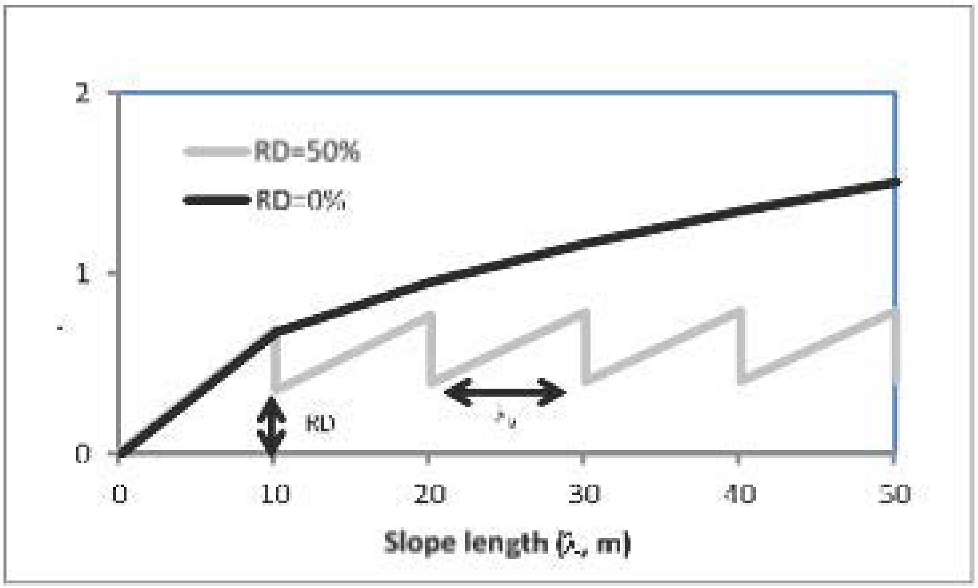


Figure 2. L factor along a 50 m hillslope, protected by contour barriers with 10 m spacing (λ_b) and 50% retention degree (RD), and unprotected (RD = 0).

A maximum 200 m hillslope length was considered in simulations so as to fall within the application range of the L factor (Wischmeier & Smith, 1978). Moreover, even though much longer hillslopes are commonly found in burnt areas (750 m in a small catchment, Costa, 2015), it is accepted that under current conditions of application of post-fire measures contour ditches should be set along the hillslopes to bound manageable treatment and recovery plots.

Seeding herbaceous vegetation as a post fire measure was simulated applying USLE C factor (Wischmeier & Smith, 1978):

$$C = CC\ SC = (1 - FC\ e^{-0.34H})\ e^{-3.5RC}$$

where CC and SC stand for, respectively, crop and surface cover subfactors, FC and RC stand for, respectively, canopy and residue cover fractions (0 – 1) and H is crop height (m).

Grassland growth rate curves exist for the main agroecological conditions typical of this region (Moreira, 2002) and they were adopted for CC subfactor calculations (Figure 3). Curves were assigned to the selected simulation scenarios according to the prevailing climatic conditions: semi-arid areas, dry sub-humid areas, wet sub-humid and humid areas. From these, cumulative growth curves were derived and grassland dry aboveground biomass converted to canopy cover fraction using the following expression, generalized from fitting curves obtained by Prabhakara et al. (2015):

$FC = \gamma\, \delta / (\delta + DM)$ or the linearized form $1/FC = \alpha + \beta\ (1/DM)$

where DM is grassland dry above ground biomass (kg ha^{-1}), α, β, γ and δ are regression parameters (original or of the linearized function) and FC was defined above. As stressed before, grasses dominate over weeds after vegetation cover installation, mainly represented by *Lollium perenne* (Moreira, 2002), and so data from Prabhakara et al. (2015) regarding this species was adopted to estimate parameters $\alpha = 0.0087$ and $\beta = 5.9777$ ($r^2 = 0.9668^{***}$). Maximum canopy heigth was set on 20 cm following expert indications (Jaime Pires, personnal comunication, May 2016), based on the assumption that burnt areas offer very limiting edaphic conditions for herbaceous vegetation development. Maximum canopy height was assumed to be reached at peak growth rate. H since seeding date to peak growth date was obtained by linear interpolation, with the same time resolution as FC, and H after peak growth rate date was kept constant at maximum. Seeding is performed over bare soil in a burnt area so that SC subfactor equals 1. The possibility of seeding again in the second year (re-seeding) was also considered and for this, SC was accounted for in the calculations, assuming that residues from the first seeding cover the surface in the second year with half of the FC at the end of the first year. C factor calculation requires rainfall erosivity distribution along the year. Figure 4 shows the cumulative curves of USLE R factor (Wischmeier & Smith, 1978), derived for this region with a time resolution of 7 days, for in average year (m) and for a highly erosive year (90 meaning percentile 90; Figueiredo, 2001). C factors obtained for these two conditions and for seeding (s) and re-seeding (rs) were labelled, respectively Csm, Cs90, Crsm and Crs90.

Post-Fire Measures Performance

Adequate combination of pertinent AI class, soil unit and slope gradient class generated 14 simulation scenarios. For each one of them the product R Krcs was calculated, which quantifies the respective potential soil loss. This is assumed as the recently burnt area erosive potential as wildfires leave bare soil directly exposed to rainfalls.

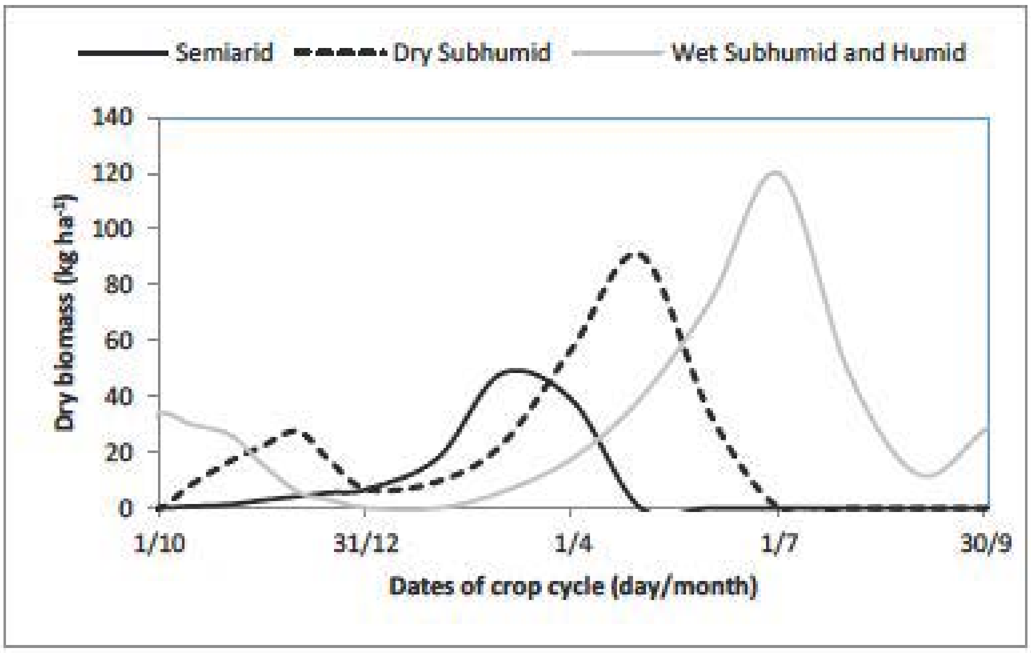


Figure 3. Grass growth rates typical for the 3 climatic domains of NE Portugal (adapted from Moreira, 2002).

