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Soil and water degradation processes in burned areas: Lessons learned from a nested approach

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ABSTRACT

Forest fires produce a major impact on soil, water and vegetation. Despite the amount of research published on this subject, there are two major problems that hamper the fully understanding of *on* and *off-site* impacts of forest fires. They include methodological problems steaming from the uniqueness of burned soil properties, easily erodible, by the fast degradation they undergo over a short period of time immediately after fire and by the meaning of the impacts at different scales.

Monitoring attempts to understand processes in burned areas are hindered by limitations of measuring techniques, that prevent the correct quantification of erosion yields and the processes that give rise to peak flows. A further limitation arises from the poor knowledge on how properties and processes at one scale influence degradation processes at larger scales, both on and off site.

This paper presents a reflection about the limitations of some of the methods and techniques more frequently used to assess erosion yields and hydrological responses following fires, and their significance at different scales of analysis.

It also shows the potential of nested approaches in the acquisition of an improved insight in to the problem and in the identification of the relevant processes at each scale and how they influence degradation processes at larger areas. It is shown that soil and land use patterns, play a crucial role in reducing or enhancing the hydrological and sediment yield and transport processes between scales.

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1. Introduction

Since the severe fire seasons of 2003 and 2005 (e.g. Ferreira et al., in press), forest fires have been high on the agenda of public concern in Portugal. Owing to the extension of the burned area, several off-site negative impacts occurred, and for the first time the hydrological response and erosion yields were apparent to the general public. In a climate change context, it is feared that in the future increasing long and hot dry spells together with the inadequacy of Portuguese forest to withstand such climate change scenarios will result in enhanced *on-site* and *off-site* environmental degradation impacts that result in property damage and even human life losses. In this context, it is of the utmost importance to understand the degradation processes at different scales and evaluate the risk of hazardous peak flow frequency and magnitude and the mobilization and deposition of sediments. For comprehensive reviews of fire impact on soil and water conservation, the reader is referred to several works, namely Neary et al. (1999), Coelho et al. (2004), Ferreira et al. (2005b), Shakesby and Doerr (2006), Doerr et al. (2006), Ferreira et al. (2007a), Hyde et al. (2007) and Shakesby et al. (2007). Wildfire substantially alters the hydrologic and geomorphic response of a catchment, so that subsequent rainfall events may trigger severe erosion (Hyde et al., 2007). Increased erosion after wildfire stems primarily from the destruction of vegetation and changes in the soil physical and hydrologic properties that reduce infiltration rates and increase availability of loose sediment (Ferreira et al., 2005b). The loss of vegetation and other ground cover due to wildfire reduces rainfall interception and attenuation, rainfall storage (Martin & Moody, 2001), and flow resistance (Meyer, 2002). Rainfall-generated runoff therefore accelerates more quickly and less is retained as pounded water, resulting in reduced residence times and reduced total infiltration. Runoff peaks sooner and at higher magnitudes than on vegetated slopes, resulting in greater shear stresses acting at the soil surface to detach and transport sediment. Fire also consumes the shallow roots that contribute to soil strength (Hyde et al., 2007).

Soil properties such as infiltration rate, porosity, conductivity, and storage capacity that lead to good hydrologic functioning can be adversely affected by fire (Neary et al., 1999).

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Fire is thought to change soil moisture in two fundamental ways, which may be contradictory depending upon the timing and distribution of rainfall. Available soil water may increase due to decreased loss from evapotranspiration (Moody & Martin, 2001; Silva et al., 2006). Inversely, the loss of shade from the canopy, loss of thermal insulation from litter, and increased heat gain due to the decreased albedo of the ash may cause soils to become hyper-desiccated, resulting in increased capillary suction or moisture potential and greater lag time to maximum infiltration rates (Hyde et al., 2007).

Fire produces a spectrum of severities that depend on the interactions between burning, intensity, duration, fuel load (i.e. live and dead materials), combustion type and degree of oxidation, vegetation type, fire climate, slope, topography, soil texture and moisture, soil organic matter content, time since last burned, and area burned (Neary et al., 1999).

Another physical response to fire in soils, relevant to degradation processes is water repellence (DeBano, 1981). Changes in the soil hydrologic properties due to wildfire include reduced infiltration due to the formation of a water repellent (hydrophobic) layer near the surface, which is created by the vaporization and subsequent condensation of organic soil compounds and is directly related to the combustion temperatures of available fuels (DeBano, 1968; Letey, 2001). The distribution of fuels and their effects on fire behavior and intensity strongly influence the formation of water repellent layers within fire-impacted soils (DeBano, 2000). This property can be found in the presence of high-severity fires and certain litter types (Ferreira et al., 2000; Coelho et al., 2004; Ferreira et al., 2005a,b). Water repellence develops as a discrete layer of soil parallel to the surface where hydrophobic organic compounds coat soil aggregates or minerals. It is formed when soil temperatures rise above 176 °C and destroyed at temperatures >288 °C (DeBano, 1981; DeBano et al., 1976). When soils are in this condition, water is prevented from wetting aggregates and infiltration declines greatly (Neary et al., 1999).

Forest fires are known to enhance soil water repellence immediately below the ash layer (Giovannini, 1987; Giovannini et al., 1988). According to Giovannini (1994), fires with temperatures above roughly 450 °C sharply increase overland flow and erosion hazard through inducing water repellent properties and, thereby, impairing infiltration. Infiltration capacity may be further reduced by sealing of surface pores by ash and fine soil particles (Martin & Moody, 2001). The aboveground vegetation and litter biomass have marked effects in the soil temperature patterns, as measured by Gimeno-Garcia et al. (2004) for experimental fires with temperatures above 600 °C. This is the reason why different fire severities can have different impacts on soil water repellence (Coelho et al., 2004; Ferreira et al., 2005a), and therefore on overland production and erosion yield.

The severity of impacts on vegetation and soil properties along with topographic factors is thought to determine the spatial distribution of post-fire erosion (Cooke & Doornkamp, 1974; Dunne & Leopold, 1978).

Burn severity typically influences the impacts of fire on soil and vegetation, and can lead to differentiate runoff and erosion responses (Ferreira et al., 2005a,b). Post-fire erosion is therefore directly related to the degree of burn severity (DeBano et al., 1996; Cannon, 1999; MacDonald et al., 2000; Huffman et al., 2001; Wondzell, 2001; Coelho et al, 2004; Ferreira et al., 2005b; Hyde et al., 2007). Shakesby et al. (2007), working in Southeast Australia ascribe minor erosion yields to forest fires, as a result of the combination of features that provide sinks to overland flow.

The abundant organic matter that contributes to surface soil structure and porosity is profoundly affected by fires. Soil structure degradation can persist from a year to decades, depending on the severity of the fire and post-fire ecosystem conditions (Neary et al., 1999).

When fire consumes vegetation and underlying litter layers that mitigate the impact of rainfall on the soil, bare soil surfaces can seal off under the impact of raindrops, resulting in much higher rates of surface runoff. The net effect is a reduction in soil moisture contents, erosion of nutrient-rich ash and A horizon sediments, and ultimately watershed drying (Neary et al., 1999).

It is commonly accepted that fire increases runoff and soil erosion (Burch et al., 1989; Imeson et al., 1992; Shakesby et al., 1993; Scott & Schulze, 1992; Scott, 1993; Andreu et al., 1994; Inbar et al., 1998; Coelho et al., 1995, in press; Pierson et al., 2002; Coelho et al., 2004; Cerdà & Lasanta, 2005; Cerdà & Doerr, 2005; Benavides-Solorio & MacDonald, 2005; Lane et al., 2006; Sheridan et al., 2007).

The severity of fire induced soil water repellence depends on a number of soil characteristics including mainly moisture content, texture and pre-fire organic matter quantity and composition (Botelho et al., 1994; Giovannini, 1994).

The extreme temperature increase as a result of fire can induce or enhance soil water repellence is often viewed as a key cause of the substantial increases in runoff and erosion following severe wildfires (Doerr et al., 2006).

