Universidade de Aveiro Departamento de Ambiente e Ordenamento
2013

MARUXA MALVAR CORTIZO

AVALIAÇÃO DO EFEITO CONJUNTO DA GESTÃO FLORESTAL E DOS INCÊNDIOS NA ESCORRÊNCIA E EROSÃO DO SOLO NO NORTE-CENTRO DE PORTUGAL

ASSESSING THE COMBINED EFFECT OF LAND MANAGEMENT AND WILDFIRE ON RUNOFF AND SOIL EROSION IN NORTH CENTRAL PORTUGAL

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Tese apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Ciências e Engenharia do Ambiente, realizada sob a orientação científica do Doutor Jan Jacob Keizer, Investigador Associado do CESAM – Centro Superior de Estudos do Ambiente e do Mar, Departamento de Ambiente e Ordenamento da Universidade de Aveiro e co-orientaçao de Peter R. Robichaud investigador do US Deparment of Agriculture, Forest Service, Rocky Mountain Research Station, Moscow, Idaho,USA.

Tese desenvolvida no quadro do Programa Doutoral em Ciências e Engenharia do Ambiente, com o financiamento de uma bolsa de doutoramento (SFRH/BD/41320/2007) da Fundação para a Ciência e a Tecnologia (FCT) e o apoio dos projectos EROSFIRE (POCI/AGR/60354/2004) e EROSFIRE II (PTDC/AGR-CFL/70968/2006), financiados pela Fundação para a Ciência e a Tecnologia (FCT) e o FSE no âmbito do III Quadro Comunitário de Apoio.

A minha tia Balbina por vivir no campo, do campo e para o campo.
Aos meu pais e irmãos por ensinaren-me todo o que sei e sou.
Ao Roque e o Sergio por existir ao meu lado.

o júri

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Doutor João Pedro Carvalho Nunes
Estagiário de Pós Doutoramento do CESAM, Centro de Estudos do Ambiente e do Mar, Universidade de Aveiro.

Doutor Peter R. Robichaud
Research Engineer, USDA Forest Service, Rocky Mountain Research Station, Moscow, Idaho, United States of America, (co-orientador).

Doutor Jan Jacob Keizer
Investigador Auxiliar do CESAM, Centro de Estudos do Ambiente e do Mar, Universidade de Aveiro, (orientador).

agradecimentos
Acknowledgments

I am indebted to all the people who, in one way or another, make possible this research.

Nunca estaria na investigação se faz uns quantos anos atrás não tivesse encontrado a Cari nas escadas do departamento a me dizer, então, queres vir amanhã ao campo?

Só pude colocar aquelas primeiras gotas de água no campo porque a Cat. Prof. Celeste Coelho tinha iniciado projetos para o estudo da hidrologia de áreas ardidas no Departamento de Ambiente e Ordenamento da Universidade de Aveiro fazia já um anos. As primeiras vezes que eu "fiz chover" no campo, e todas as que lhe seguiram não teriam sido possíveis sem os ensinamentos de Anne-Karine Boulet e de Antonio Ferreira. Claro que, sem o meu orientador Jacob Keizer, seus conselhos e sua motivação, nunca eu teria regressado para o mundo da ciência e muito menos ter feito um mestrado e um doutoramento. Obrigada Jacob pela tua infinita vontade de medir, assim este a chover, tronar ou faça sol, sem teu interesse esta tese não existiria.

Devo e quero agradecer também a outras muitas pessoas que me ajudaram, ensinaram, e compartiram comigo todos este tempo e trabalho, tanto em Aveiro como em outros lugares do mundo.

Todos os "erosivos" passados e presentes da universidade de Aveiro, pelo seu esforço e trabalho no campo, no laboratório e assim como pela partilha de idéias e conhecimentos: Raquel Ferreira, Sergio Prats, Mark Lagewaard, Mart Houmann, Angela García-Monje, David Herrera, Marta Oñate, Ana e Ana, Pedro Cascão, Elena Palacios, Isabel e Estefanía, Pieter van Broeckhuysen, Amadou Seck & David de Vos, Wouter Beekman, Joost Jansen, Joost Koenders & Ilse Leeftink, Robert Broekhuis & Martijn van den Aker, todos eles fizeram possível a recolha de dados no Erosfire, a base de compartir boas molhaduras e aqueles suores de 35ºC no campo; Virginia M.F.G. Pereira pela sua estimável ajuda com os perfis de solo; Ana Sofia Santos pelo seu trabalho no laboratório; Jorge Lucena, Carmen Magalhães e Joaquim Sande Silva disponibilizaram tempo e meios da Escola Agrária de Coimbra para analisar amostras de solo. Sergio leu, revisou e ajudou com a estatística e formatação. João Nunes pelas suas "brain storm", Isabel Fernandes, Paula Maia, Ana Vasques, Silvia Regina, Diana Vieira, Marife Varela uniram-se ao trabalho no Erosfire-II.

A José Antonio Vega y todo el equipo de Lourizán por su apoyo y comprensión durante el tiempo que pase con ellos, Cristina, Chema, Enrique, muchas gracias.

I am also gratefully indebted to my co-supervisor Peter Robichaud because he helped me to understand what the data taught me and the importance of the “big picture”. He also gave me the opportunity during the time that I spend in Moscow to learn about hydrology, forest fires, modeling, statistics and field work with him and the hydrology and soil erosion crew: Bill Elliot, Bob, Joe, Natalie, Sarah, Louise, Will, many thanks for the shared times. During field work in Montana I had the opportunity to learn and share moments with Lee MacDonald who had the patience to understand and improve my ideas about this thesis. Mary Ann helped me with the paper work, always a difficult issue. Also Martha, Patrick, Louise and Ann Storrar who hosted me as family. John Crock was a very good climber partner but also taught me about trees and plants in the amazing Idaho landscape. Thanks to all!

To all the people I met in conferences, sharing field work, and exchanging concepts and ideas. Especially the people from the FUEGORED research net: Artemi, Merche, Vicky, Jorge, Andrea, Cesar, Antonio, Paulo, Xavi, Oscar, Angeles, Teresa, Joanet and many more....from who I had learned many things; not only about science but about life. Desde otros lugares de la Península me mostraron no solo que lo que hacemos interesa a todos sino que todos tenemos dificultades muy parecidas para superar. Obrigada e Força!

Esta tese de doutoramento não seria possível sem o apoio financeiro da Fundação de Ciência e Tecnologia, através duma bolsa de doutoramento (SFRH/BD/41320) e também através do financiamento dos projetos EROSFIRE, EROSFIRE II. Gostaria ainda de agradecer a empresa Serraic Lda. por fornecer e aplicar o “hydromulch” e a brigada de incêndios de Arganil pela sua colaboração. SAS-Portugal também e agradecida por prover a licencia do programa de analise estatístico SAS.

Os agradecimentos são das ultimas folhas que escrevo, mas estão no inicio desta tese, pois sem essas pessoas o trabalho nunca teria sido feito. Assim, estas ultimas linhas que escrevo são para a minha família e amigos, sem eles nunca cá teria chegado. Aos meus pais, Célia e Antonio, por me ter criado e atendido desde que ando neste mundo, como igualmente fizeram meus irmãos, Ana e Fernando. Ao Roque, por ser meu despertador durante esta ultima fase da escrita, fazendo-me acordar para mamar às 6 horas da manhã impedindo assim a minha preguiça boiar na cama. Ao Sergio, por tudo e mais alguma coisa.