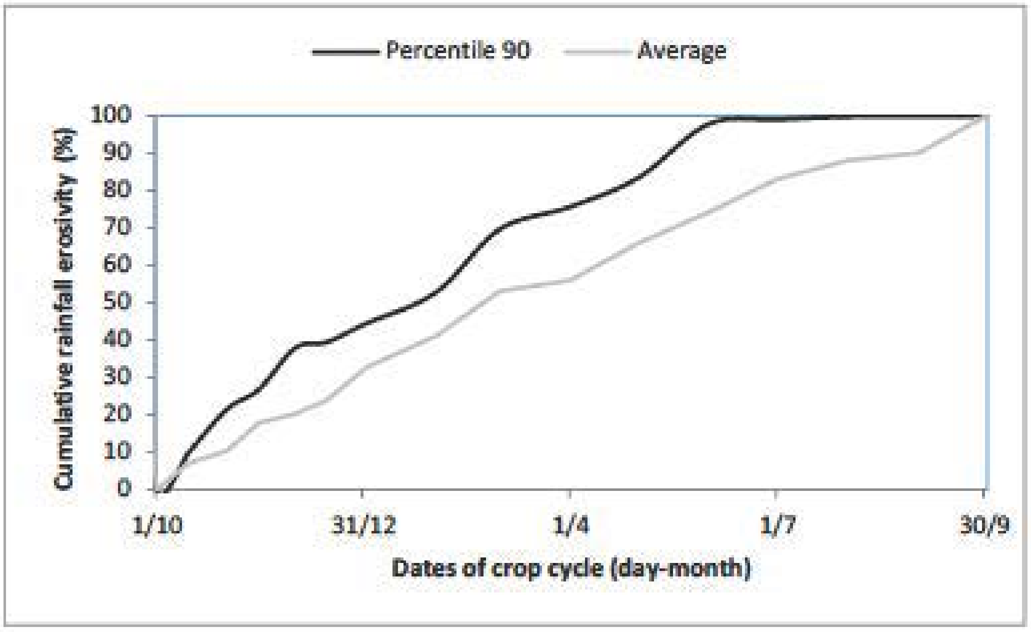


Figure 4. Cumulative distribution of rainfall erosivity (USLE R factor,%) along an average year and a highly erosive year (percentile 90) in NE Portugal (Figueiredo, 2001).

Post-fire erosion control measures are meant to reduce this potential to tolerable erosion rates under different implementation scenarios. C and L factors calculated for post-fire measures were multiplied by potential erosion calculated for each scenario to assess their performance: for barriers, Lb and C = 1 (bare soil); for seeding and re-seeding, L = 3.01 (200 m long hillslope) and Cs or Crs, respectively; for combinations of both measures, Lb and Cs or Crs. Measures performance was classified as low, moderate, and high according to post-fire measures ability to reduce erosion rates to, respectively, more than 10 Mg ha^{-1} y^{-1}, 10 – 2 Mg ha^{-1} y^{-1}, and less than 2 Mg ha^{-1} y^{-1}. These thresholds were adapted from Arnoldus (1977), defining soil loss tolerance for shallow soils with non-renewable substract (the lower rate) and for deep soils with renewable substract.

RESULTS AND DISCUSSION

Simulation Scenarios

The soil map units selected as simulation scenarios are characterized not only by the dominant soil unit but also by the dominant climatic domain where these soils evolve, as well as by the prevailing dominant topographical conditions. The regional representation of the simulation scenarios, discriminated by climatic domain, soil unit and slope gradient class was presented in Table 1 and Table 2 presents the corresponding USLE factor values for each scenario, together with the respective potential erosion estimate.The regional climatic domains do not equally represent the Aridity Index (AI) classes under which soils occur, with "Terra Quente" with annual precipitation lower than 600 mm better representing the Semiarid AI class (83% of the AI class), whereas the "Terra de Transição" regional domain with annual average precipitation from 600 to 800 mm, representing 60% of the Dry Sub-humid AI class area. Due to the wider set of regional climatic domains included in the Wet Sub-humid and Humid AI class, the selected scenario – "Terra Fria de Planalto," with 100 to 1200 mm annual precipitation – represents the AI class to a lesser extent (45%). USLE R factors calculated for each AI class are 671, 812 and 1188 MJ ha^{-1} mm h^{-1}, respectively, from the driest to the wettest. A considerable part of Bragança District is covered by the 7 selected soil untis (59%). Soil unit selected for Semiarid AI class, schist derived Eutric Leptosols (Ieox), covers 53% of this class area, and ranks second on areal representation of the selected soil units, with about 65 000 ha (10% of Bragança District area). The most represented soil unit selected, schist derived Dystric Leptosols (Idox), covers 42% of the Dry Sub-humid AI class area and 39% of the Wet Sub-humid and Humid AI class, summing up about 180 000 ha (28% of Bragança District area). Ranking third in areal representation, the schist derived Dystric Cambic Leptosols (Idbx) cover about 60 000 ha (9% of Bragança District area) split, as the Idox, in the Dry Sub-humid (14% of AI class area) and the Wet Sub-humid and Humid (12% of AI class area). The other 4 selected soil units are much less represented in the respective AI class and in Bragança District. They include Dystric Leptosols (Idog) and Umbric Leptosols (Iug) both granite derived, with 11% and 6% of the Dry Sub-humid AI class, respectively, and Umbric Leptosols, schist derived (Iux) and meta-basic rocks derived (Iub), respectively with 13% and 5% of the Wet Sub-humid and Humid AI class area, all four covering 77 000 ha in Bragança District (12%). Soil rock fragment content is high (30% – 50% volume) in 3 out of 9 selected soil units, the remainder being moderate (15% – 30%). While USLE K factor calculated for the fine earth fraction ranges from 0.059 (Idox) to 0.022 Mg ha^{-1} per unit R (Iug), the values corrected to account for rock fragments effect decrease to a range of 0.027 (Idox) – 0.008 (Idog), an effect most visible in those soil units with high stoniness (Ieox, Idog, Iub).The most represented slope gradient class is steep (25-30% to 45-50%), where selected soil units occur under Semiarid AI class in 47% of this class area, as well as under Dry Sub-humid AI class (31%). In the former AI class, slopes are generally steeper as the slope gradient class very steep (> 45-50%) prevails in 32% of this AI class area, while in the latter moderate slope gradient class (12-15% - 25-30%) ranks second in area extent with 28%. This slope gradient class alone covers 59% of the Wet Sub-humid and Humid AI class area. USLEs factors calculated for the 3 slope gradient classes are 2.9, 5.4 and 7.9, respectively from the gentler to the steeper.