In contrast to the generation or enhancement of repellence usually reported following forest fires of similar severity, Doerr et al. (2006) found that burning caused widespread destruction of repellence. The mineral soil depth to which repellence was destroyed (0.5–5 cm) was found to increase with burn severity. Below this charred wettable layer, occurs the persistence of pre-existing water repellence or the enhancement due to the coalescence of hydrophobic substances to the soil particles surface. Two years after the fire, the frequency of extreme repellence persistence was reduced in the surface and subsurface relative to unburned terrain.

The magnitudes of change in erosion and hydrological processes depend in part on the severity and spatial variability of water repellence (Jungerius & DeJong, 1989; Ritsema & Dekker, 1994; Coelho et al., 2004; Ferreira et al., 2005b). Some authors found low soil erosion rates after a fire (Emmerich & Cox, 1992; Kutiel & Inbar, 1993). Coelho et al. (1995, in press) found erosion rates of 2 Mg ha^{-1} yr^{-1} immediately following a forest fire, which was significantly higher when compared with mature forest stands (0.02 Mg ha^{-1} yr^{-1}), but significantly lower when compared with other forest management practices such as rip-ploughed areas, where erosion yields reach 51.4 Mg ha^{-1} yr^{-1}. The significance of erosion at burned areas, despite the small amount of sediment exported, lays in the loss of the only nutrient pool from poor mountain and range land soils.

In burned forest environments, overland flow responses can be enhanced by reduced infiltration capacity, partly as a result of the development or enhanced effectiveness of a water repellent layer (Sevink et al., 1989; Imeson et al., 1992; Doerr et al., 1996; Coelho et al., 2004; Ferreira et al., 2005b). The impact of different fire intensities on soil water repellence spatial distribution and on overland flow and erosion yields is explained elsewhere (Coelho et al., 2004; Ferreira et al., 2005b). Shakesby et al. (2000), however, questioned whether erosion hazard is related in such a straightforward manner with soil water repellence.

With the ashes on the soil surface representing a substantial part of the nutrient stock, the occurrence of overland flow, shortly after fire, constitutes a serious soil degradation risk (Ferreira et al., 1997, 2005b), whose off-site effects are often overlooked.

This paper outlines 20 years of research performed by the authors in Central Portugal. Following the experiments performed during this period, the authors came to the conclusion that there were two main obstacles to the fully understanding of the magnitude and meaning of forest fires on soil and water degradation processes at different scales. One relates to the inadequacy of single methods used to provide an adequate insight on how changes induced by forest fires influence soil and water degradation at different scales, the second has to do with the particularities, namely the fast nature of degradation processes and the factors and thresholds that control those degradation processes.

This study discusses the limitations of several current methodologies to study soil and water degradation, with particular emphasis to the problems posed in burned areas. It discusses the advantages of a nested approach as a way to improve the insight on the functioning of geomorphic systems at different scales, giving particular attention to the role and effects of thresholds on the spatial connections between different system compartments, the role of spatial patterns and the meaning of properties and processes operating at one scale over the processes at the scale immediately above.

2. Methodological issues

Common techniques used to measure soil and water degradation, listed below, present several problems in assessing properties and processes, namely:

1. It is difficult, due to spatial heterogeneity and the diversity of processes involved, to integrate all the responses into one value, being of erosion rates, peak magnitude or response time;
2. Results seldom fully provide information about where the material comes from and moves to, about deposition and re-working;
3. The rates are scale dependent. If the study is concentrated in an area with a high water and sediment output (i.e. a gully or rill area), erosion yields and runoff coefficients are expected to be high. If the assessment includes wider, undisturbed areas, the final water and sediment output will be significantly lower. This will probably be more relevant information for societal use. The integration of results from neighboring areas with different characteristics is one of the most challenging tasks, that can only be fully achieved through the understanding of the processes involved, to determine the sign and magnitude of impacts at wider areas and especially at off-site locations; and
4. Extreme events are responsible for exceeding the thresholds that impair hydrologic and erosion impacts (e.g. by triggering for instance the amount of water capable of causing fluvial and bedrock erosion). This implies a rare combination of processes at one scale, able to change properties and trigger abnormal processes downslope and downstream, at larger areas. The transfers of large amounts of sediments from the slopes to streams, bank abatement or catastrophic bedload transport are examples of geomorphic processes that occur as a result of extreme events.

2.1. Measurement problems

Since the techniques provide a limited insight of the properties or processes they address, and sometimes even interfere with the properties and processes they are supposed to measure (i.e. change characteristics, produce boundary effect, address processes and properties at a inadequate scale, etc.), it is of the utmost relevance to acknowledge their limitations that must be taken it into account in the scientific process.

Measuring problems may arise from observation and the limitation of the techniques used, namely:

a) changes induced by the methodologies used;
b) the choice of sampling areas and sites, that may not be representative; and
c) poor use of the techniques.

These problems may be reduced by the establishment of detailed procedures and consequent experimental designs set to minimize standard deviation and to address directly the defined hypothesis in a clear and unambiguous way (Ferreira and Coelho, 2001).

Several methods are frequently used to address soil and water degradation processes following fires. All of them present intrinsic problems that add to the particular characteristics of burned areas to hinder an easy understanding of the sign and magnitude of properties and processes change.

The problems posed by some of the more popular techniques to assess soil and water degradation processes are presented on Table 1 and discussed below.

Soil profiling devices, an upgrade of soil erosion pins, present several problems: The time lag between measurements has to be large

Table 1
Methodological problems of some techniques commonly used in soil and water degradation processes

Measuring technique	References	Main problems
Soil profiling devices	Shakesby et al. (1991); Shakesby (1993); Shakesby et al. (2002)	1 — Only applicable for long time lags, typically >1 yr 2 — Difficult to use in pre-burned mature forests, due to the dilution of the mineral/organic soil limit. 3 — Limited insight on how processes act
Plots	Cammeraat (2004) Ferreira and Coelho (2001) Morgan (1995)	1— Dependent on location in the hillslope 2 — Overestimates runoff and erosion 3 — Bounded plots are close systems with no exchanges with surrounding areas and therefore degrade and attain exhaustion faster. 4 — Border effect
Rainfall simulators	Lane et al. (2004) Calvo et al. (1988) Cerdà et al. (1997) Bowyer-Bower and Burt (1989) Walsh et al. (1998) Esteves et al. (2000) Alba (1997)	1 — Bounded plots are close systems with no exchanges with surrounding areas and therefore degrade and attain exhaustion faster. 2 — Border effect 3 — Difficulty in matching natural rainfall characteristics.
Small catchments	Wilson (1999), Croke et al. (1999) Molnar et al. (2002) Cammeraat (2004) Scanlon et al. (2004) Coelho et al. (2006)	1 — Coarse insight on on-catchment processes. 2 — Unable to provide which, how and where the processes act to produce catchment response. 3 — Limited information on thresholds and controls, and how they are attained on space and time.
Tracers	Foster et al. (1994) Dalgleish and Foster (1996) Blake et al. (1999) Chambers and Garwood (2000) Chappell and Warren (2003) Blake et al. (2006) Soulsby et al. (2006) Tetzlaff et al. (2006)	1 — Very difficult to provide rates or any other form of quantification. 2 — Difficult to provide a continuous record of processes in space and time.

enough to prevent disturbance caused by repeated measurements that can mask the true impact of sediment erosion, transport and accumulation. The method fails to provide a detailed insight on how processes act, and the ability to describe and explain the processes responsible for the observed profile differences is limited.

Independent of their size, *Plots* fail to provide insights of what is happening at the landscape as whole, in what concerns overland flow and erosion rates. Evans (1995) found that in general, erosion measured on plots or estimated from plot-based formulae is considerably higher than those measured in farmers' fields, by a two to ten factor. Comparing with wider scales, plots often register higher erosion yields. The only exception occurs when the stream erodes its' banks, as pointed out by Trimble (1983), or in burned areas as discussed in this paper.

Runoff/erosion measurements carried out on plots, either open or bounded, were found to give results that were largely dependent on their location on the hillslopes with respect to vegetation structures (Cammeraat, 2004). These limitations were found to be a woefully limitation to their use to predict future trends and to produce risk maps (Boardman, 2006).