Palavras-chave

incêndio, escorrência, erosão, simulação de chuva, repelência à água do solo, lavrar, corte e extração, eucalipto, pinheiro, “hydromulch”

Resumo

Em todo o mundo tem sido verificado uma elevada reposta hidrológica e erosiva, e por vezes até extrema, em terrenos afetados por incêndios florestais. Contudo, no caso do norte-centro de Portugal, pouca investigação tem sido realizada sobre o impacte de vários tipos de gestão (como o tipo de lavragem, corte e retirada da madeira queimada ou tratamentos pós-fogo de mitigação da erosão) na resposta hidrológica e erosiva de áreas recentemente ardidas. Este estudo tem como objetivo a medição da escorrência e erosão do solo em plantações de eucalipto e pinheiro durante o primeiro, segundo e terceiro ano a seguir a um incêndio. O efeito de diferentes técnicas de preparação do solo (lavragem na direção do declive, lavragem seguindo as curvas de nível e terraços inclinados), do corte e retirada da madeira queimada, assim como da aplicação de “hydromulch” (tratamento pós-fogo) sobre a escorrência e erosão do solo, foi comparado com outras áreas ardidas mas não alteradas pela lavragem ou tratamentos pós-fogo. Uma monitorização intensiva da escorrência, erosão e das variáveis selecionadas foi realizada com o intuito de determinar os factores-chave nos processos de geração de escorrência e erosão pós-fogo, assim como de sua variação temporal e espacial. Uma especial atenção foi dada à repelência à água do solo dado seu suposto papel para a geração de escorrência. Experiências de chuva simulada (RSE’s) repetidas no tempo, parcelas de escorrência a micro-escala e barreiras de sedimentos (“sediment fence”) foram executadas e/ou instaladas imediatamente depois do incêndio em sete encostas. Os dados de escorrência e erosão com chuva natural foram comparados com os dados de RSE’s, o que se revelou útil na avaliação da adequabilidade dos dados de precipitação simulada relativamente à natural.

Comparando com estudos anteriores, os resultados apresentam coeficientes de escorrência (20-60%) comparáveis, mas perdas de sedimentos (125-1000 g m^{-2}) inferiores, a outros no âmbito nacional e especialmente fora de Portugal. As discretas taxas de sedimentos são coerentes com um historial de intenso do uso do solo na região. Na avaliação dessas perdas de sedimentos deve ser considerada a pouca profundidade e pedregosidade destes mesmos, assim como a alta taxa de matéria orgânica (50%) nos sedimentos erodidos. Quanto às medições de erosão nos locais lavrados, estas foram limitadas pela disponibilidade de sedimentos, devido ao longo periodo ocorrido (vários anos) desde que as encostas foram lavradas.

A alteração da cobertura de manta morta devido às actividades de corte e extração da madeira pós-fogo incrementou substancialmente as perdas de sedimentos no eucaliptal e no pinhal. A efectividade do “hydromulch” na redução de escorrência (70%) e erosão (83%) foi atribuída ao efeito protetor proporcionado pelo tratamento. Este tratamento, também afetou significativamente a cobertura vegetal e outras propriedades do solo, que por sua vez também reduziram o risco de erosão.
A quantidade de precipitação foi o primeiro factor em explicar a variância da escorrência, no entanto, uma mudança de quantidade, para intensidade da precipitação como factor principal foi detectada quando a cobertura do solo aumenta, ou quando existe alguma capacidade de infiltração (condições de hidrofílicas). A perda de sedimentos foi controlada pela intensidade da precipitação e a cobertura do solo. O efeito da repelência à água do solo, sobre a geração de escorrência, não é directo já que os valores totais de repelência não são suficientes para avaliar seu impacte hidrológico. Contudo, a repelência à água explicou a variabilidade na geração de escorrência nos modelos específicos por áreas, com maior eficácia que os modelos gerais. Adicionalmente, a humidade do solo está melhor relacionada com os níveis de repelência à água do solo do que a precipitação antecedente. Os resultados da chuva natural confirmaram que as RSE’s representaram bem as taxas específicas de perda de sedimentos, o seu conteúdo em matéria orgânica, assim como as diferenças entre locais lavrados e não lavrados. As RSE’s também registraram a componente sasonal na produção de escorrência e sedimentos, atribuída ao efeito da repelência à água do solo.

Estes resultados têm implicações para a modelação da erosão e práticas de conservação do solo em áreas ardidas da região, ou zonas com o mesmo tipo de uso de solo, clima e características do solo. As perdas de solo medidas em conjunto com a crescente frequência em que as áreas ardidas e não ardidas estão a ser lavradas, sugerem que a lavragem não é efectiva para a conservação do solo florestal. É recomendado o corte da madeira queimada com menos impacto, permitindo a conservação da manta morta para a proteção do solo. Dada a elevada eficiência do “hydromulch” em reduzir escorrência e erosão, esta técnica é indicada para áreas especialmente vulneráveis e sensíveis.

Key-words

wildfire, runoff, erosion, rainfall simulation, soil water repellency, plough, logging, eucalypt, pine, hydromulch

Abstract

Strong and sometimes extreme responses in runoff and soil erosion following wildfires have been reported worldwide. However, in the case of North-Central Portugal, little research had been carried out regarding the hydrologic and erosive impacts of several land management activities in recently burnt areas (such as ground preparation, post-fire logging or post-fire mitigation treatments). This study aims to assess post-fire runoff and soil erosion response on Eucalypt and Maritime pine plantations during the first, second and third years following wildfires. The effect of several pre-fire ground preparation operations (ploughed down-slope, contour ploughed and inclined terraces), post-fire logging activities (on both the eucalypt and pine plantations), as well as the application of hydromulch (a post-fire emergency treatment) on overland flow and soil erosion were compared to burnt but undisturbed and untreated areas. The intensive monitoring of runoff, soil erosion and selected soil properties served to determine the main factors involved in post-fire runoff and soil erosion and their spatial and temporal variation. Soil water repellency deserved special attention, due to its supposed important role for overland flow generation. Repeated rainfall simulation experiments (RSE's), micro-scale runoff plots and bounded sediment fences were carried out and/or installed immediately after the wildfire on seven burnt slopes. Micro-scale runoff plots results under natural rainfall conditions were also compared to the RSE's results, which was useful for assessing the representativeness of the data obtained with artificial rainfall.

The results showed comparable runoff coefficient (20-60%) but lower sediment losses (125-1000 g m^{-2}) than prior studies in Portugal, but especially outside Portugal. Lower sediment losses were related with the historic intensive land use in the area. In evaluating these losses, however, the shallowness and stoniness of the soils, as well as the high organic matter fraction of the eroded sediments (50%) must not be overlooked. Sediment limited erosion was measured in all the ploughed sites, probably due to the time since ploughing (several years). The disturbance of the soil surface cover due to post-fire logging and wood extraction substantially increased sediment losses at both the pine and eucalypt sites. Hydromulch effectiveness in reducing the runoff (70%) and sediment losses (83%) was attributed to the protective high coverage provided by hydromulch. The hydromulch significantly affected the soil cover and other soil properties and these changes also reduced the soil erosion risk.

The rainfall amount was the main factor explaining the variance in runoff. However, a shift from rainfall amount to rainfall intensity was detected when either the surface cover or the infiltration capacity (hydrophilic conditions) increased. Sediment losses were controlled by rainfall intensity and surface cover. The role of soil water repellency on runoff generation was not consistent; the overall repellency levels alone were not enough to assess its hydrological impact. Soil water repellency explained runoff generation in the specific-sites model better than in the overall model. Additionally, soil moisture content was a better predictor for soil water repellency than antecedent rainfall. The natural rainfall results confirmed that RSE's were able to capture the specific sediment losses and its organic matter content as well as the differences between the ploughed and unploughed sites. Repeated RSE's also captured the seasonal variations in runoff and sediment losses attributed to soil water repellency.