Table 2. USLE factors R (rainfall erosivity), K (soil erodibility), Krc (K corrected for the effect of rock fragments cover),s (slope gradient factor), and potential eorsion (RKS) for the 14 simulation scenarios.

Scenario[1]	R (MJ ha^{-1} mm h^{-1})	K (Mg ha^{-1} R^{-1})	Krc	S	RKS[2] (Mg ha^{-1})
1. SAR_ Ieox_VST	671	0.055	0.014	7.9	71
2. SAR_ Ieox_STP				5.4	49
3. DSH_Idox_STP	812	0.059	0.027	5.4	119
4. DSH_Idox_MOD				2.9	63
5. DSH_Idbx_STP		0.035	0.016	5.4	71
6. DSH_Idbx_MOD				2.9	38
7. DSH_Idog_STP		0.034	0.008	5.4	37
8. DSH_Idog_MOD				2.9	20
9. DSH_Iug_STP		0.022	0.010	5.4	43
10. DSH_Iug_MOD				2.9	23
11. WSH_Idox_MOD	1188	0.059	0.027	2.9	92
12. WSH_Iux_MOD		0.035	0.016		55
13. WSH_Idbx_MOD		0.035	0.016		54
14. WSH_Iub_MOD		0.042	0.010		35

[1] See Table 1. [2] Potential erosion actually calculated with Krc.

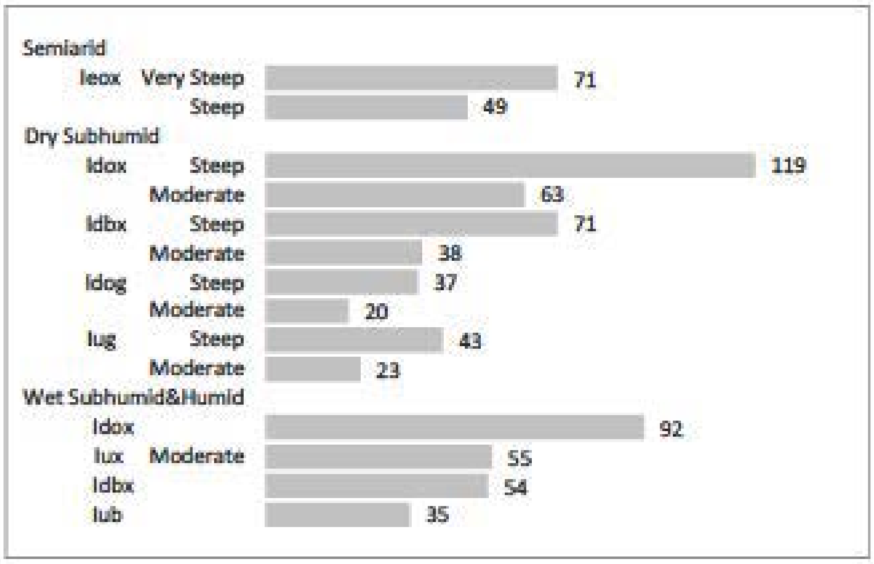


Figure 5. Potential soil loss (USLE factors RKS, Mg ha^{-1} y^{-1}) on scenarios of post-fire erosion control measures in Bragança District, as defined by climate domain, soil unit and slope gradient (see Table 1 for symbols).

Results show the high potential erosion risk prevailing in the region, that may be converted in an actual risk in burnt areas. The regional topography of this mountain territory primarily determines severe erosion risk, which is enhanced in the case of burnt areas. Wildfires dominantly occur in scrubland and forest land, which commonly cover soils less suitable for agriculture, slope steepness and shallow depth being the main soil limitations. As so, burnt areas are actually those most susceptible to erosion in Bragança District.

On the other hand, although soil eordibility of the fine earth is generally high, in particular in schist derived soils that are dominant in this region, the high surface rock fragment cover of these soils sharply reduces their actual erodibility. This helps explaining the soil loss rates experimentally measured in mountain cropland (Figueiredo, 2001; Figueiredo et al. 2012) and in degraded environments, where rock fragment cover is high. Figueiredo et al. (2013) and Fonseca et al. (2017) reoport an average as low as 1.4 Mg ha^{-1} y^{-1}, recorded in six 4 m long microplots in the first year after a prescribed fire, while Prats et al. (2016) shows 9.5 Mg ha^{-1} y^{-1}, also in microplots (5 m long) in the first year after a wildfire, in both cases soils having a considerable rock fragment cover (> 20%), the highest soil loss records in burnt areas presented by Fernández & Vega (2016) are around 60 Mg ha^{-1}. Results of erosion experiments in burnt areas, besides their large scatter, rarely surpass 50 Mg ha^{-1} y^{-1} and in average they are far below that value. Fernández & Vega (2016) stress the large overestimate of soil loss rates outcoming from RUSLE and PESERA erosion models applied in Galicia (Spain) burnt areas, and they elaborate on the contribution of soil rock fragments to explain discrepancies between observed erosion rates and the 5 times higher model output. The potential erosion rates calculated for the 14 scenarios, under these circumstances, are within the range of other model estimates and are taken as an useful indication for scenarios ranking in erosion susceptibility.

Performance of Contour Barriers

Contour barriers were simulated for spacing (λ_b) ranging from 10 m to 50 m and for retention degree (RD) ranging from 0 to 100%. Simulations outcome L factor values for a maximum 200 m long protected hillslope. Performance of contour barriers combining the whole range of simulated λ_b and RD was analyzed but only a selection of examplary combinations is presented here, each parameter being classified according to the perception of its practical application in the field (Table 3).

L factor for a 200 m long hillslope is 3.01 and applying contour barriers it decreases to 0.87 (L_b) in the least performing combination (barriers with long spacing and low retention degree) and to 0.07 in the best performing combination (short spacing and high retention degree). This is equivalent to 29% and 2% of the relative soil loss estimated for the unprotected hillslope (L_{brel}). Figure 6 depicts the variation of L_{brel} along the hillslope, for the range of RD in short, medium and long barrier spacing. It shows that the most important decrease in relative soil loss occurs in the first upslope barriers, which is better percieved for the 10 m barrier spacing. It also shows that low RD (10%) do not provide effective reduction in relative soil loss.