Bounded plots are close systems that in the particular case of burned areas will tend to exhaustion of sediment source. In addition, they suffer from edge effect, which alters water and sediment processes between the bounded area and the exterior. Edges also induce abnormal hydrological and erosion processes, due to disturbances produced by edge installation. The edge effect decreases with the size of the bounded plot (Ferreira & Coelho, 2001).

Plots present some advantages, such as the control of the variables inside the plot (Morgan, 1995), allow the quantification of overland flow and erosion rates at a given period per unit of area, allow an estimation of the water infiltrated, and a detailed spatial and temporal assessment of hydrological and erosion processes.

Being an artificial unit, plots are unable to provide information about the processes along natural units such as entire slopes, namely accumulation and remobilization processes (Morgan 1995; Ferreira et al., 1997). The same is valid for slope hydrological processes (e.g. Ferreira et al., 1997, 2000).

Field *Rainfall simulators* are used to reproduce as much as possible the characteristics of natural rain, namely in what concerns rainfall intensity, size and distribution of rainfall drops, and their terminal velocity (Hudson, 1993). Plots have various sizes. A very popular rainfall simulator, describer by Calvo et al. (1988) and modified by Cerdà et al. (1997) uses a 0.24 m^2 plot, Bowyer-Bower and Burt (1989) used an Amsterdam rainfall simulator with a 0.5 m^2 plot, Walsh et al. (1998) used a 1 m^2 plot with a Plymouth model. The EMPIRE model uses 50 m^2 plots (Esteves et al., 2000), and there are references to plots up to 100 m^2 (Alba, 1997) and 300 m^2 (Wilson, 1999; Croke et al., 1999), to quote only a few. Rainfall simulator plots present the same problems and assets of any other plot.

Rainfall simulators can be divided in two groups, those who form individual drops (e.g. Leighton-Boyce et al., 2005), that fall under the force of gravity, and those where the pressure is controlled by a pressure device and is distributed as evenly as possible by a sprinkling device (e.g. Cerdà et al., 1997).

Many of the more popular rainfall simulator models have plots smaller than 1 m^2, where the potential exhaustion and edge effect is enhanced. At microplot scale, the type of soil surface, defined in terms of plant cover and plant type, rock pavement, crust and seal development and cracks, constitutes the first control for runoff discharge (Cantón et al., 2001). Soil surface roughness is also important since it reduces overland flow velocity and water is pounded in small depressions (Cammeraat, 2004).

Gravity drop rainfall simulators have difficulties to mimic natural rainfall patterns, if a method to random the spatial distribution of raindrops is not included, and pressure rainfall simulators are difficult to calibrate to achieve a homogeneous rainfall distribution throughout the plot area.

The natural hydrological regime is a product of complex interactions at *small catchment* scale. The onset of changes in the physical environment of streams and rivers is often dictated by these interactions (Molnar et al., 2002).

Catchments are suitable for the investigation of horizontal processes. They are closed systems suitable for the modelling of cycles of water and sediments at the landscape scale, having natural boundaries and a hierarchical organisation (Steinhardt & Volk, 2003).

Catchment perspective provides a basis for studying the physical linkages between precipitation, runoff, and sediment transport on a continuous long-term basis. The dominant processes are space and time dependent, and range from short-term response to floods, to long-term evolution (Molnar et al., 2002).

The dominant runoff processes generating stream flow are strongly influenced by the catchment physical characteristics such as geology, topography, soils and vegetation. These factors influence catchment landscape structure and spatial organisation which, in turn, determine the distribution of water flow paths, the patterns of water storage and residence time distributions (Soulsby et al., 2006).

Catchment shape influences the rate at which flows concentrate and converge into the main drainage channel. Erosion is concentrated in areas of convergent runoff such as colluvial hollows and other hillslope depressions, leading to the potential for gully formation. Additional topographic factors can also play an important role in erosion processes, namely surface roughness, drainage density, drainage area, basin shape and aspect (Hyde et al., 2007).

Topography, vegetation cover and soil properties are crucial variables for runoff production and erosion. Erosion or deposition occurs locally, depending on the supply and type of sediment, the erodibility of the surface, and flow magnitude.

Catchment topography is known to influence the hydrological flowpaths and degree of erosion (Scanlon et al., 2004). Soil distribution was found to exert the strongest influence on flow path partitioning and mean residence times in a Scottish catchment (Soulsby et al., 2006).

The major advantage is to monitor a natural system without the disturbances produced by monitoring devises on hydrological and sediment processes discussed above. Nevertheless the processes monitored are the result of the upscaling of soil and slope processes, which may imply that processes at a smaller scale may not have any significance at a larger scale.

Threshold assessment is a key issue to understand how properties and processes at one scale influence processes at wider scales, and to explain unusual processes and events. Bedload transport is one of such processes. As pointed out by Coelho et al. (2006), not all the catchment contributes actively to bedload transport, which only occurs under very extreme events. The amount of bedload transported is not only the result of sediment transmission from selected slope sections to the catchment channel, but also the result of bank erosion.

Catchment monitoring, i.e., the collection of temporal and spatial data of relevant hydrological and sediment processes, is crucial within the integrated catchment assessment framework. Catchment monitoring is complicated by the fact that the relevant processes operate at different temporal and spatial scales. This requires a nested approach to be adopted, and that catchment data are collected at micro to macroscales (Molnar et al., 2002).

Water management concerns are increasingly demanding stronger research focus on larger catchment scales and the need for upscaling (Soulsby et al., 2006). Nevertheless, catchment approaches are limited in accurately translating process-dependent controls of landscape characteristics and organisation on water movement. Recent work suggested that geographical variation in ‘places’ of interest to hydrologists may frustrate attempts to find scale invariant controls on processes in hydrology. Thus, there remains a requirement to explore alternative tools that help integrate the insights from process studies with accessible descriptors of catchment characteristics (Soulsby et al., 2006).

Tracers can provide a further insight on dominating water and sediment processes, flow paths need to be tracked. The chemistry of water solutes, or the use of other tracers, can provide valuable information (Casper et al., 2003). Finger-printing techniques such as sediment magnetic susceptibility (Blake et al., 2006), ^{137}Cs, ^{210}Pb and ^{7}Be (Blake et al., 1999) can offer powerful though time-consuming approaches to establishing the source of the sediment (Boardman, 2006).

Tracers provide a valuable approach to improve the understanding about hydrological and erosion processes, although their limitations make it impossible to obtain some kind of reliable quantification. ^{137}Cs provide an alternative method to assess erosion processes (Chappell & Warren, 2003). The ^{137}Cs technique for estimating net soil flux is commonly based on establishing the local amount of ^{137}Cs deposited from atmospheric weapons testing, mainly during the 1960s. This 'local reference ^{137}Cs inventory' should come from a site that has been undisturbed by erosion or deposition. The rate of net soil redistribution is based on the relationship between the amount of ^{137}Cs at the reference site and the amounts in cultivated fields (Chappell & Warren, 2003). The direct measurement of soil flux (erosion and deposition) by erosion (as of that by water) is difficult due to the high spatial and temporal variability of erosion processes (Chappell & Warren, 2003).

The use of geochemical and isotopic tracers has proved a valuable aid in field research orientated towards integrating process understanding at larger spatial scales (Kendall & Coplen, 2001; Soulsby et al., 2003). Using tracers within nested catchment studies, in conjunction with modelling techniques, can greatly aid the identification of runoff sources (Soulsby et al., 2006). Whilst use of tracer data to infer processes at the catchment scale needs careful interpretation in terms of equifinality, when combined with process-based knowledge derived from independent hydrometric studies, can prove extremely useful (Soulsby et al., 2006). The use of tracer techniques was shown to provide detailed insight of the scaled hydrological and hydrochemical response of these nested catchments under high flow and low flow conditions (Tetzlaff et al., 2006).

The rare attempts to give rates of soil loss from field surveys using tracers, got to the conclusion that accounting for losses is not easy and highly questionable (e.g. Foster et al., 1994; Dalgleish & Foster, 1996; Chambers & Garwood, 2000).

Their use alone cannot provide net rates of erosion or runoff production, although they can be valuable tools to infer processes, and therefore improve the knowledge on the hydrological and erosion systems, especially if nested with some of the techniques described above.