These results have implications for post-fire soil erosion modelling and soil conservation practices in the region, or areas with the same land use, climate and soil characteristics. The measured sediment loss, as well as the increasing frequency of ploughing in recently burnt and unburnt eucalypt stands, suggests ploughing is not an effective as a soil conservation measure. Logging activities with less impact are recommended in order to maintain the forest litter protecting the soil surface. Due to its high effectiveness in reducing runoff and soil erosion, hydromulch is recommended for highly sensitive and vulnerable areas.

Palabras - clave

incendio, escorrentía, erosión, simulación de lluvia, repelencia al agua del suelo, labrar, corte y extracción, eucalipto, pino, “hydromulch”

Resumen

En muchas partes del mundo y en terrenos afectados por incendios forestales se han registrado respuestas hidrológicas y erosivas altas o extremas. No obstante, en el caso del centro-norte de Portugal, existe poca investigación sobre el impacto de varios tipos de gestión (como el tipo de labrado, tala y extracción de la madera quemada o tratamientos post-incendio para la mitigación de la erosión) en la respuesta hidrológica y erosiva de áreas recientemente ardidas. El objetivo de este estudio es la medición de la escorrentía y erosión del suelo en plantaciones de eucalipto y pino, durante el primer, segundo y tercer año tras el incendio. El efecto de diferentes técnicas de preparación del suelo (labrado a favor de la pendiente, siguiendo las curvas de nivel o terrazas inclinadas), de la tala y retirada de la madera quemada así como de la aplicación de “hydromulch” (tratamiento post-incendio) sobre la escorrentía y la erosión fue comparado con áreas ardidas pero no alteradas por el labrado o tratamientos post-incendio. Fue realizada una monitorización intensiva (aproximadamente semanalmente) de la escorrentía, erosión y algunas variables seleccionadas, con el objetivo de determinar los factores clave en los procesos de generación de la escorrentía y la erosión post-incendio, así como su variación temporal y espacial. La repelencia al agua del suelo recibió una atención especial debido a su supuesto papel en la generación de escorrentía. Experiencias de lluvia simulada (RSE’s) repetidas en el tiempo, parcelas de campo a micro-escala y trampas de sedimentos (“sediment fence”) fueron ejecutadas y/o instaladas inmediatamente después del incendio en siete laderas. Los datos de escorrentía y erosión de lluvia natural fueron comparados con los datos de RSE’s, lo que resultó especialmente útil para evaluar la representatividad de los datos de lluvia artificial frente a la lluvia natural.

Los resultados muestran valores de escorrentía (20-60%) comparables pero menores perdidas de sedimentos (125-1000 g m^{-2}) que estudios anteriores en Portugal, pero especialmente fuera de Portugal. Las tasas bajas de sedimentos están en concordancia con un uso del suelo intensivo en la zona. Igualmente, para evaluar las bajas pérdidas de sedimentos deben ser considerados factores como la poca profundidad y pedregosidad de los suelos así como la alta tasa de materia orgánica (50%) en los sedimentos erosionados. En todas las áreas labradas, debido al tiempo transcurrido desde el labrado (varios años), la erosión fue limitada por la disponibilidad de sedimentos.

La alteración del cubierto de manta muerta debido a la tala y extracción de la madera quemada incrementó sustancialmente las pérdidas de sedimentos en el eucaliptal y el pinar. La efectividad del “hydromulch” para reducir la escorrentía (70%) y la erosión (83%) puede ser atribuida a la cubierta protectora proporcionada por el tratamiento. Adicionalmente, el tratamiento afectó significativamente la cobertura y otras propiedades del suelo, lo que también contribuyó a reducir el riesgo de erosión. La cantidad de lluvia fue el primer factor en explicar la variación de la escorrentía. Aunque, un cambio de cantidad a intensidad de lluvia como factor principal es detectado cuando aumenta la cubierta del suelo o bien alguna capacidad de infiltración está presente (condiciones de hidrofilia). La pérdida de sedimentos fue controlada por la intensidad de lluvia y la cobertura del suelo. El efecto de la repelencia al agua del suelo sobre la generación de escorrentía no es directo, ya que los valores totales de repelencia no son suficientes para evaluar su impacto hidrológico. La repelencia al agua explica la generación de escorrentía mejor en los modelos específicos por áreas que en los modelos generales. Adicionalmente, la humedad del suelo resulta ser un mejor indicador para la repelencia al agua del suelo que la precipitación previa. Los resultados de lluvia natural confirman que las RSE’s capturaron bien las tasas específicas de pérdida de sedimentos, su contenido en materia orgánica así como las diferencias entre laderas labradas y no labradas. Las RSE’s repetidas también capturaron la componente estacional de la escorrentía y sedimentos atribuida al efecto de la repelencia al agua del suelo.

Estos resultados tienen implicaciones para la modelación de la erosión y prácticas de conservación del suelo en áreas ardidas de la región, o zonas con el mismo tipo de uso del suelo, clima y características del suelo. Las pérdidas de suelo medidas conjuntamente con la creciente frecuencia en que las áreas ardidas o no ardidas están siendo labradas, sugieren que el labrado no es efectivo para la conservación del suelo forestal. Son aconsejables talas y cortes cuidadosos de la madera quemada con menor impacto y que permitan la conservación de la manta muerta para la protección del suelo. Dada la alta efectividad del “hydromulch” para reducir la escorrentía y la erosión, se recomienda esta técnica para áreas especialmente vulnerables y sensibles.

Contents

1 Introduction

1. Introduction

1.1 The occurrence of wildfires in Portugal

Portugal and the Mediterranean countries of Europe in general have a long land-use history, during which high density human populations have systematically managed and used the agricultural and forest lands (Moreira et al., 2001). In the past century, however, land use in the Mediterranean Basin has suffered major transformations. A generalized rural exodus caused land abandonment and, at the same time, afforestation of former agricultural land (Moreno, 1999). In north-central Portugal, there was first a shift from grazing lands to Maritime Pine (*Pinus pinaster* Ait.) plantations in the 1930s. In the 1970s, eucalypt – an exotic tree species (*Eucalypt globulus* Labill.) - was introduced and, due to its faster growth and higher economic profitability, then gradually replaced the Maritime Pine stands (Coelho 1995a). Eucalypt has become the principal tree species in Portugal, covering 812.000 ha or 26 % of the forested area (AFN, 2011).

The above mentioned changes in land use have raised widespread concerns about the sustainability of the current situation in Portugal, also because profound changes in the landscape are often associated with increasing rates of habitat loss and fragmentation (Teixido et al., 2010). The traditional agro-silvicultural system was characterized by the extensive exploitation of the forest resources for timber, fuel, grazing, livestock bedding, and cropping (Rego, 1992). Also, prescribed fires were used to clear forest lands for grazing and/or cropping. The resulting landscape was a highly heterogeneous and had a patchy organization of multiple habitats with elevated biodiversity but also low wildfire risk. This low fire risk was still evidenced during the decade from 1950 to 1960, when, on average, some 5.000 ha year^{-1} were burnt by wildfire in Portugal (Ferreira et al., 2009). By comparison, during the past three decades (1980-2010), over 3.000.000 ha were burnt in Portugal, which corresponds to roughly 110.000 ha year^{-1}, (AFN, 2011) (Figure 1). This increase in wildfire incidence and burnt area is generally attributed to a combination of land abandonment and subsequent shrub encroachment, on the one hand, and, on the other, widespread afforestation with flammable tree species, both leading to an increase in fuel accumulation (Moreira et al. 2001; Lloret et al. 2002; Moreira et al. 2009; Carmo et al. 2011; Shakesby, 2011).

Wildfires have become the most important factor for land cover change in Portugal (Pereira and Santos 2003). They also constitute a major threat to the economic viability of commercial forestry and to the ecological health of the ecosystems affected by high fire incidence (Nunes et al., 2005). A recent study estimated that the wildfire return interval for the various ecological regions in Portugal now varies between 23 and 52 years, with the interval being shortest for the region where this research occurred (Fernandes et al., 2012).