Within the simulation range, RD is a much more important parameter to be controlled when apllying contour barriers, as even for the long barrier spacing a RD as high as 90% decreases L_b to 0.15, and L_{brel} to 5% (Table 3). A reduction to 50% relative soil loss is obtained with RD 10% for 10 m barrier spacing while for 50 m barrier spacing it requires RD 25%. To reach a reduction to L_{brel} 0.1 (10% relative soil loss), RD 60% and 85% are required, respectively for 10 m and 50 m barrier spacing, meaning an increase in RD requirements between the two spacings compared for this range of relative soil loss (Figure 7). In all depicted barrier spacings, for RD 50%, RD 70%, and RD 90%, L_{brel} falls below 0.3, 0.2 and 0.05, respectively, and these RD may be taken as exemplary of low to high barrier retention performance. Figure 7 can be used as a monograph to set the adequate combination of barrier spacing and retention degree according to projected relative soil loss.

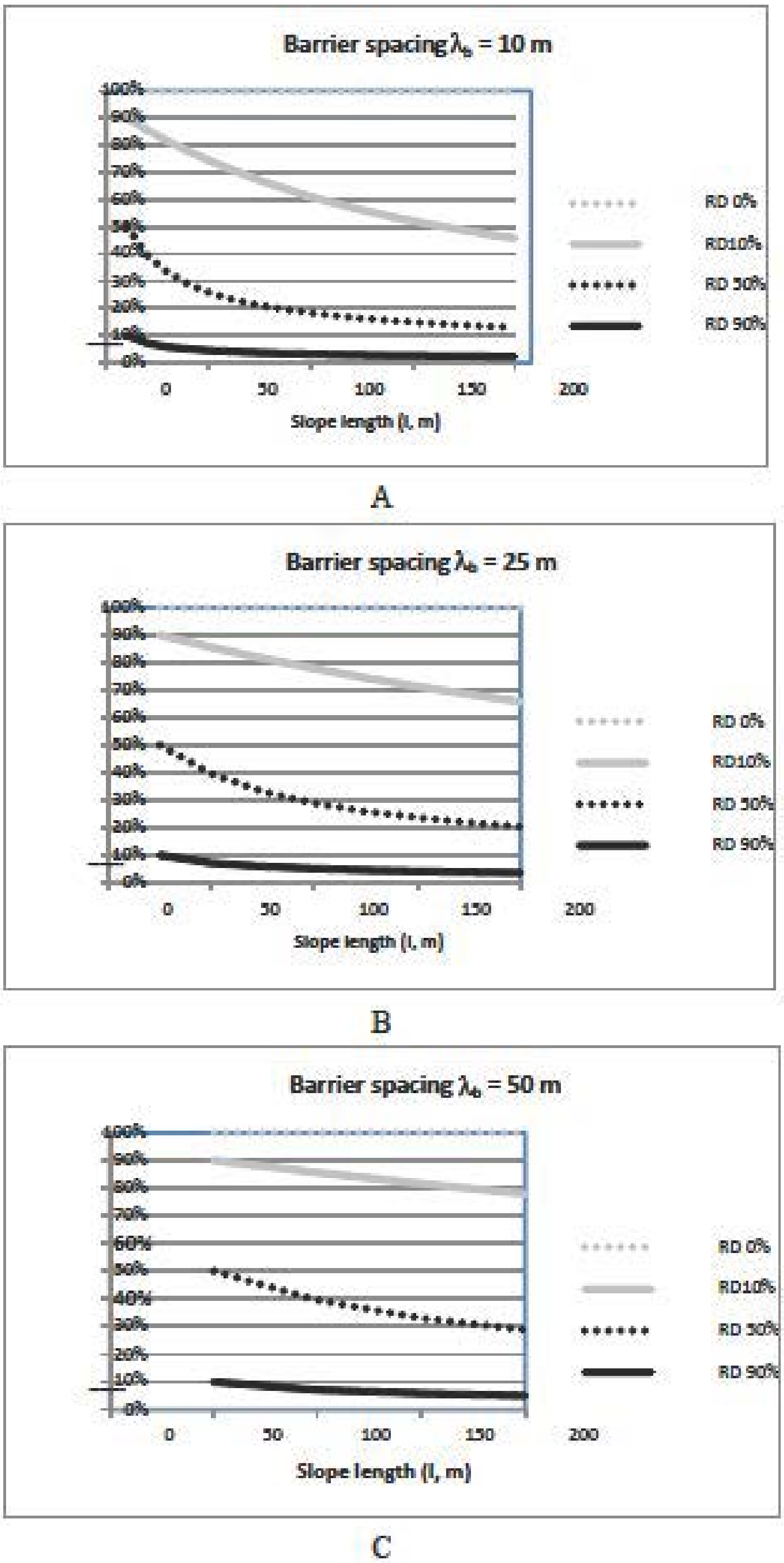
Burnt vegetation contour barriers tested by Badía et al. (2015) showed high performance in erosion control, while Fernández & Vega (2016) experiments yielded results qualifying barriers as a low performance technique. In the two studies, interpretation of the experimental design described by the authors highlights that the single barrier parameter tested was retention degree and not spacing.

Table 3. USLE L factor for a 200 m hillslope protected with contour barriers (L_b) with different barrier spacing and retention degree (L_{brel} is%, of L for unprotected hillslope)

Barrier spacing (λ_b)	Barrier retention degree RD					
	Low 50%		Moderate 70%		High 90%	
	L_b	L_{brel}	L_b	L_{brel}	L_b	L_{brel}
Short 10 m	0.39	13%	0.21	7%	0.07	2%
Medium 25 m	0.61	20%	0.33	11%	0.11	4%
Long 50 m	0.87	29%	0.47	16%	0.15	5%

Performance of Seeding

USLE C factor values obtained for the average year and the highly erosive year under the 3 climate domains allow estimating the effect of post-fire seeding on reducing soil loss (Figure 8a). The highest Cs value corresponds to the Semiarid in higly erosive year.(0.63 or 63%), and the lowest to the Wet Subhumid and Humid in average year (33%). In the 3 climatic domains Cs is around 10% lower in the average year (Csm) when compared with the highly erosive year (Cs90). Even though with similar pattern of variation, much lower results are obtained for the re-seeding technique (Figure 8b), where Crs ranges from 0.15 to 0.06.



A

B

C

Figure 6. Variation of relative soil loss (L_{brel}) along a 200 m hillslope as affected by contour barrier retention degree (RD) for different barrier spacing (λ_b): (A) 10 m, (B) 25 m, (C) 50 m.