Following the methodological problems posed by the various techniques employed to quantify water and sediment fluxes in the landscape and to achieve an improved insight on the functioning of processes at different scales, their interrelation and thresholds, a *Nested approach* was developed.

The results of integrated analysis enable the calculation of scenarios allowing the derivation of land use variants adapted to the landscapes natural conditions showing positive effects (decrease) on material out-wash from landscape parts and material inputs into surface water and ground water. Nevertheless, numerous and complex methodological problems arise with such analysis, as well as with the investigation and assessment of the landscape water balance and water-bound material fluxes on the meso-scale (Steinhardt & Volk, 2003). Nested approaches can be used to identify the relevant issues that can result in real on and off off-site environmental impacts at different scales.

They can also be used to find improved solutions to environmental problems requiring the understanding and prediction of natural and anthropogenic patterns and processes on all spatial and temporal scales. In fact, most studies have been carried out on small scales, and thus our knowledge is mostly limited to local scale environmental systems and interactions. For bridging this gap, research dealing with regional scale analysis and assessment has to focus on the question on how does spatial heterogeneity at meso-scale levels affect processes (Steinhardt & Volk, 2003).

Nested approaches, pursuit by the research at the basis of this paper allowed an improved insight on the interactions between processes acting at different scales under a simplified context, resulting from the complete burn of all the vegetation and litter layer that no longer become obstacles to the generation and transmission of water and sediment fluxes. This implies the reduction of obstacles to the progression of hydrological and erosion processes at the soil and slope scale, and the reduction of buffer effect provided by discontinuities derived from the diversity in land uses, such as near stream riparian ecosystems. At burned areas, new properties are generated. These change the regulation functions, defined by Steinhardt and Volk (2003) as those regulating runoff, groundwater recharge, groundwater protection, buffer functions of the soil, etc. These disruptions, and the impact they produce at different scales allow us to better understand whose are the key features of the processes at a given scale that influence processes at wider scales, namely in what concerns thresholds and flow paths.

Numerous and complex methodological problems arise with nested approaches, since some variables are scale dependent (e.g. runoff generating thresholds were found to be scale dependent for semi-arid environments (Cammeraat, 2004)). Cantón et al. (2001) also mention the scale effect, (i.e. decrease in runoff depth as scale increases). Furthermore, natural hydrological variability is expressed at different timescales, which include inter annual variability. Within a year, one can easily identify a regular seasonal component in the hydrographs, and daily variability is caused by individual rainfall events (Molnar et al., 2002).

Nested approaches pose several problems, such as the meaning and sign of properties and processes at one scale over the wider scales, or the impact of spatial patterns over processes at one given scale and on their upscaling.

A major difficulty in passing from one scale to another is the lack of suitable tools that adequately represent small small-scale process complexity in a meaningful way at wider scales (McDonnell, 2003). Detailed process studies are often limited to small 'siege' catchments (typically a few km^2 in area) where intensive process studies are highly focused and illuminating, though resulting insights in many cases are not easily extrapolated elsewhere (Soulsby et al., 2006).

The complexity, inherent to catchment systems, generally becomes more basic at wider spatial scales as the averaging of processes often results in simpler emergent properties of systems behavior (Soulsby et al., 2006).

Due to scale multiplicity in spatial patterns, scale holds the key to understand pattern–process interactions. Processes like macropores fluxes, soil erosion, air mass exchange, ground water table oscillation, etc, are assigned to a given scale. Empirical studies indicate that many phenomena tend to line up approximately along the diagonal direction in a space–time scale diagram. For instance, small-scale processes last short time periods and large-scale processes last accordingly longer (Steinhardt & Volk, 2003) (Fig. 1).

Other variables such as antecedent conditions and event characteristics are also important in determining the specific features of erosion, hydrological and hydrochemical response to individual events (see for instance Soulsby et al., 2006; Tetzlaff et al., 2006).

Scale-specific approaches require scale-specific investigation methods and result in scale-specific information and insights. One possible approach consists in the identification of spatio-temporal hierarchies of processes to classify them according to their temporal (duration: short-term to long-term) and spatial scale/dimension

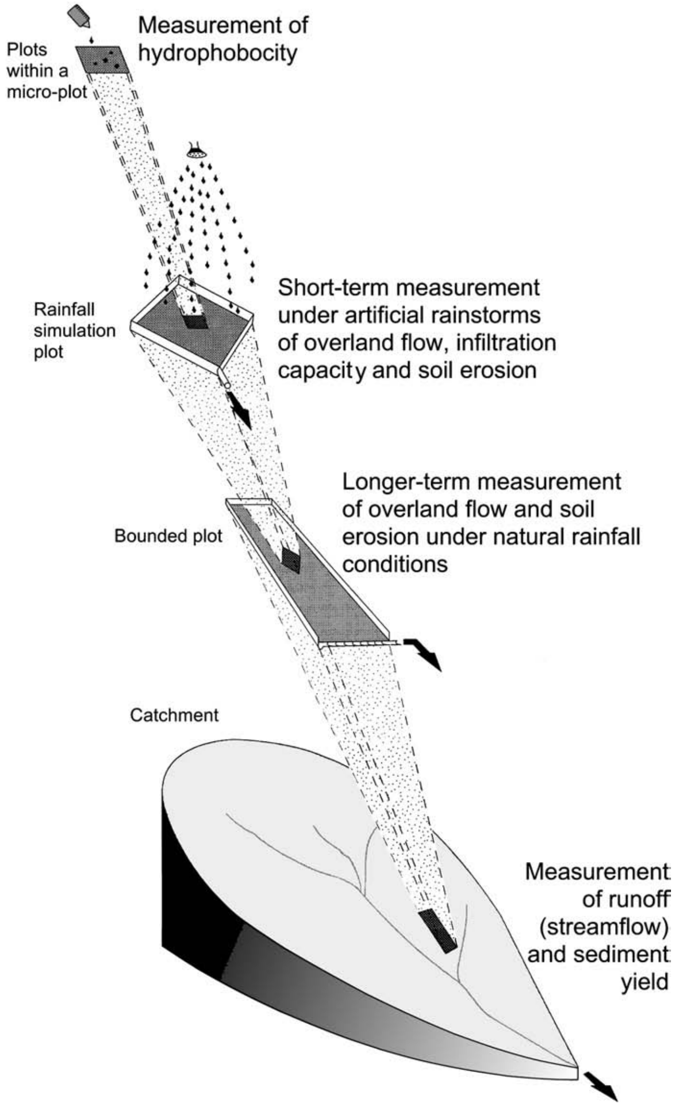

Fig. 1. Nested approach (after Shakesby et al., 2000).

(range: small to large), as well as to their intensity (Steinhardt & Volk, 2003).

2.2. Specific problems posed by burned areas

Burned areas present several limitations to the single methodologies presented above, severely hampering data reliability and the capacity to infer and test the hypothesis about the role of patterns and processes on the soil and water degradation processes and on off off-site environmental impacts.

The main specific limitations posed by burned areas are:

(i) The fast soil and water degradation processes that occur immediately after the fire (e.g. Ferreira et al., 1997, 2005a,b), make virtually impossible to have a calibration period right after the fire, to test differences between intervened and control areas. This is particularly relevant if the efficiency of mitigation measures is to be tested. The sharp change of post-fire conditions hinders any direct comparison between different solutions.

(ii) The presence of a soil water repellent layer poses severe problems to the monitoring, since the insertion of any kind of measuring device in the soil will disrupt the continuity of the soil water repellent layer, providing macropores to the infiltration of overland flow and therefore directly interfering with the soil moistening patterns that influence soil and water degradation processes. Special attention has to be drawn when performing soil destructive sampling campaigns, inserting probes in the soil, or installing boundaries in the soil (i.e. such as in microplots and plots).

(iii) Due to the fast degradation processes, the boundary effect is particularly relevant when installing plots or microplots. Insertion has to be performed with a minimum of disturbance, and mitigation procedures have to be implemented, such as the re-build of the soil water repellent layer with some kind of sealant. This last option may prove problematic since it can distort the erosion results and have to be used carefully.