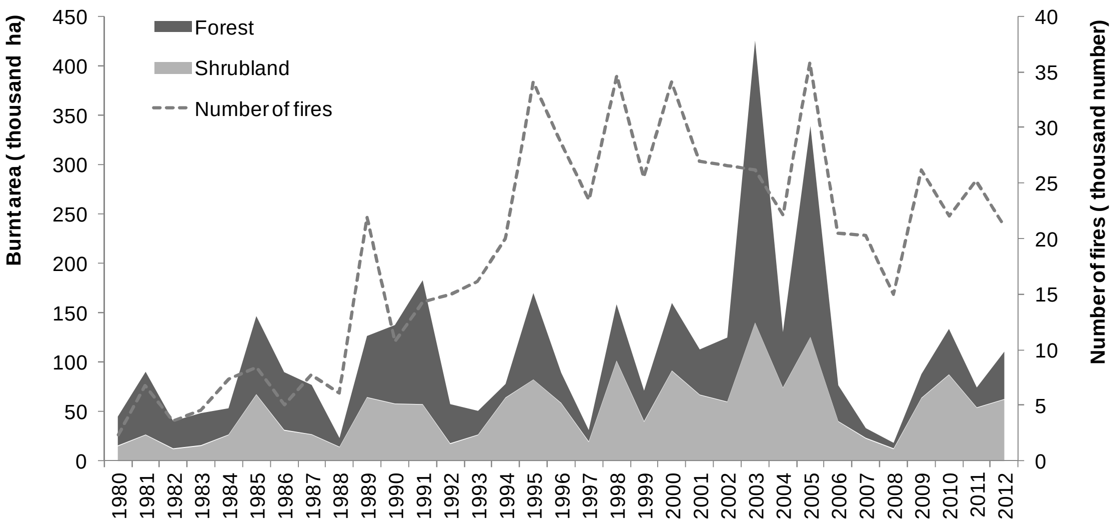

Figure 1. Number of wildfires and burnt area in Portugal from 1980 to 2012 (ICFN, 2012).

1.2 The effects of wildfires on runoff and soil erosion

Wildfires can be a major contributor of soil erosion and land degradation, provoking a disturbance whose impacts decrease with time during the so-called “window-of-disturbance” (Cerdà and Doerr, 2005; Shakesby, 2011). Fires have been found to induce changes in soil’s physical, chemical and biological properties, in vegetation and fauna, and in geomorphological and hydrological processes, including water quality (Debano et al., 1998; Doerr et al., 2000; Shakesby and Doerr 2006; Vila-Escalé et al., 2007; Doerr et al., 2009a; Llorret and Zedler 2009, Moody and Martin 2009; Mataix-Solera et al., 2011; Campos et al. 2012). The changes in soil properties and the (partial) consumption of the protective vegetation and litter cover are frequently considered to be the major factors enhancing post-fire runoff and associated sediment losses (Shakesby, 2011).

Strong and sometimes extreme responses in runoff and erosion following wildfires have been reported worldwide (e.g. Blong et al., 1982; Díaz-Fierros et al. 1987; Soto et al., 1994; Inbar et al., 1997; Prosser and Williams, 1998; Soto and Díaz-Fierros, 1998; Úbeda and Sala, 1998; Robichaud et al, 2000; Cerdà and Doerr, 2005; Spigel and Robichaud, 2007; Fernández et al., 2011; as was extensively reviewed by Shakesby and Doerr, 2006 and specifically for the Mediterranean countries by Shakesby, 2011). Many factors affect the generation of overland flow and the following sediment transport in the rapidly changing post-fire environments. Rainfall and its characteristics are the main factors controlling soil erosion (Benavides-Solorio and MacDonald, 2005; Vega et al., 2005, Spigel and Robichaud, 2007; Scott et al., 2009). Time-elapsed since the fire within the window of disturbance is also an important factor, with the first rainfall events being the most erosive ones as the soils are still largely bare and most vulnerable (Wagenbrenner et al., 2006, Spigel and Robichaud, 2007, Gonzalez-Pelayo et al., 2006). Vegetation and litter cover also play an important role in soil erosion response through the direct protection of rainfall drops impacts, their water retention capacity and the protection of soil to overland flow (Shakesby and Doerr, 2006). The burning of the vegetation leads also to a reduction in transpiration and evaporation. Ash cover can initially enhance infiltration capacity and reduce overland flow (Cerdà and Doerr, 2008; Leighton–Boyce et al., 2007; Woods and Balfour 2008; Cerdà and Robichaud, 2009), but, in addition, ash can block the soil pores and increase the likelihood of overland flow (Scott et al., 2009). Bare soil exposure leaves the soil unprotected and more susceptible to rain drop impact and overland flow removal (Terry and Shakesby, 1993; Benavides-Solorio and MacDonald, 2005). In stony soils, rock fragment cover tends to delay runoff, increase infiltration rates and diminish the soil erosion rates (Cerdà, 2001; Zavala et al., 2010).

Soil water repellency is widely considered one of the main factors in enhancing runoff generation following wildfire (e.g. Shakesby and Doerr, 2006; Leighton-Boyce et al., 2007; Sheridan et al., 2007; Cerdà and Robichaud, 2009). The effects of burning and its influence on soil water repellency can be highly variable (Doerr et al., 1996; Doerr et al., 2004). Infiltration excess overland flow (Horton overland flow) is generated as a result of post-fire soil water repellency, but the presence of a wettable surface layer above a strongly repellent layer can induce a shallow layer of saturation overland flow (Doerr et al. 2009a). In north-central Portugal, soil water repellency is widely held to play a key role in the temporal patterns of the hydrological post-fire response, especially in eucalypt plantations (Prats et al., 2012; Malvar et al., 2011, 2013 (see chapter 2 and 3), Ferreira et al., 2000; Leighton-Boyce et al., 2007; Coelho et al., 2004). Both long unburnt and recently burnt eucalypt stands in the region are typically associated with very high to extreme repellency levels under dry soil moisture conditions (e.g. Doerr et al. 1998, 2003, 2006; Leighton-Boyce et al., 2005; Keizer et al., 2005a, 2005b, 2008). A recent review of fire effects on soils has identified the need for more research on the relative effects of soil water repellency, ground cover, soil sealing and soil disaggregation as well as the effects of rehabilitation treatments on post-fire infiltration and runoff (Cerdà and Robichaud, 2009). Additional studies are needed to determine the relationship between soil water repellency and infiltration rate measured either at point, plot or larger scale (Doerr et al., 2009a).

Besides wildfire itself, post-fire forestry practices can contribute markedly to an enhanced hydrological and erosion response in recently burnt areas (Fernández et al., 2007; Shakesby, 2011). In the region under study, rip-ploughing in down slope direction to prepare eucalypt planting was found to increase sediment losses to rates well beyond those immediately after fire (Walsh et al., 1995; Shakesby et al., 1996). Soil preparation operations, such as contour ploughing and terracing (Figure 2), are also regularly used in north-central Portugal, but their erosion implications have been poorly studied so far. The role of past operations in post-fire erosion (e.g. when the ploughing occurred several years before the wildfire) has equally received little research attention, even though the region's forest lands are an intricate mosaic of terraced, ploughed and unploughed terrains (Figure 3).

In north-central Portugal, several post-fire soil erosion studies, across spatial scales ranging from plot to small catchment, were carried out during the 1990's and the early 2000's (e.g. Walsh et al., 1995; Shakesby et al., 1993,1994,1996; Ferreira et al., 1997; Coelho et al., 2004; Ferreira et al., 2005b, 2008). Nevertheless, most of these studies did not address the erosion in first 1-2 years after the fire and they were related mainly with pine (Ferreira et al., 2005b) rather than eucalypt stands. Likewise, other fire related erosion research needs, the evaluation of land management (Fernandez et al., 2010; Shakesby, 2011) and soil conservation measures (Robichaud, 2005) had received less attention, with only a few studies (Walsh et al., 1995; Shakesby et al., 1994; 1996; Prats et al., 2012).