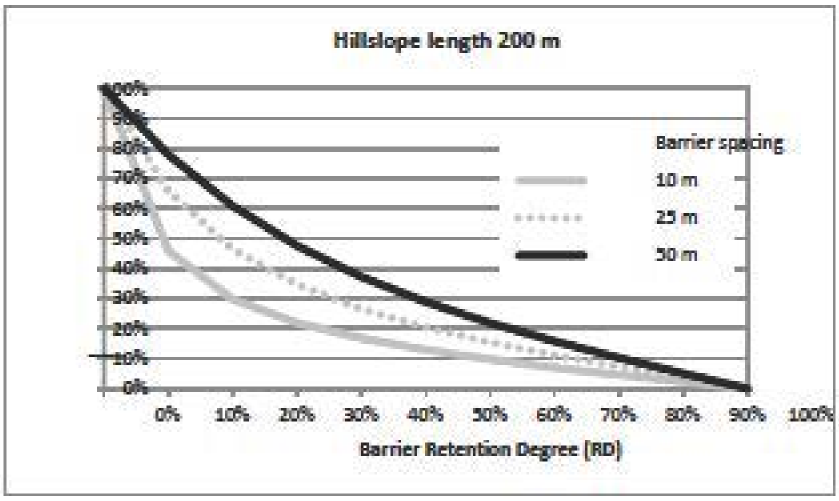


Figure 7. Combined effects of contour barrier spacing (λ_b) and retention degree (RD) in relative soil loss (L_{brel}) for a 200 m hillslope (RD 0% means no barrier installed).

The Cs values express the low performance of seeding as in the better scenario (Granite derived Dystric Leptosols, Idog, on moderate slope, under Dry Subhumid conditions, with 20 Mg ha^{-1} y^{-1} potential soil loss), the application of this measure for reference 200 m long hillslope (L = 3.01), would result in an estimated erosion rate far above the tolerable (Arnoldus, 1977). Vega et al. (2014) found an even lower performance when comparing sown with untreated burnt plots, with a reduction to about 80% in the first year after fire soil loss. In their experiment (Galicia, Spain), vegetation had a low growth rate and reached about 70% cover after one year, similar in both sown and untreated plots, and there was a small of the sown species to total herbaceous vegetation cover, meaning that the main goal of the technique was not effectively achieved and these results were also found at a smaller scale in a rainfall simulation study by Fernández et al. (2012). In fact, seeding is aimed at accelerating ground cover by vegetation, to limit soil loss in the first post-fire year, as spontaneous vegetation recovery rates is currently low, especially in drier conditions as those of Central and NE Portugal. Prats et al. (2016) and Vieira et al. (2016) report 20% cover by adventitious vegetation in the first year after fire in the Central Western Mountains of Portugal. In NE Portugal, sown herbaceous vegetation cover evolution was observed after a large and severe wildfire (Costa, 2015) and Figure 9 shows that, besides the poor vegetation development, soil cover was not uniform, resulting in a patchy pattern of distribution, common in arid environments (of which burnt areas may be considered ecological equivalents), whose effects on water erosion processes were addressed to by Bochet et al. (2006) and Nouwakpo et al. (2016). Both coverage on the need of better understanding feedbacks between erosion and vegetation development pathways in order to improve recovery strategies in degraded areas. Seeding again a burnt area in the second year after fire is not a currently referenced practice. As seeding is a low performance measure and recovery of adventitious vegetation up to an erosion control effective soil cover is a slow process, re-seeding was simulated in this work in order to assess if it could improve the weak effect of seeding in soil protection. Simulation results are encouraging and this is a result of accounting for the residues of the first crop cycle as an extra protection layer over the soil.

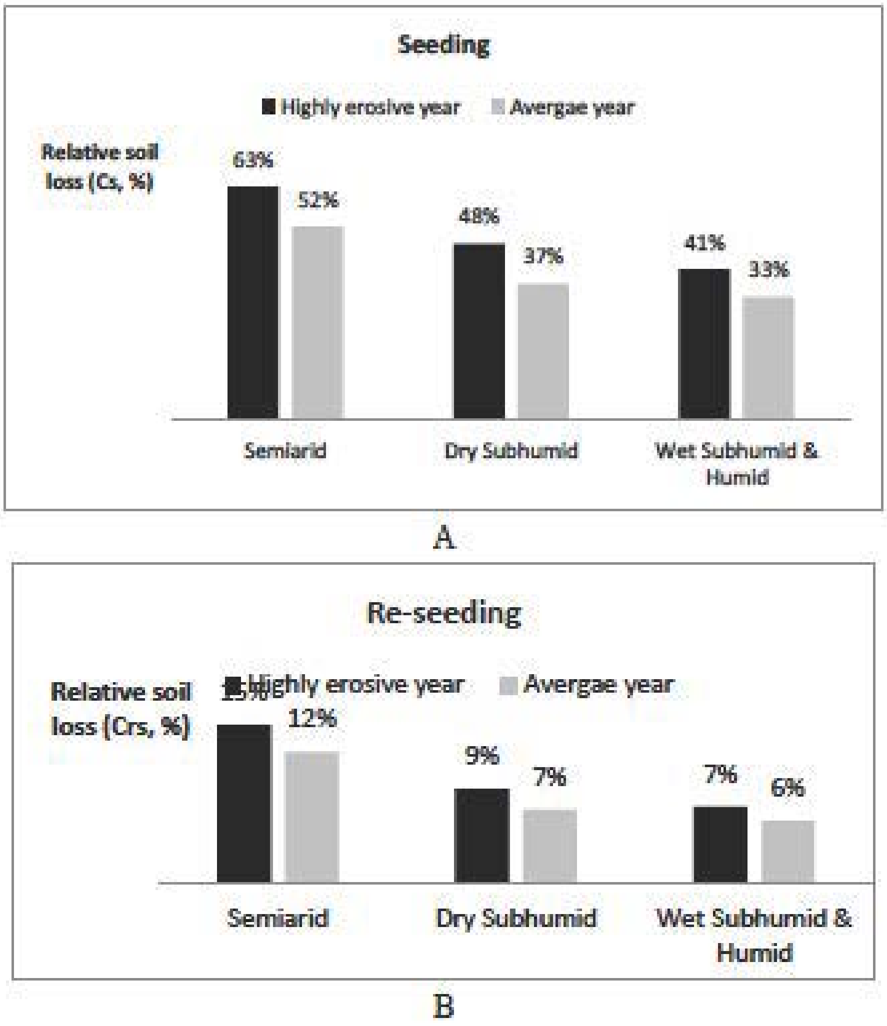


Figure 8. USLE C factor for seeding (A) and re-seeding (B) as a post-fire erosion control measure, obtained with typical grass growth rates under the 3 climate domains, for average and highly erosive years.

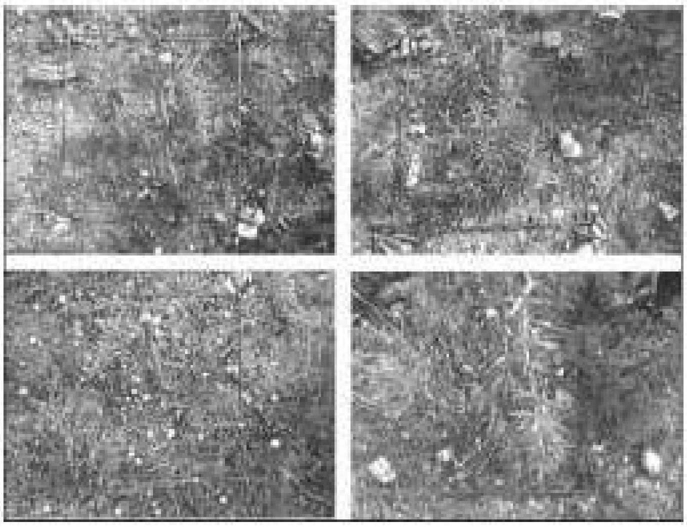


Figure 9. Vegetation cover in a severely burnt area where seeding was applied as post-fire measure: examples from Picões wildfire, July 2013, Alfândega da Fé, NE Portugal (seeding in November 2014, photos in May 2015; quadrat 0.7mx0.7m). (Source: Costa, 2015).