(iv) Due to the fast degradation processes, the limitations of bounded plots are expected to be more relevant, especially on what concerns the obstacles to the free flow of water and sediment downslope, and consequently a faster reach of an entropy state.

3. Study areas

This paper covers several experiments performed at various sites located in the mountains of central Portugal (Fig. 2). The geographical coordinates, type of burn, antecedent weather and pre-burn vegetation conditions for each study area, are listed in Table 1.

The study areas lie within the transition between Atlantic and Mediterranean climate zones, with 700 to 1400 mm of rainfall per year on average: Caramulo Mountain (1000–1400 mm yr^{-1}), Coimbra (950–1100 mm yr^{-1}), Lousã mountain (1100 mm yr^{-1}) and Mação area (700–1000 mm yr^{-1}). Rainfall is generally concentrated during the period from October to May, whereas July and August are dry months.

All the study sites are underlain by Precambrian schists and shallow stony umbric leptosol soils. The soils are generally <15 cm in depth, containing a sandy loam to loamy sand texture. The soils have an A and a C horizon and a low organic matter content, averaging 14% (Table 2). Vegetation is typically composed of commercial forest stands (i.e. *Pinus pinaster* and/or *Eucalyptus globulus*) with a thick shrub understorey.

Measurements were made at several locations in the Central Portuguese Region where either prescribed fires or wildfires occurred, as shown in Table 2 and Fig. 2. Permanent plots were installed either on burned sites (wildfires, prescribed fires) or on control sites with mature unburned vegetation in the Caramulo Mountains. Rainfall simulation experiments were performed in three distinct geographic areas: (i) the Gestosa, Cadafaz and Aigras experimental sites in Lousã Mountain, (ii) the Senhor da Serra site near Coimbra and (iii) the Caratão catchment, in the Mação area, near to the Tejo River.

Rainfall simulation experiments and plots were performed in Humic Cambisols, overlaying the schist–greywacke complex in the Center of Portugal, in slopes with slope angles in the range of 17°–22°. The monitored catchments are typically smaller than 1.5 km^{-2}, highly dissected with steep slopes with a top convexity and with no basal concavity.

4. Results and discussion

4.1. Impact of soil patterns on overland flow and sediment yields

Forest fires consume the whole litter layer and small bushes, leading to a complete change in vegetation and top soil structures. Fires in northern and central Portugal commonly consume the L, F and where present, H organic layers as well as most of the understorey vegetation (Ferreira et al., 2005b).

The abundant organic matter that contributes to surface soil structure and porosity is profoundly affected by fires (Neary et al., 1999), resulting in a significant reduction of soil roughness and vegetation obstacles to the

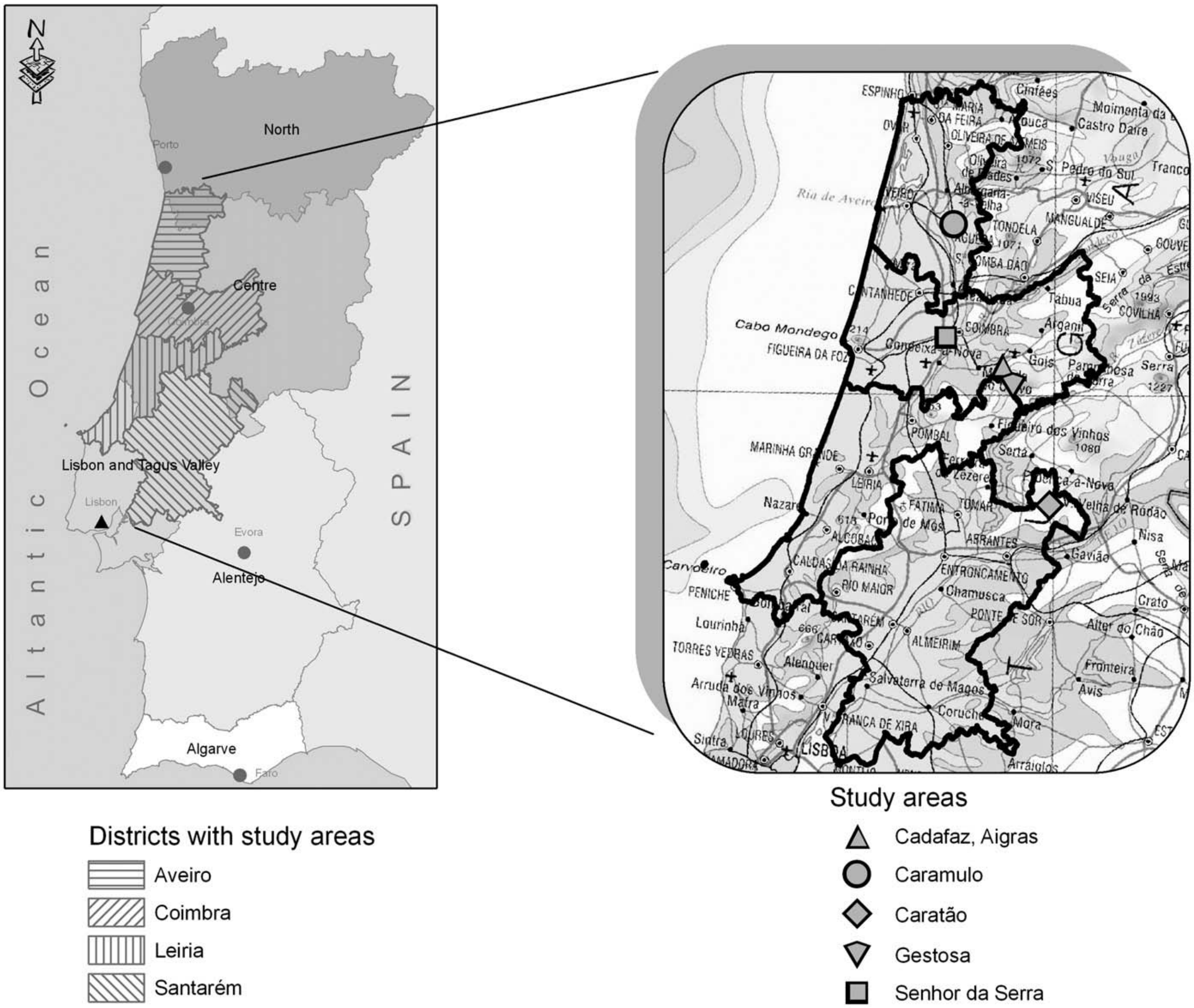

Fig. 2. Location of the study areas.

progression of overland flow and therefore to sediment transport. Fire sharply reduces soil and vegetation heterogeneity.

The loss of vegetation and litter layer and the sealing effect produced by soil water repellence layer limits infiltration to hydrophilic and macropore areas, whilst producing an almost impervious surface that enhances Hortonian overland flow and produces bigger and more prompt peak flows. These occur with a higher frequency following intense rainfall events (Ferreira et al., 2005b). Water repellence develops as a discrete soil layer, parallel to the surface, where hydrophobic organic compounds coat soil aggregates or minerals (DeBano, 1981).

Coelho et al. (2004) showed that different fire intensities produce different spatial patterns of water repellent soils. The values are presented on Table 3, showing that fire, with special emphasis for wildfires; sharply increases the severity of soil water repellence characteristics. Wildfires tend to present a high spatial homogeneity. Unlike prescribe fire, where hydrophobic spots are intersperse with hydrophilic areas where infiltration occurs, soils affected by wildfires present strong hydrophobic characteristics (Molarity of an Ethanol Droplet MED > 13), in a more uniform pattern. Vegetation and litter, as discussed, have little control on overland flow generation and sediment transport at burn areas. This implies that soil water repellence patterns may have an overwhelming importance on overland flow and sediment transport generation and behavior downslope.