Figure 2. Terrace construction in progress after a wildfire in Soutelo (Sever do Vouga-Portugal).

Figure 3. Illustrations of highly variable hillslope conditions generated due to different post-fire land management operations on mostly small land properties. Left: Recently burnt terraced and eucalypt planting hillslope with an unploughed section from a different land owner in the middle. Right: Tracks, roads, terraced, logged and “unmanaged” slopes after a fire in Sever do Vouga (Portugal).

1.3 Predicting soil erosion risk and its mitigation in recently burnt areas

Given the typically elevated risk of soil erosion in recently burnt areas, operational tools are needed to help forestry managers assess the erosion potential and possible post-fire interventions, including “no management” (Fernandez et al., 2010). Many models exist for predicting runoff and erosion but only a few have been adapted to post-fire environment (Robichaud et al., 2009). Still, progress in understanding wildfire-induced soil erosion might be best achieved by shifting to a paradigm of large-scale bioregional variants rather than continuing to try to apply a ‘one-size-fits-all’ post-fire soil erosion model to all regions (Shakesby et al., 2007). A model-based risk assessment tool for the specific conditions of the Portuguese main forests (also including other regions in the N-W Iberian Peninsula) should take into consideration regional factors such as: (i) socio-economic factors affecting fire ignition and recurrence as well as land management and property; (ii) pronounced spatial variability as a consequence of multiple pre- and post-fire management options (unploughed, rip-ploughing, terracing, logging, new planting, regrowth or no action) in small size land properties mosaic with a dense network of forests tracks and roads; (iii) pronounced temporal-seasonal variability in runoff and sediment losses.

In Portugal, only after the severe fire seasons of 2003 and 2005 have forest fires become an important public concern (Ferreira et al., 2008) which motivated an institutional effort towards a post-fire soil erosion risk assessment and subsequent mitigation strategies (Figure 1). The National Water Institute (INAG) did, in fact, predict soil erosion risk in recently burnt areas, producing a nation-wide map based on the “Universal Soil Loss Equation” (USLE) (Wischmeier and Smith 1978, INAG, 2003; Brandão and Rodrigues, 2006). INAG’s application of USLE, however, had several drawbacks. First, the empirical-based USLE model was designed as a management tool for agricultural lands. Second, and perhaps most important, was the almost total lack of field data supporting the model’s suitability (calibration and validation) for post-fire conditions (e.g. Laflen and Moldenhauser, 2003; Morgan, 2005). Such a lack is highlighted by the map legend showing soil erosion classes of 0-1, 1-2, 2-4, 4-8, 8-16 and >16 t ha^{-1} year^{-1}. Those values were well above most of data found in the literature for Mediterranean countries (many plot-scale studies recording first year post-wildfire losses of 1 t ha^{-1} and the majority were <10 t ha^{-1}; e.g. Shakesby, 2011). Third, the map concerning the immediate post-fire situation had limited temporal variability, even though the natural conditions change rapidly after fire, including the intensive land management. Subsequently, several government manuals to guide rehabilitation and restoration strategies were published (DGRF, 2005; SNIRH, 2005), but those manuals were focused on post-fire soil mitigation treatments, the selection of target areas was not mentioned, or the selection was based on USLE. Some research efforts have been made to verify USLE for post-fire conditions or to apply other models, such as the Morgan-Morgan-Finney model (MMF, Morgan, 2001) (Vieira et al., 2010). More recently, with the main aim of scientific knowledge transfer, a publication on fire ecology and burnt areas restoration (Moreira et al., 2010) provided an overview of the global and specific Portuguese research needs and forest conditions. In this book, the intervention areas selection criteria is a combined tool of high degradation risk, low regeneration capacity indicators and values at risk. The soil erosion hazard is calculated based on USLE.

In Portugal, post-fire emergency treatments have rarely been employed, although this situation is changing due to the implementation of EU Rural Development Programme (2007-2013), such as PRODER-funded stabilization measures (under sub-Action 2.3.2.1 “Restoring Forestry Potential”) for selected 2010 and 2012 burnt areas. Institutional technical reports were elaborated to propose and evaluate emergency treatments for specific wildfires (29 technical reports between 2010 and 2012; ICFN, 2012). The selection of target areas was not mentioned, or was vaguely expressed as based on slope angle (slope angle > 20º) or on field-based surveys. In the case of the Tavira 2012 wildfire (Algarve-South Portugal), the selection of the soil erosion risk areas was determined by using the Modified USLE model (MUSLE; Renard et al., 1991). In that case, the Regional Forestry authority produced a map which predicted soil losses ranging from less than 5 t h^{-1} $year^{-1}$ to more than 200 t h^{-1} $year^{-1}$ (ICNF, 2012). The predicted values were again an over estimation of most of the available post-fire erosion data in Portugal or other Mediterranean countries. In spite of the institutional effort, the lack of data and information, as well as the lack of communication between scientists and land managers, revealed limitations in the advancement towards appropriate post-fire management strategies. In addition, the majority of private forest owners are unfamiliar with post-fire intervention techniques. Their intervention relies on logging and (re)plantation with eucalypts, frequently after ploughing or terracing. Nonetheless, many land owners would be keen to learn more about these techniques and even would consider implementing them, if the financial burden is minimal (Coelho et al., 2011). At this early stage of post-fire mitigation treatments application, the problem is obtaining agreement among professionals and researchers involved in forest fire management, as to how to identify areas for intervention (Ferreira et al., 2009). In such a context, the development of a predictive post-disturbance erosion model tool, tailored to the specificities of post-fire conditions in Portugal's forests seems appropriate.

1.4 Measuring post-fire runoff and erosion risk

A major difficulty in developing a post-fire soil erosion risk assessment tool is the collection of representative data on runoff and erosion. Direct measurement of hillslope runoff and erosion may be expensive, complex, and labour-intensive but it is indispensable for developing and refining predictive models of the post-fire response, both with and without erosion mitigation measures (Robichaud, 2009). Few datasets provide the necessary detail to calibrate or validate the model performance accurately, especially when the description of the temporal-spatial heterogeneity of soil loss is a goal (Brazier 2004). Therefore, several reviews have noted the necessity to focus on monitoring soil erosion by field measurements rather than on modelling (Brazier 2004; Verheijen et al., 2009). Ideally, the approaches to field measurement would be developed in conjunction with process-based models (Verheijen et al., 2009) including temporal and spatial variations of soil water repellency (Lemmnitz et al., 2008). Thus, though monitoring of soil loss is vital for model improvement, it must also be treated as a goal in itself to aid soil conservation and to inform managers and policy makers alike as to the erodibility of soils (Brazier 2004). The EROSFIRE project (Keizer et al., 2006, 2007) set out to develop a model-based risk assessment tool for Portugal conditions in a combined measurement and modelling approach. Rainfall simulation experiments (RSE's) were selected as the principal method for gathering the data required for initial calibration of the process- based model MEFIDIS (Nunes et al., 2005) for post-fire conditions, much along the lines of the approach applied in Nunes et al. (2009a, 2009b).