Discussion on Measures Application

Measures application in the 14 simulation scenarios set for Bragança District output an estimated soil loss rate, classified according to tolerance thresholds (Arnoldus, 1977). Figure 10 to Figure 13 depict the number of simulation scenarios for which a measures qualify with high, moderate and low performance, according to those soil loss classes.

As already indicated above Seeding is low performance (actually not performing) for any simulation scenario, while re-seeding has moderate performance in 8 out of 14 scenarios when C is assessed for the average year (Figure 10). This number drops to 4 out of 14 if C is calculated for the highly erosive year, meaning that for planning purposes this measure should be recommended only for these 4 scenarios, which are: Dry sub-humid areas with Dystric Leptosols, granite derived, on steep and moderate slope, and with Umbric Leptosols, granite derived, on moderate slopes; Wet sub-humid and Humid areas with Umbric Leptosols, over basic rocks, on moderate slope. Areas of typical occurrence of such application conditions correspond to higher elevation or wetter zones where those soil parent materials outcrop. Conversely, this measure should not be applied on schist derived soils, the most erodible ones, and in Semi-arid areas of Bragança District.

Contour barriers application very much depends on the selected combination of spacing and retention degree, this last design parameter being the most critical one (Figure 11). Low RD (50%) barriers are not recommended for most scenarios, as only 2 out if 14 outcome tolerable soil loss estimates for short barrier spacing (10 m). The same low performance persists with moderate retention barriers (RD 70%) whose recommendation in medium and long spacing (25 and 50 m, respectively) is restricted to granite derived Dystric and Umbric Leptosols on moderate slope, under Dry sub-humid conditions. Tolerable soil loss estimates rise to 6 out of 14 scenarios for RD 70% with 10 m spacing. High retention degree of contour barriers is essential to make them performing in most of Bragança District burnt areas. For medium and long spacing, it is actually not recommended only in the case of the most susceptible scenario – schist derived Dystric Leptosols on steep slopes under Dry sub-humid conditions. For 50 m spacing, the other 3 scenarios where 90% RD barriers qualified as low performance outcome a soil loss estimate very close to 10 Mg ha^{-1} y^{-1}. Short spacing barriers with 90% RD are the most performing, outcoming tolerable soil loss estimates in all 14 scenarios, in 2 of which it shows a high performance, with an estimated soil loss rate below 2 Mg ha^{-1} y^{-1}, in the least susceptible scenarios (granite derived Dystric and Umbric Leptosols on moderate slope under Dry sub-humid conditions).

Shortening barriers spacing represents higher application cost and material requirement. In fact, barriers are handmade and a higher number of barriers increases working time, meaning labour cost. On the other hand, a higher number of barriers requires higher availability of their raw material, which very much depends on local prefire land use, fire severity and post-fire intervention strategy. Besides, making barriers with material transported from outside the burnt area is not in the scope of this measure. Hence, in spite of their higher performance, short spacing barriers might be of limited application. Furthermore, high retention degree barriers are more time consuming or require more specialized work, which represents higher labour cost, meaning this might not be a feasible option in all cases. Lower performing solutions as medium and long spacing and moderate and low retention barriers may be more often necessarily selected under current application conditions.

This justifies seeking for improvements in post-fire erosion control by combining contour barriers with seeding. Results of the application to the simulation scenarios considering the average erosive year are presented in Figure 12 that show improvements as compared to the individual application of both measures (Figures 10 and 11). For high RD barriers, the combination with seeding is fully performing in all scenarios, being highly performing in 3 out 14 in the longer barrier spacing, and in the majority of scenarios in the medium spacing. Yet, for moderate RD (70%), this measure combination has low performance in 3 and 6 scenarios for 25 and 50 m spacing, respectively. For low RD, the combination is better than the measures individually applied but still lacks the desible possibility of unrestricted recommendation. If re-seeding is considered in burnt areas treated with contour barriers, results sharply improve, recommending this option in all 14 scenarios (Figure 13).