These soil water repellence patterns are thought to be responsible for the differences when scaling up from micro plots to plots (Table 4). Although reporting to different time scales and rainfall amounts and intensities, a comparison can be performed, since the rainfall simulations were performed in the vicinity of the 16 m^2 plots. For each land use, a 50 m transect was performed close to the plot positions, a survey on soil water repellency was then performed along that transect. Seven rainfall simulations were then performed, covering all variability found. A relative comparison, having the mature pine as control land use, shows a much sharper decrease in overland flow and sediment yield for the prescribed fire site compared with the wildfire. Since all rainfall simulations were performed during 1 h under 50.5 mm h^{-1}, and the plots were monitored for an entire year after fire, the relative comparison shows a sharper decrease for the prescribed fires when compared with the other land uses. This can be ascribed to the higher heterogeneity of soil water repellence patterns.

Processes at a given scale are dependent of a set of properties and processes at that scale and the scale immediately below, that ultimately influence a set of less scale dependent variables, that Steinhardt and Volk (2003) called as essential landscape functions. These include functions such as “continuity” (i.e. homogeneity or heterogeneity), “transmissibility” (i.e. presence or absence of significant ruptures), buffer functions, connectivity, event chronology, fragmentation,

Table 2
Study area locations and characteristics

Rainfall simulation plots (0.24 m^2)						
	Caratão	Aigra Nova	Cadafaz	Gestosa	Caratão	Senhor da Serra
Latitude	39°35′50″N	40°06′45″N	40°06′18″N	40°02′41″N	39°35′50″N	40°05′16″N
Longitude	07°56′37″W	08°08′05″W	08°02′15″W	08°10′10″W	07°56′37″W	08°24′45″W
Burn type	No burn	No burn	Prescribed fire	Experimental fire	Wildfire	Wildfire
Previous land use	Mature pine	“Mato” (shrubs)	“Mato” (shrubs)	“Mato” (shrubs)	Mature pine	Mature pine
Permanent bounded plots (16 m2)						
	Caratão	Aigra Nova	Aigra Nova	Caratão	Cabeço de Cão	Serra de Cima
Latitude	39°35′50″N	40°06′45″N	40°06′45″N	39°35′50″N	40°38′27″.6	40°36′37″.5
Longitude	07°56′37″W	08°08′05″W	08°08′05″W	07°56′37″W	8°06′45″	8°20′19″.2
Burn type	No burn	No burn	Prescribed fire	Wildfire	Wildfire	Rip-ploughed
Previous land use	Mature pine	“Mato” (shrubs)	“Mato” (shrubs)	Mature pine	Mature pine	Burned pine
Small catchments						
Catchment	Altitude range	Aspect	Location		Area	Dominant land use
	m		Latitude North	Longitude W Greenwich	(Km^2)	
Lourizela	466–160	SSE–NNW	40°38′27″.6	8°06′45″	1.1	Burned pine
Caratão	397–245	WNW–ESE	39°35′50″	7°56′37″	0.56	Burned pine
Serra de Cima	475–280	E–W	40°36′37″.5	8°20′19″.2	0.51	Rip-ploughed
Bouça	540–170	ENE–WSW	40°32′55″.1	8°18′45″.9	0.61	Mature forest

regulation functions such as elasticity, resistance and resilience to perturbation. Fire can be seen, especially in fire prone regions, such as Mediterranean areas, as an event that alters water and sediment processes' connectivity at various scales and among different landscape compartments.

The differences between the natural and artificial rainfall intensities and the scale effect may account for the decrease in erosion rates from microplot to plot scale, especially because erosion is overland flow driven. Fires present a significant increase in overland flow generation when compared with unburned witness areas. Fire intensity seems to play an important role, since overland flow amounts are more than fourfold those of prescribed fires in average. This can be ascribed to the differences in the severity and spatial distribution patterns of soil water repellency. As expected, at wider areas, both overland flow and erosion rates decrease significantly. Nevertheless, the decreases are sharper for prescribed fires than for wildfires.

A possible explanation to the observed data has to do with soil water repellency distribution patterns, as shown in the conceptual model presented in Fig. 3. Under wildfire conditions, soil water repellence is high and evenly distributed. With the exception of some macropores, the entire burned area is highly hydrophobic, and under unbounded situations, overland flow and sediment transport find little obstacles to their progression downslope. In fact, by inducing an enhanced connectivity as a result of the continuous soil water repellence pattern and eliminating obstacles to water and sediment movement as a result of vegetation and litter layer disappearance, fire induces an increase in water and sediment transport downslope.

As a consequence, transmission of water and sediments to the stream is thought to grow downslope. The bounded plots technique introduces a barrier to the natural progression of overland flow and sediments downslope, which may explain the plots' lower responses when compared with those of burned catchments found by Ferreira et al. (1997). In addition, as a close system, it is expected to suffer faster degradation, i.e. without a supply from upslope, the soils within bounded plots are expected to run out of ashes and nutrients at a faster rate than nonbounded areas, whilst due to the break in connectivity, they will yield less overland flow.

Evidence given by Ferreira et al. (2005b) shows that even at catchment scale, sediment exploitation after fire is a fast process, lasting less than one year.

The higher runoff at catchment scale, compared with the amount of overland flow from bounded plots contradicts the findings of Cantón et al. (2001) and Cammeraat (2004) that noticed a decrease in runoff depth as scale increases. One reason is that although presenting the same spatial pattern, the obstacle provided by the boundary breaks the connectivity of water and sediments downslope.

As pointed out by Ferreira et al. (1997, 2005b), and Lane et al. (2004), the first rainfall events after fire may not produce overland flow and erosion if the ash storage capacity is not exceeded.

Prescribed fire presents a more heterogeneous pattern of soil water repellence. Side by side with spots with strong soil water repellence, some hydrophilic spots occur, where water can infiltrate and sediments be trapped, providing a buffer to connectivity linkages along the slope (Fryirs et al., 2007). For this reason, both overland flow

Table 3
Soil water repellent characteristics for selected burned and unburned land uses, using the MED (molarity of an ethanol droplet) technique

Land use	Mature pine	Shrubs	Prescribed fire	Wildfire
		n=25		
		(% Ethanol)		
Average	0.64	4.24	4.12	20.96
Min	0	0	0	13
Max	5	18	13	24
Median	0	0	5	24
Mode	0	0	5	24
Standard deviation	1.35	7.07	3.63	3.74

Table 4
Overland flow and erosion yields for rainfall simulations and 16 m^2 bounded plots

		Mature pine	Shrubs	Prescribed fire	Wildfire
Overland flow	Rainfall simulation (% rainfall)	5.6	<1	14.6	65.8
	16 m^2 plot (% rainfall)	0.09	0.05	0.08	11.6
Erosion rates	Rainfall simulation (g/m^2/h)	0.4	<detection limit	6.5	15.6
	16 m^2 plot (ton/ha/yr)	0.02	0.08	0.2	2.2

Rainfall simulation measurements were performed for 1 hour at 50.5 mm h^{-1}; 16 m^2 plots' results are cumulative values for the first year after fire.