In this thesis, elaborated on the framework of the EROSFIRE project, plot runoff and erosion were measured at medium-short term intervals under simulated and natural rainfall. RSE's have been widely used to study hydrological and erosion processes in recently burnt woodland areas, especially at spatial scales of 1 m^2 and less (e.g. Sevink et al., 1989; Imeson et al.,1992; Kutiel et al.,1995; Benavides-Solorio and MacDonald, 2001; Johansen et al., 2001; Cerdà and Doerr, 2005; Coelho et al., 2005;

Ferreira et al.,2005a; Rulli et al., 2006; Leighton-Boyce et al., 2007; Sheridan et al., 2007). Despite the temporal variability observed in post-fire runoff and sediment losses, the bulk of those RSE's studies refer to a singular time span after wildfire. Only Cerdà and Doerr (2005) and Sheridan et al. (2007) measured runoff and sediment over various time periods after the fire. In Portugal, few field RSE's studies have been carried out in recently burnt eucalypt stands (Leighton-Boyce et al., 2007) or in other prevailing forest types (Walsh et al., 1998; Coelho et al., 2004; Ferreira et al., 2005a).

RSE's remove the variability of natural rainfall, allowing rainfall and runoff measurements to be related to infiltration and erosion rates with more confidence (Cerdà and Robichaud, 2009a). RSE's can avoid the confounding effects of temporal and spatial variability and, thus, facilitate the comparison of results obtained at different times after a particular wildfire, as well as in study areas burnt by different wildfires (e.g. Cerdà, 1998) or with different land management (e.g. Malvar et al., 2011, 2013, chapter 2 and 3). To overcome the difficulties of monitoring the high spatial-temporal variations of post-fire runoff and erosion, RSE's were used as a comparatively cheap and fast method to gather significant amounts of data under distinct land management conditions. To capture the pronounced temporal variability in hydrological and erosion processes following wildfires, repeated RSE's field campaigns were carried out in six field campaigns during a two years time period after fire. However, RSE's have well-known limitations in terms of reproducing natural rainfall events (e.g. Rickson, 2001). The additional monitoring of similar micro-plots, at the same sites and during the same two post-fire years, allowed the direct comparison of natural and artificial rainfall results. Few studies have employed both methods simultaneously thus this is an important advancement in science since exhaustive comparison of both methods had rarely been made.

Dependency of erosion measurements on spatial and temporal scale is well known (Morgan, 2005; Shakesby and Doerr, 2006; Ferreira et al., 2008). At the micro-plot scale employed in this study, either with natural or artificial rainfall, the plots do not reflect the continuity of the system. However, the plots present some advantages, such as the control of the variables inside the plot (Morgan, 2005), allowing the quantification of overland flow and erosion rates at a given period per unit of area, an estimation of the water infiltrated, and a detailed spatial and temporal assessment of hydrological and erosion processes. Closed plots also provided a comparison of different responses at the same spatial scale. Nevertheless, variability between replicated plots is observed and it can be explained by natural variability and partly by the alteration of field measurement (measurement variability) (Nearing et al., 1999). Long term monitoring periods are needed in order to produce realistic soil erosion assessment. However, a medium-short term monitoring period provided qualitative conclusions and the identification of areas that are especially exposed to erosion (Leser et al., 2002).

1.5 Aim and objectives

The main aim of this thesis is to contribute to a better knowledge of the hydrological and soil erosion response, at the patch scale, in recently burnt areas by focussing on the role of pre- and post-fire forest land management conditions. Furthermore, the collected runoff, erosion and ancillary data are envisaged as a basis for testing and adapting existing soil erosion models, for post-fire conditions. The specific objectives were to:

1. Quantify post-fire overland flow generation and associated sediment losses at seven forest stands that typify the range of post-fire conditions in north-central Portugal, including : (i) eucalypt and maritime pine plantations, (ii) a range of soil preparation techniques that had been carried out before the wildfires (i.e. unploughed, rip-ploughed in down-slope direction and along contours, and terraced), (iii) three types of post-fire land management: no management, logging and tree removal and hydro-mulching, which is a post-fire emergency treatment;

2. Determine the spatial variation as well as temporal patterns in the post-fire runoff and erosion response during the first two years following fire, by implementing multiple-plot experimental designs and by repeated rainfall simulation experiments (RSE's) on multiple occasions, and by monitoring erosion plots with a high temporal resolution (1 weekly intervals);

3. Identify the key factors explaining post-fire runoff and soil erosion, in particular rainfall amount, (simulated) rainfall intensity and land-use related variables such as soil water repellency and ground cover, including effects of hydromulching;

4. Address the similarities of repeated rainfall simulation experiments (RSE's) with natural rainfall conditions, by comparing the runoff and erosion rates and their temporal patterns produced by the RSE's with those by natural rainfall events;

5. Determine the temporal patterns in post-fire soil water repellency in two eucalypt stands, and relate them to changes in antecedent rainfall and soil moisture contents.

1.6 Thesis structure

The present thesis was done as part of the framework of two FCT-"Fundação Ciência e Tecnología" funded projects; the EROSFIRE (POCI/AGR/60354/2004) and the EROSFIRE-II (PTDC/AGR-CFL/70968/2006) with co-funding by FEDER through the POCI2010 Programme and the research grant of the author (SFRH/BD/41320/2007).

The thesis is structured in three main topics:

1.6.1 Part 1: Post-fire soil erosion risk assessment:

Post-fire overland flow generation and soil erosion response was measured in two Portuguese forest types, *Eucalyptus globulus* Labill and *Pinus pinaster* Ait. The studied burnt areas were located in North-Central Portugal (Figure 4). Measurements were carried out with different methodologies under contrasting pre- and post-fire land management (Table 1).

In Chapter 2 repeated rainfall simulation experiments (RSE's) were used to gather post-fire runoff and soil erosion data in two eucalypt stands with two different pre-fire land management (unploughed vs. down slope rip-ploughing). Chapter 3 was an extension of Chapter 2 in two ways. On the one hand, it included pre-fire contour ploughing and terracing, two other pre-ground preparation operations that, unlike down slope ploughing, are well-established soil conservation practices. On the other hand, two additional unploughed eucalypt plantations that were burnt by a different wildfire in which one was logged during the study period (Table 1). In both chapters, two rainfall intensities were applied; high (45-50 mm h^{-1}; intensity comparable to the maximum hourly rainfall for a 100-year return period measured at the Aveiro rainfall station) and extreme (80-85 mm h^{-1}; maximum hourly rainfall ever recorded in Portugal). The RSE's were done at fixed plots on four occasions during the first year following wildfire and on two additional occasions during the second year.

In Chapters 4 and 5, runoff and soil erosion was measured under natural rainfall conditions with high temporal resolution (weekly) across different plot size classes, from micro-plot (0.25 m^2) to plot scale (10 m^2).

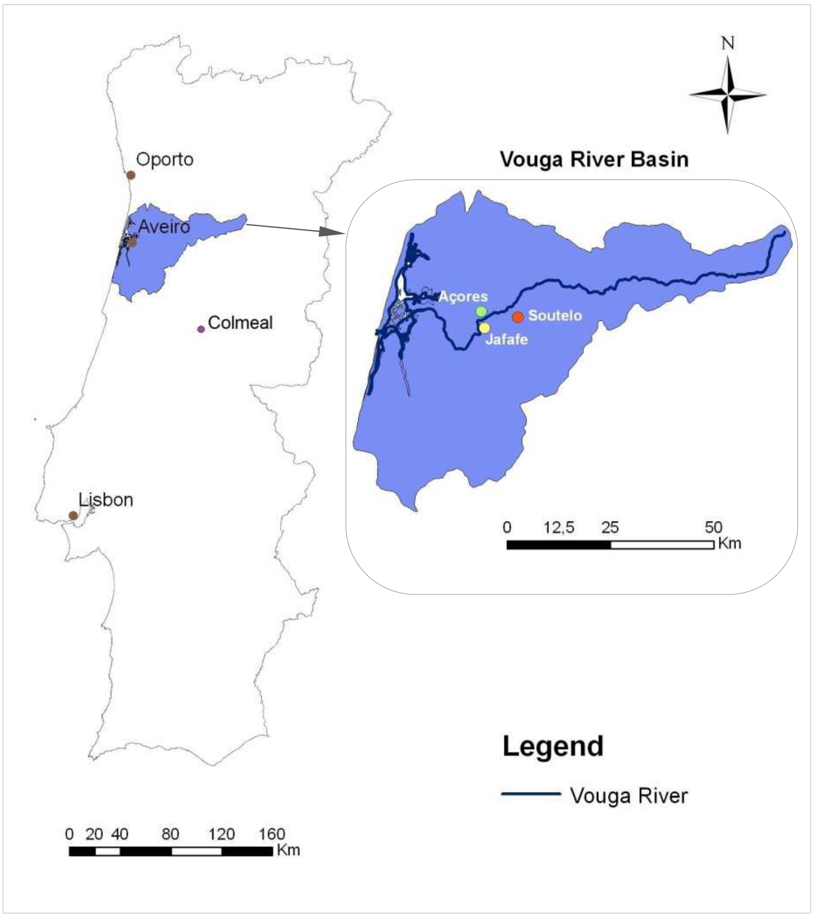

Figure 4. Location of the main Portuguese cities, the University of Aveiro, the Colmeal study site and the Açores, Jafafe and Soutelo study sites within the Vouga river basin.