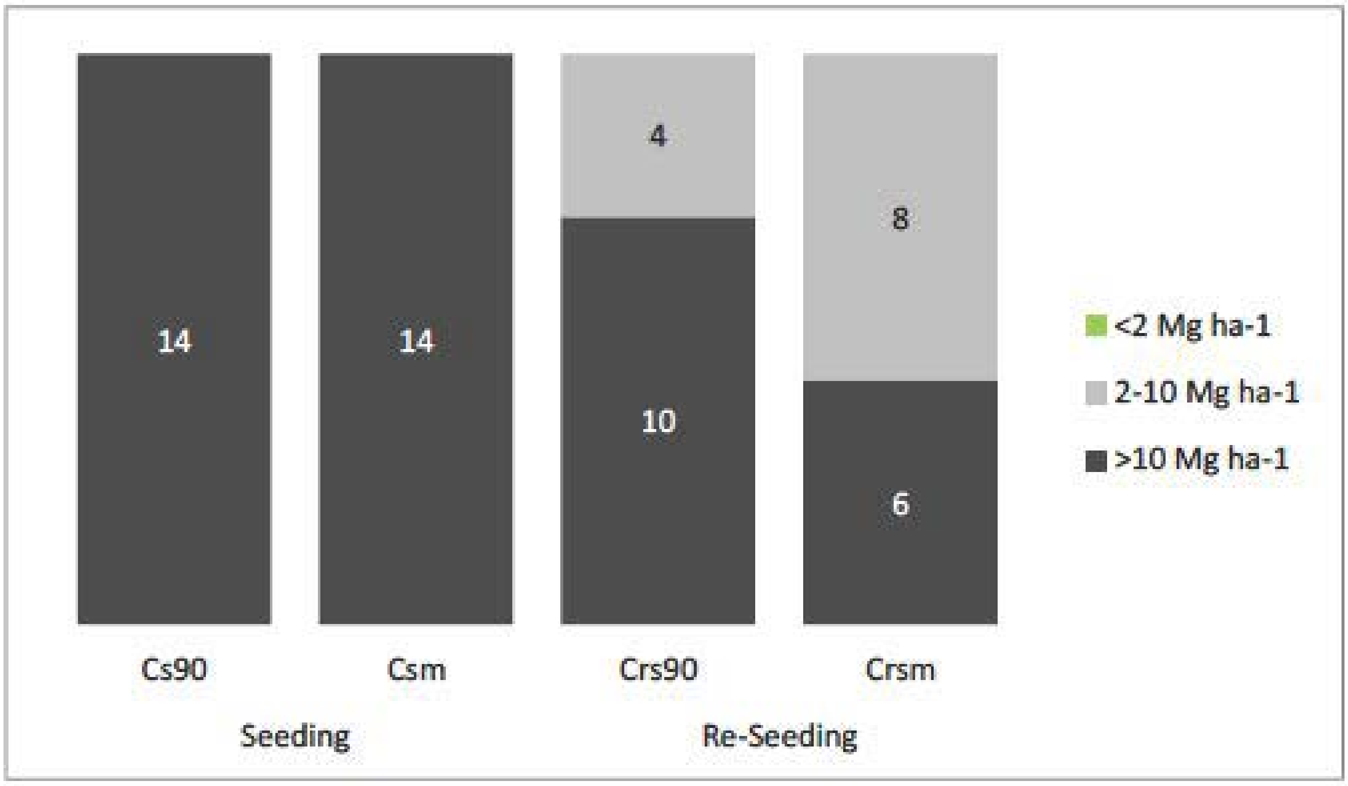


Figure 10. Number of simulation scenarios according to erosion control performance of post-fire measures applied (high, moderate and low), defined by estimated soil loss class (respectively, < 2, 2 – 10 and > 10 Mg ha^{-1} y^{-1}): seeding and re-seeding for average (Cm) and highly erosive year (C90).

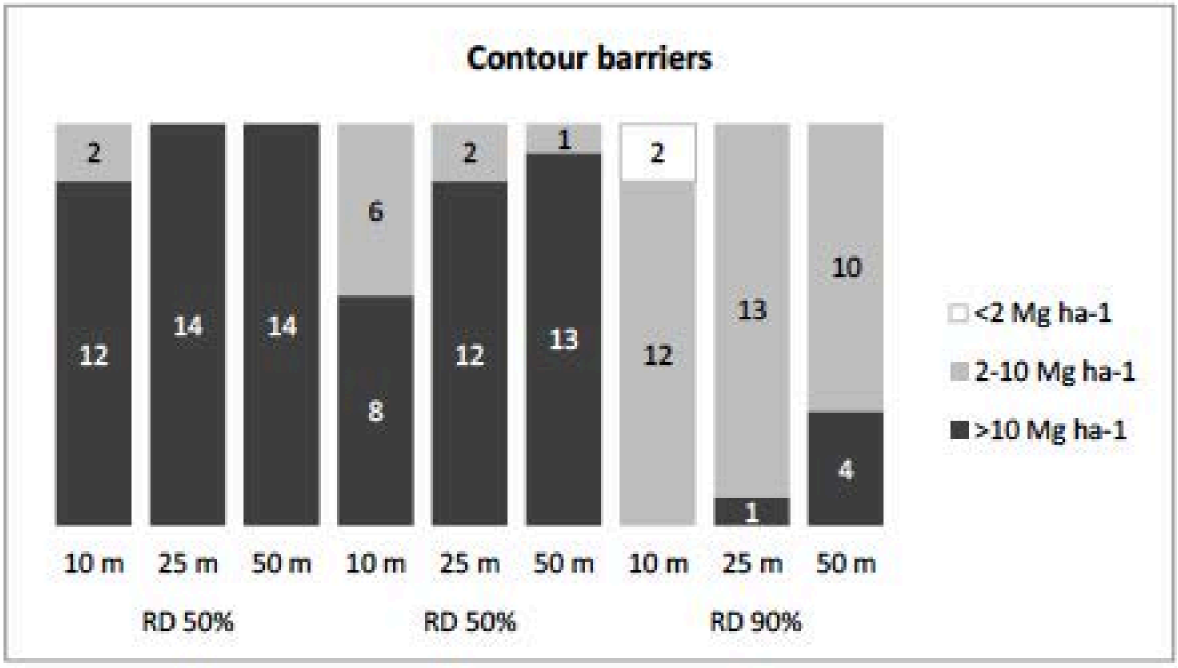


Figure 11. Number of simulation scenarios according to erosion control performance of post-fire measures applied (high, moderate and low), defined by estimated soil loss class (respectively, < 2, 2 – 10 and > 10 Mg ha^{-1} y^{-1}): contour barriers with different spacing (in m) and retention degree (RD in %).

Consideration on the cost of these improvements is necessary and this is actually a critical issue for burnt areas recovery (and degraded land in general). In fact, as marginal areas, mostly unsuitable for a productive use, burnt areas recovery is very much dependent on available public resources and technical advice to implement adequate post-fire measures.