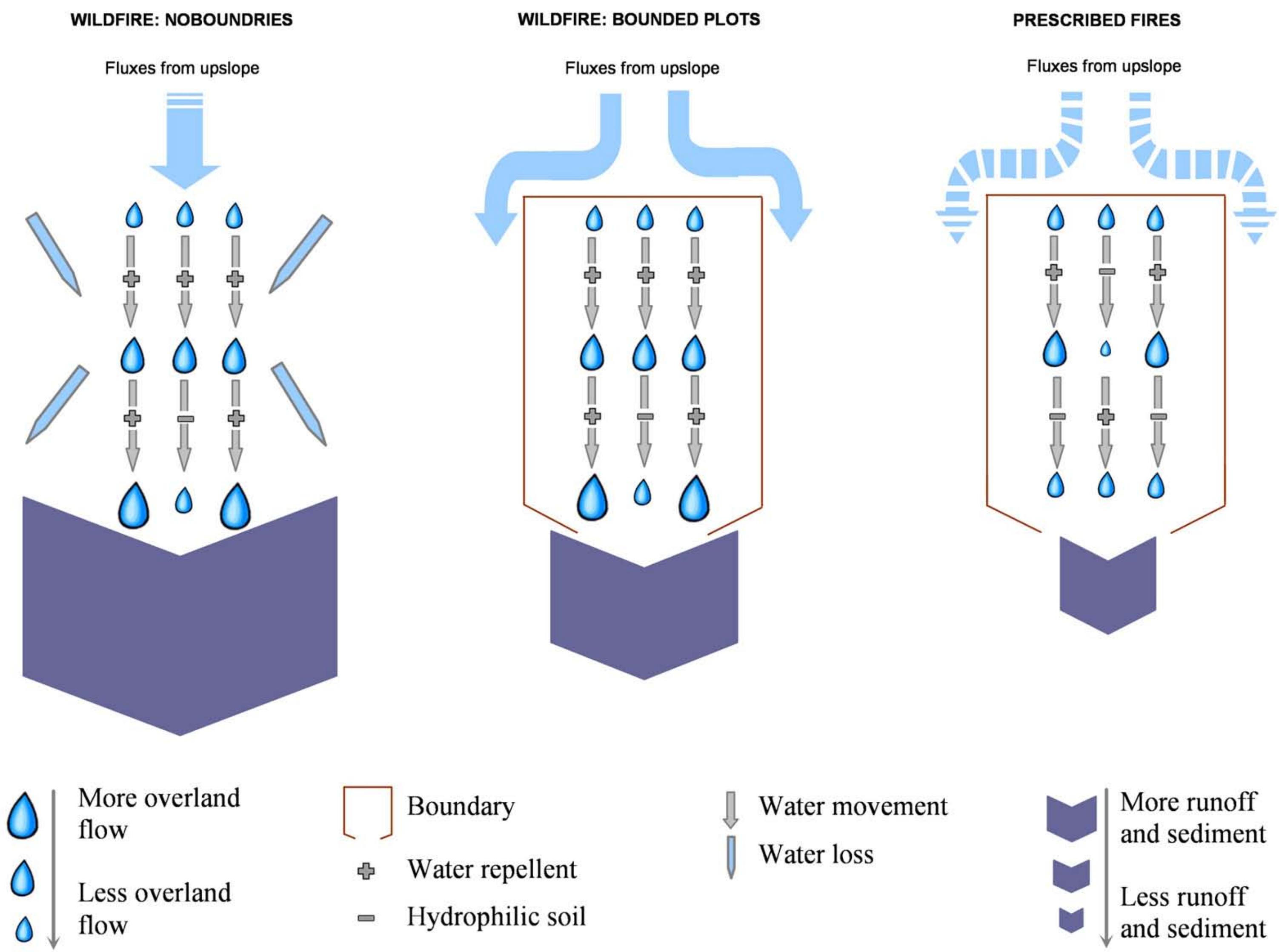

Fig. 3. Overland flow and erosion yield for different soil water repellence patterns in burned areas.

and erosion yields at the 16 m^2 plots are significant lower than for wildfire.

Despite the increases in overland flow and erosion rates at slope scale, when compared with nonburned areas, pointed out by almost all authors, (with the exception of Lane et al., 2004; Shakesby et al., 2007), since the majority of the studies were performed at plot scale, a major question remains: What is the real impact of forest fires at larger areas and which are their off off-site implications. This is especially relevant since as pointed out by Shakesby and Doerr (2006), the amounts may not be significant, and that they only gain relevance when compared with the undisturbed areas, where overland flow and especially erosion virtually do not occur.

4.2. Impact of disruptions at catchment level

Several authors point out major changes on hydrological and sediment (dissolved, suspended and bedload) transport (Scott & van Wyk, 1990; Scott, 1992; Scott Lavabre et al., 1993; Ferreira et al., 1997; Ferreira et al., 2005a; Coelho et al., 2006) at small catchment scale.

Runoff at catchment scale depends on how valley segments and land systems fit together and are connected across a catchment to explain across-catchment variability in patterns of (dis)connectivity and flux (Brierley et al., 2006). Cammeraat (2004) found that the losses of water in the channel, the spatial connection between different response units, and to the drainage pathways are dominant processes controlling runoff at sub-catchment scale. Hydrological responses at hillslope, microcatchment and sub-catchment scales are within the same order of magnitude and do not differ much with respect to their threshold values.

The comparison of overland flow at plot level with catchment runoff for mature forests and for burned areas (Table 5) shows that burned plots and catchments have a significantly higher response when compared with the mature forest ones. The difference is higher than that commonly ascribed to forest stands interception, which is typically lower than 20% for the forest stands in the area (Ferreira, 1996). This can be ascribed to the presence of a hydrophobic layer and to the reduction of obstacles to the overland flow progression, as pointed out before, together with the absence of plant transpiration right after the fire (Silva et al., 2006). A major difference between the two land uses has to do with the transmission of water from the slopes to the catchment channel. The high infiltration capacity values presented by the mature forests induce a transfer through the soil, and despite the low overland flow generation that occurs only at very extreme rainfall events, when the soil becomes saturated catchment runoff represents 3.2% of the rainfall during a dry hydrological year (Ferreira et al., 1998).

Comparatively, the values of overland flow and runoff for the burned areas are more than tenfold those of mature forests (for overland flow the values are one hundredfold higher). Despite the lower increase from plot to catchment, runoff at catchment level represents almost 50% of the total rainfall amount during the first year after burn. The formation of a hydrophobic layer induces a Hortonian response, may be hampered by the presence of macropores, especially in the burned pine areas, where the combustion of rotten root systems (as a result of successive forest thinning management practices) forms extensive macropore systems. Although macropore networks can account for some of the differences between the overland flow and runoff amounts (i.e. they provide an alternative pathflow to transmit water from the slope to the channel), these can also be ascribed to the fact that plots are close systems that represent a break in connectivity of slope hydrological processes. They destroy the connectivity of downslope processes, as shown in Fig. 3. A final explanation is that plots may be placed at unrepresentative locations, where flows are less important, such as ridges or the upper parts of slopes. These places are expected to present smaller amounts of water and sediment flows, since the cumulative downslope effect is virtually nonexistent. It is postulated that sites further downslope would have higher yields as the result of the enhanced connectivity. Further research is needed to clarify this issue.

A further insight is given by comparing rip-ploughed plots and catchments with plots and catchments burned by wildfires (Table 6). At plot level, rip-ploughed areas present much higher values than those of burned areas. In fact, for rip-ploughed plots, overland flow is almost fourfold and erosion more than sevenfold those of burned plots. Despite the impressive soil loss rates and overland flow amounts, these differences are not reproduced at the catchment level. In fact, rip-ploughed areas show a reduction from 46.4% in overland flow to 17% in catchment runoff. The burned areas show an opposite response to the “decrease in runoff depth with broader scales” tendency reported by Cantón et al. (2001) and Cammeraat (2004). In fact, whilst overland flow represents 12% of rainfall at plot scale, runoff increases to 48.5% at catchment level. This can only be ascribed to the presence of a break in connectivity between the slope and the stream at the rip-ploughed catchment. The ploughed catchment presents a buffer zone of undisturbed land uses around the catchment channel, and this is enough to trap sediments (Table 7) and promote overland flow infiltration. At burned areas, there are no obstacles to the transmission of water and sediments from the slopes to the catchment channel, other than geomorphologic (e.g. concave slope bottoms) or man-made (e.g. terraces, roads) ones, which are absent from the monitored catchments. Therefore catchment response is enhanced.

Table 7 presents data for two rainfall events that illustrate this reality. An extreme rainfall event (115.1 mm in less than 12 h) produced 12.3% runoff and 0.7 kg of sediment per hectare, much lower than expected given the erosion rates measured at plot scale, where in average, during the first year after ploughing, for that amount of rainfall would be around 5 ton ha^{-1}. This can only be ascribed to the buffer zone between the disturbed area and the catchment channel. On the other hand, a small rainfall event, with 18.9 mm falling in a little more than 12 h resulted in the runoff of 44.2% of the rainfall and a sediment yield of 17.9 kg ha^{-1}.