1.6.2 Part 2: Simulated versus Natural rainfall:

The RSE's results of chapter 2 can be directly compared with the natural rainfall results of chapter 4 since the measurements were done with equal plot sizes, at the same sites and during the same post-fire period. The RSE's require much less time and effort and are easily repeatable compared to natural rainfall plots. Therefore, direct dataset comparison is intended to asses RSE's as an alternative method to gather erosion data.

Statistical analyses were carried out, on both simulated and natural rainfall datasets, to get a further insight into the temporal and spatial variability of hydrological and soil erosion response after fires. However, due to basic methodology differences (mainly in the number of observations) the statistical methods employed in each case were not the same. The limited number of samples gathered with simulated rainfall posed difficulties to verify the key assumptions underlying the parametric tests.

Table 1. General site and applied measurement methodologies characteristics.

Fire	2005 fire				2006 fire		2008 fire
Location	Açores	Açores	Jafafe	Jafafe	Soutelo	Soutelo	Colmeal
Site code	UP05_A1	DP05 _A2	CP05_J1	ST05_J2	UP06_S1	UP06_S2	
Coordinates	40º40'46''N	40º40'45''N	40º40'22''N	40º40'23''N	40º40'53''N	40º40'54''N	40º08'42''N
	8º26'54''W	8º26'55''W	8º26'41''W	8º26'36'' W	8º20'43''W	8º20'45''W	7º59'16'' W
Land use	Eucalypt	Eucalypt	Eucalypt	Eucalypt	Eucalypt	Eucalypt	Pine
Land management							
Pre-fire rotation cycle	>2	>2	>2	>2	>2	>2	-
Pre-fire ground preparation operations	Unploughed	Ploughed down-slope	Contour ploughed	Incline terracing	Unploughed	Unploughed	Unploughed
Post-fire operations	-	-	-	-	-	Logging	Logging
Post-fire soil erosion control treatment	-	-	-	-	-	-	Hydromulch
Measurement Methodology							
Rainfall simulation experiments; number	RSE's; 24	RSE's; 22	RSE's; 22	RSE's; 20	RSE's; 22	RSE's; 22	-
Natural rainfall; readouts number	Natural rainfall; 71	Natural rainfall; 71	-	-	-	-	Natural rainfall; 70
Plot number ; size (m^2)	4; 0.28	4; 0.28	4; 0.28	4; 0.28	4; 0.28	4; 0.28	4;0.25 4;0.50 6;10

Therefore, rank-based descriptive statistics and non-parametric statistical tests were used. The Mann-Whitney U-test and the Kruskal–Wallis test were employed to test overall differences, whereas the Wilcoxon's signed-ranks test and the Friedman test were used to assess differences in paired observations, either neighbouring plots or repeated RSE's on the fixed plots. In the natural rainfall dataset, the runoff and erosion variables were transformed in order to fit the normality assumption. Over the transformed variables the repeated analysis of variance (ANOVA-2way) was performed in order to determine the site and time influence on runoff and erosion measurements. Multiple regression models were used to determine the significance of a set of independent variables (related with rainfall characteristics, ground cover, soil water repellency and other selected soil properties) over the measured runoff and sediment losses.

1.6.3 Part 3: Key factors affecting runoff and sediment losses:

Intensive collection of ancillary data was done in conjunction with the monitoring of runoff and sediment losses measured with simulated and natural rainfall. This data collection, mainly to assess the degree and changes in plot surface cover and selected soil properties, allowed for the identification of key factors affecting the overland flow generation and the sediment losses in post-fire environments. Soil water repellency was a recurring factor across all the study sites and methodologies in this thesis. In Chapter 6 the soil water repellency temporal and spatial variation was analyzed in detail for an unploughed and down-slope rip-ploughed eucalypt sites. Antecedent rainfall and soil moisture were studied as possible explanatory variables for the observed temporal and spatial soil water repellency patterns. Soil water repellency was measured using the "Molarity of Ethanol Droplet" (MED-test). Since the ethanol concentrations were discrete values rather than continuous, non-parametric statistical tests were used to analyze the soil water repellency data.

Chapter 2: Post-fire overland flow generation and inter-rill erosion under simulated rainfall in two eucalypt stands in north-central Portugal.

Environmental Research 111 (2011) 222–236

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Post-fire overland flow generation and inter-rill erosion under simulated rainfall in two eucalypt stands in north-central Portugal ☆

M.C. Malvar, S.A. Prats, J.P. Nunes, J.J. Keizer *

Centro de Estudos do Ambiente e do Mar (CESAM), Departamento de Ambiente e Ordenamento, Universidade de Aveiro, 3810-193 Aveiro, Portugal.

ARTICLE INFO

Available online 28 September 2010

Keywords:
Wildfire
Eucalypt
Field rainfall simulation experiments
Runoff
Sediment losses

ABSTRACT

The aim of this study was to improve the existing knowledge of the runoff and inter-rill erosion response of forest stands following wildfire, focusing on commercial eucalypt plantations and employing field rainfall simulation experiments (RSE's). Repeated RSE's were carried out in two adjacent but contrasting eucalypt stands on steep hill slopes in north-central Portugal that suffered a moderate severity fire in July 2005. This was done at six occasions ranging from 3 to 24 months after the fire and using a paired-plot experimental design that comprised two pairs of RSE's at each site and occasion. Of the 46 RSE's: (i) 24 and 22 RSE's involved application rates of 45–50 and 80–85 mm h^{-1}, respectively; (ii) 22 took place in a stand that had been ploughed in down slope direction several years before the wildfire and 24 in an unploughed stand.

The results showed a clear tendency for extreme-intensity RSE's to produce higher runoff amounts and greater soil and organic matter losses than the simultaneous high-intensity RSE's on the neighbouring plots. However, there existed marked exceptions, both in space (for one of the plot pairs) and time (under intermediate soil water repellency conditions). Also, overland flow generation and erosion varied significantly between the various field campaigns. This temporal pattern markedly differed from a straightforward decline with time-after-fire and rather suggested a seasonal component, reflecting broad variations in topsoil water repellency. The ploughed site produced less runoff and erosion than the unploughed site, contrary to what would be expected if the down slope ploughing had occurred after the wildfire instead of several years before it. Finally, sediment losses at both study sites were noticeably lower than those reported by other studies involving repeat RSE's, i.e. in Australia and western Spain. This possibly reflected a history of intensive land use in the study region, including in more recent times after the widespread introduction of eucalypt plantations.