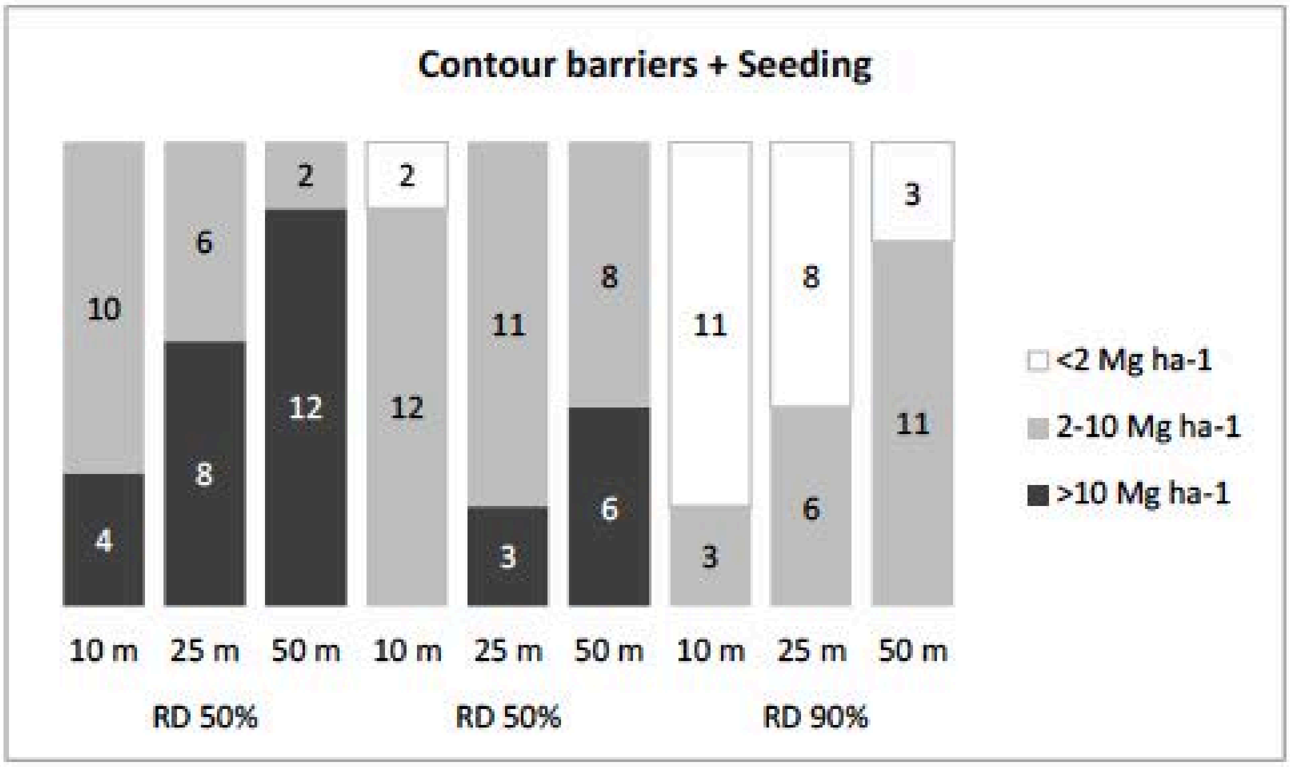


Figure 12. Number of simulation scenarios according to erosion control performance of post-fire measures applied (high, moderate and low), defined by estimated soil loss class (respectively, < 2, 2 – 10 and > 10 Mg ha^{-1} y^{-1}): contour barriers with different spacing (in m) and retention degree (RD in%) combined with seeding in average year.

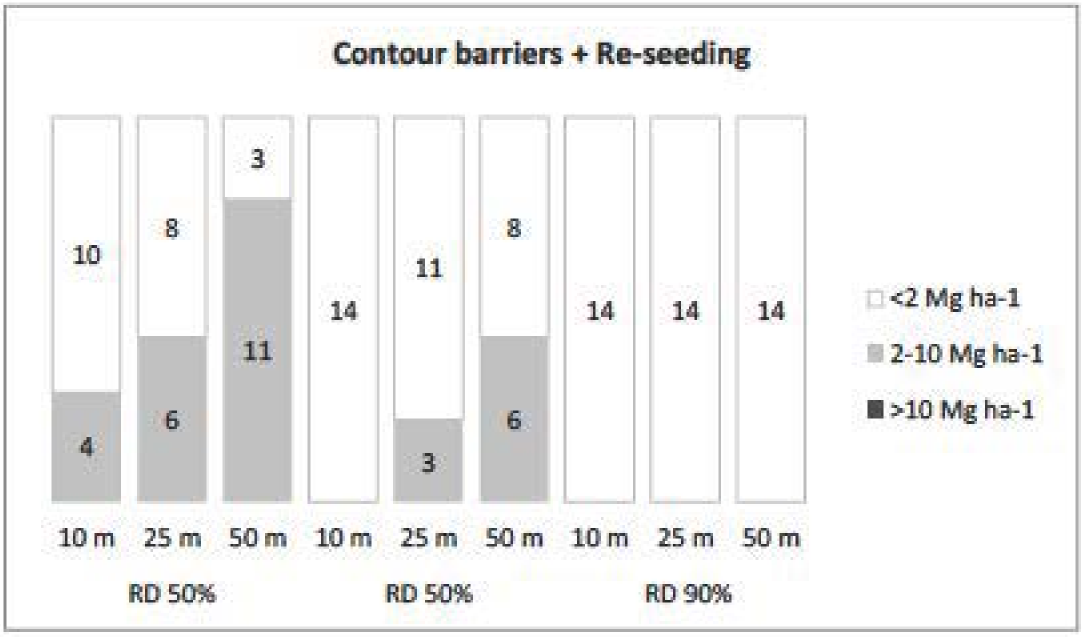


Figure 13. Number of simulation scenarios according to erosion control performance of post-fire measures applied (high, moderate and low), defined by estimated soil loss class (respectively, < 2, 2 – 10 and > 10 Mg ha^{-1} y^{-1}): contour barriers with different spacing (in m) and retention degree (RD in%) combined with re-seeding in average year.

CONCLUSION

Burnt areas in Bragança District, NE Portugal, are among the most susceptible to land degradation by water erosion, as wildfires occur dominantly in forests and scrubland, which cover marginal tracts, non suitable for agriculture. As a mountain area, Bragança Dstrict, depicts a strong relief determining severe potential erosion risk. Post-fire erosion control measures are necessary to mitigate environmental damages following wildfires.

The application of post-fire erosion control faces design constraints due to the scarce experimental supporting data to better ground performance, but they also face implementation constraints, mainly associated to local factors as remote location, harsh terrain, local materials and labour availability, decisive to keep cost effectiveness in acceptable range.

This research is a simulation exercise for assessing the relative performance of selected post-fire erosion control measures under common implementation conditions in Bragança District, taken as application scenarios. Simulations run on 14 scenarios, selected to representative burnt areas throughtout this naturally diverse region. Scenarios combine the prevailing climatic domains (Semiarid, Dry sub-humid, Wet sub-humid and Humid), the most common soils and the dominant topographical conditions. Estimates of USLE factors R, K and S, ranked scenarios susceptibility according to potential erosion estimates. Application of erosion control measures was simulated exploring USLE C factor, estimated for seeding, and L factor estimated for contour barriers, selected as low cost post-fire measures. A procedure is proposed to include barriers design parameters (spacing and retention degre) in L calculation. Performance of these measures varies according to implementation scenarios, the most performing being recommended for wide regional application, for their ability to reduce soil loss to tolerable rates.

As expected from data provided in literature, seeding has low performance and it is not recommended as a single post-fire measure to control erosion in burnt areas. Expected post-fire slow and limited recovery of adventitious vegetation cover on poor soils is not effectively complemented by seeding. Re-seeding or seeding again in the second post-fire year after fire is proposed to improve this measure performance and simulation results recommend its application where soil parent material is other than schist. In fact, soils in granitic areas and also over basic rocks have lower erodibility than the schist derived ones, and these require more performing measures than re-seeding.

Contour barriers have higher performance, yet dependent on design parameters. Increasing barrier retention degree is a more effective option than reducing spacing between barriers, showing the importance of installing well built contour barriers. Short spacing barriers (10 m) are the most performing, and combined with high retention degre (90%) results in a recommended option in the 14 scenarios. Yet, cost constraints, not addressed to in this paper, may limit its wide application.

The combination of the two measures – seeding and contour barriers – is much higher performing than their individual application, allowing its recommendation even with moderate barriers retention degree, except in the most susceptible areas (steep slopes with schist derived Dystric Leptosols). Its wide application across the region is recommended with high retention degree barriers. Re-seeding in a hillslope treated with contour barriers is a highly performing option, recommended for all scenarios.

Results of the research point out the importance of adequately designed post-fire measures, adapted to the regional diversity of potential erosion conditions, in order to mitigate impacts and accelerate recovery of NE Portugal burnt areas.

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