Once again, soil/land use patterns seem to play an important role in affecting the values at wider areas, with the transmission of processes from one scale to the other being dependent of the continuity/discontinuity of spatial patters. Fig. 4 presents a comprehensive conceptual model. In fact, where patterns are variable, either for small areas, such as the patterns resulting of prescribed fires (where soil water repellence is highly variable), or at wider areas, such as

Table 6
Overland flow and runoff measured at plot and catchment level, and rate of erosion per millimetre of rain at plot level

	Overland flow/runoff		Erosion	
	Plot (% rainfall)	Catchment (% rainfall)	Plot (ton/ha/mm)	Catchment
Burned	12	48.5	0.004	–
Ploughed	46.4	17	0.03	–

Table 5
Overland flow and runoff yield at mature forest and burned plots and catchments

	Rainfall (mm)	Overland flow (16 m^2 plot)	Runoff (catchment)
Mature	986	1.2 mm (0.12%)	32 mm (3.2%)
Burned	982	117.4 mm (12%)	476 mm (48.5%)

Table 7
Runoff and sediment yield at small (<1.5 km^2) disturbed catchments

	Rainfall (mm)	Runoff (mm)	Sediment yield (kg ha^{-1})
Ploughed	115.1	14.2 mm (12.3%)	0.7
Burned	18.9	8.4 mm (44.2%)	17.85

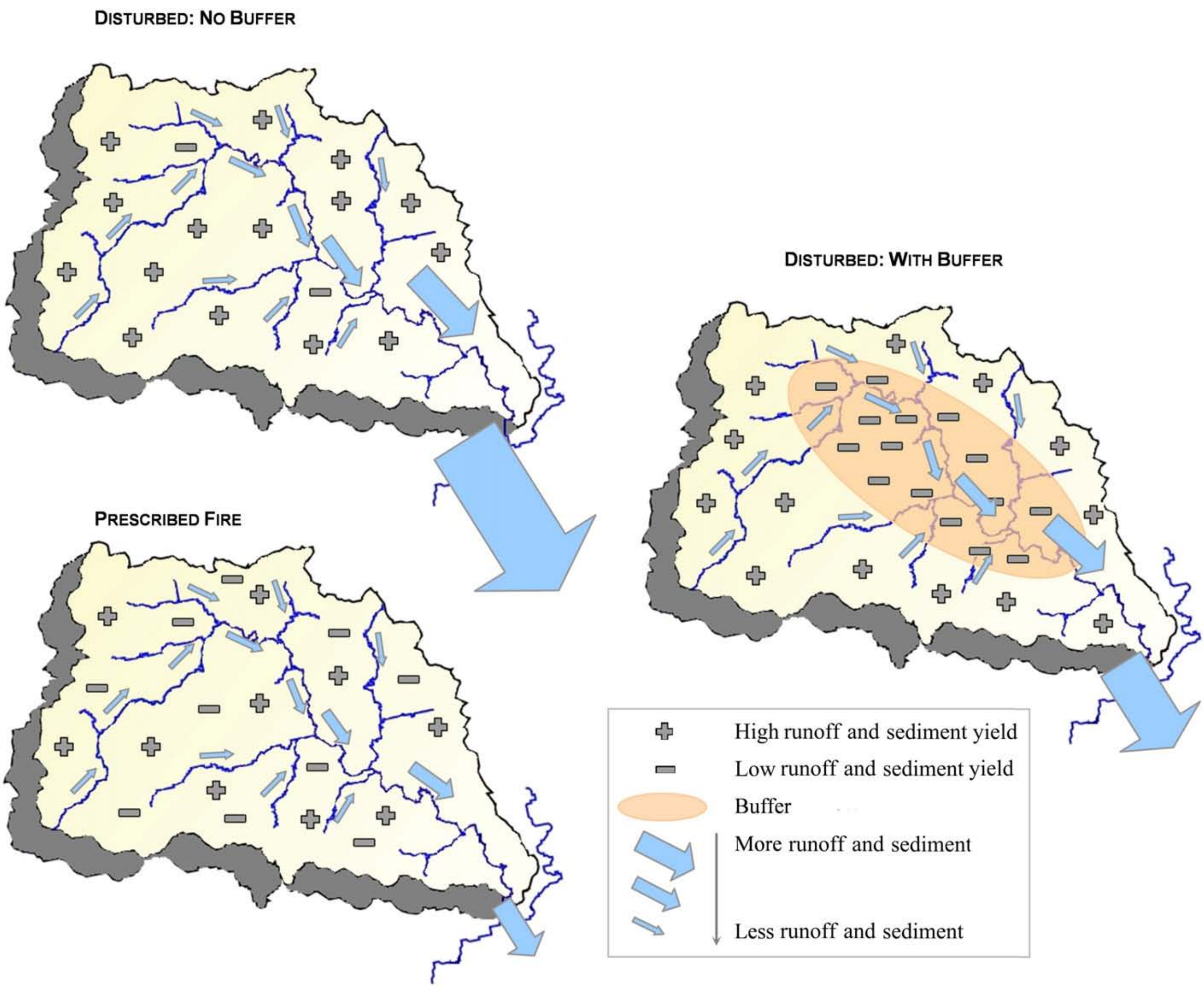

Fig. 4. Runoff and sediment exploitation at small catchment level.

catchments, we expect small amounts of runoff and sediment exploitation. This is nevertheless still to be proven experimentally, since there are no published data available on prescribed fire impacts at catchment scale. Runoff and erosion from highly disturbed areas can also be mitigated if a conservative land use forms a buffer around the catchment channel.

Therefore, key issues in soil and water transfers from one scale to the other and the magnitude of off off-site impacts produced by fires, seem to be the damage severity and the extension of disturbed areas, with particular emphasis on how they impact the connectivity of water and sediment fluxes, especially if they impact the way fluxes come together to influence processes at either areas.

The loss of relevance from one scale to another and more important, the properties and process thresholds that influence the occurrence of a scale continuity, that often results in catastrophic events, need further research.

Runoff and erosion typically have different thresholds at different scales when changes in dominant processes take place. An important question is whether or not processes that are active at one specific scale interact and contribute or interfere with broader scale processes (Cammeraat 2004). Spatial patterns, and especially, spatial heterogeneity related to differences in soil properties and vegetation are thought to be extremely important over scale and thresholds. Process connectivity plays an important role in this process (Brierley et al., 2006; Fryirs et al., 2007). The role of initial conditions of the soil surface is crucial, namely the spatial distribution of static soil surface properties and the dynamic state of the soil surface (Cammeraat, 2004).

5. Conclusions

Despite the methodological problems posed by burned areas, which may hinder the reliability of measurements and make the implementation of traditional experimental designs difficult, they represent a unique, more simplified context (without vegetation and litter layer induced variability). The main differences steam from the different patterns of soil water repellence that result from various fire intensities. This means that, in spite of the enhanced monitoring problems of single techniques, burned areas offer a new insight into how properties and processes interact at different scales. To attain these objectives, a nested approach is required, integrating scales from point to catchment level.

The results show that soil/land use spatial patterns play an important role in the magnitude of processes at a given scale and that the connectivity of water and sediment processes influences processes response at wider systems. Although many of the links are not yet well understood, a conceptual model is presented to explain how this connectivity works.

In burned areas, the spatial distribution of severe soil water level repellence is related to fire severity. In severely burned areas, soil water repellence is more extreme and evenly distributed, whilst in low intensity burns, soil water repellent spots alternate with hydrophilic areas where infiltration is possible. The more homogeneous pattern results in enhanced overland flow production downslope, as a result of enhanced connectivity, while whilst the low intensity burns present lower overland flow and sediment yields. This implies that prescribed fires are less destructive in terms of soil and water degradation processes and are therefore suitable for fire prevention strategies.

The spatial distribution of patterns (i.e. soil and vegetation patterns), also play an important role when moving from slope to catchment scales. In fact, if no obstacle exists to the overland flow and eroded sediment progression, the fluxes reach the catchment channel easily, producing higher runoff amounts when compared with the undisturbed land uses or with cases where a buffer land use occurs between the disturbed area and the catchment channel. The impacts of burned areas on peak lows and sediment transport of large river catchments is still poorly understood, although of utmost relevance to understand the off off-site impacts of forest fires.

Despite the methodological problems posed by burned areas, which increase the probability of errors and the accuracy of measurements, the use of integrated nested approaches has proven a valuable tool to put the data acquired from the various methodologies into perspective and to improve our insight and knowledge on the processes, their thresholds and how spatial distributed patterns influence the occurrence of processes at wider scales.

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