1. Introduction

As thoroughly discussed by Shakesby and Doerr (2006), through their effects on soil properties as well as on vegetation and litter cover, wildfires can lead to considerable changes in geomorphologic and hydrological processes. Previous studies in various parts of the world, including Portugal (e.g. Shakesby et al., 1993, 1996; Walsh et al., 1992, 1995; Ferreira et al., 2005b, 2008), have revealed strong and sometimes extreme responses in runoff generation and associated soil losses following wildfire, especially during the earlier stages of the so-called "window-of-disturbance". Besides wildfire itself, post-fire forestry practices can strongly influence overland flow and erosion in recently burnt areas (e.g. Shakesby et al., 1994; Walsh et al., 1995; Fernández et al., 2007). For example, rip-ploughing during the window-of-disturbance was far more damaging in terms of soil loss than fire (Shakesby et al., 1994).

The need for a model-based tool for assessing erosion risk following wildfire and, ultimately, for guiding post-fire land management, like the Erosion Risk Management Tool (ERMiT) for the Western USA (Robichaud et al., 2007), is overtly evident in the case of Portugal. Over the past decades, wildfires in Portugal have devastated on average around 100.000 ha each year, with dramatically higher figures for dry years like 2003 and 2005 (Pereira et al., 2005). Furthermore, the frequency of wildfires in Portugal is expected to remain the same or to increase in the future (Pereira et al., 2006). In relation to fire occurrence, the widespread introduction of commercial eucalypt plantations (principally of *Eucalyptus globulus* Ait.) in central Portugal (including in the study area) in combination with their proneness to fire deserves special reference. Furthermore, post-fire erosion risk is expectedly higher in eucalypt stands than, for example,

☆ The present study was funded by the Foundation for Science and Technology (FCT) of Portugal, with co-funding by FEDER through the POCI2010 Programme, in the framework of projects PHOENIX (POCI/AGR/58896/2004) and EROSFIRE (POCI/AGR/60354/2004) and research grants of MMC (SFRH/BD/41320/2007), SPA (SFRH/BD/33392/2008) and JPCN (SFRH/BPD/39721/2007).

* Corresponding author. Fax: +351 234370309.
E-mail address: jjkeizer@ua.pt (J.J. Keizer).

0013-9351/$ - see front matter © 2010 Elsevier Inc. All rights reserved.
doi:10.1016/j.envres.2010.09.003

Maritime Pine forest, another common and fire-prone forest type in central Portugal, namely, eucalypt stands are typically associated with pronounced soil water repellency (Doerr et al., 1996, 1998; Keizer et al., 2005b, 2008; Leighton-Boyce et al., 2005), on the one hand, and on the other, water repellency is widely considered one of the main factors in enhancing runoff generation and the associated soil losses following wildfire (e.g. Shakesby and Doerr, 2006; Leighton-Boyce et al., 2007; Sheridan et al., 2007).

Following the dramatic wildfire season of summer 2003, the EROSFIRE project (Keizer et al., 2006, 2007) set out to develop such an erosion prediction tool tailored to the specificities of post-fire conditions in Portugal's forests. Field rainfall simulation experiments (RSE's) were selected as principal method for gathering the data required for initial calibration of the process-based model MEFIDIS (Nunes et al., 2005) for post-fire conditions, much along the lines of the approach applied in Nunes et al. (2009a, 2009b). In spite of the well-know limitations of RSE's in terms of reproducing natural rainfall events and emulating runoff/erosion processes beyond small spatial scales (e.g. Rickson, 2001), they have been widely used for studying hydrological and erosion processes in recently burnt woodland areas, especially at spatial scales of 1 m^2 and less (e.g. Imeson et al., 1992; Kutiel et al., 1995; Sevink et al., 1989; Benavides-Solorio and MacDonald, 2001; Johansen et al., 2001; Cerdà and Doerr, 2005; Coelho et al., 2005; Ferreira et al., 2005a; Rulli et al., 2006; Leighton-Boyce et al., 2007; Sheridan et al., 2007). However, the bulk of these studies concerned singular moments in time-after-fire, not addressing for example the seasonal component in post-fire runoff and erosion that is often observed in longer-term plot monitoring studies under natural rainfall conditions (e.g. Shakesby et al., 1993, 1994). Also, the individual studies generally involved a single rainfall intensity. As far Portugal is concerned, surprisingly few field RSE studies have been carried out in recently wildfire-burnt stands of eucalypt (Leighton-Boyce et al., 2007) or, for that matter, in other prevailing forest types (Walsh et al., 1998; Coelho et al., 2004; Ferreira et al., 2005a).

The main aim of the present work was to explore repeated field campaigns of RSE's for a better knowledge and understanding of overland flow generation and associated sediment losses in recently burnt commercial eucalypt plantations. To this end, RSE's were carried out in two eucalypt stands on four occasions during the first year following wildfire and on two additional occasions during the second year. Two adjacent sites were selected for expectedly representing contrasting risks of post-fire erosion, with the site that had been rip-ploughed presenting a greater risk than the neighbouring unploughed site.

The specific objectives were to determine how overland flow generation and sediment losses varied at the micro-plot scale with (i) high *vs.* extreme simulated rainfall intensity (45–50 and 80–85 mm h^{-1}); (ii) time since fire and associated changes in initial conditions, in particular soil water repellency; (iii) within- and between-site characteristics at a ploughed *vs.* unploughed slope.

2. Materials and methods

2.1. Study area and sites

The present study was carried out in two adjacent commercial eucalypt (*Eucalyptus globulus* Ait.) plantations in the Açores locality of the Albergaria-a-Velha municipality of north-central Portugal (Fig. 1). The two study sites were located at approximately 40°42′N, 8°29′W and 60–70 m elevation, and comprised steep but short slopes bounded by paths (Table 1).

The study sites burned during early July 2005 in a wildfire that affected a total area of about 16 km^2, which was largely covered by eucalypt plantations. The complete consumption of the litter and herb cover, together with the partial consumption of the shrub layer and tree crowns, suggested that fire severity at both sites had been moderate (Shakesby and Doerr, 2006; Table 1). Judging by remaining tree stumps, the two sites had undergone at least two eucalypt (re)growth cycles prior to the fire. The two sites were selected for their contrasting land management practices and, as mentioned above, expectedly distinct risks of post-fire soil erosion. At the unploughed Açores1 site, trees had been planted without apparent evidence of mechanical ground operations, resulting in an undisturbed soil profile. At the ploughed Açores2 site, a clear pattern of shallow ridges and furrows (up to 20 cm high) running down the slope was present. Rip-ploughing (i.e. mechanical ploughing using a ripper with one to three teeth that rupture the upper soil horizons in a vertical plane without altering their disposition) in preparation for planting is a common practice in this region and, judging by the stand age, would have taken place around 5 years prior to the fire.

The study area is situated at the transition of the region's two major physiographic units, the Littoral Platform dominated by Ceno-Mesozoic deposits and the Hesperic Massif dominated by pre-Ordovician schists and greywackes and Hercynian granites (Ferreira, 1978; Pereira and FitzPatrick, 1995). The soils are mapped – at a scale of 1:1,000,000 – as a complex of Humic Cambisols and, to a lesser extent, Dystric Litosols (Cardoso et al., 1971, 1973). At both the study sites, two soil profiles were excavated in the middle and at the bottom of the study slopes. The soils corresponded to Umbric or Dystric Leptosols (FAO, 1988), depending on the depth of their A horizons. They were shallow (5–40 cm depth) soils developed over schists and had sandy loam textures and high organic matter contents (8.8–10.4%). These soil characteristics differed little between the two sites, which also agreed with the fact that rip-ploughing supposedly does not alter the disposition of the soil layers. Even so, the observed soil differences were duly considered in the discussion of the RSE results.

The climate of the study area can be characterised as humid meso-thermal, with a prolonged dry and warm summer (Köppen Csb) DRA-Centro (1998). Fig. 1 shows the locations of the study sites as well as of the nearest climate station (Estarreja: 40°47′N, 8°35′W, 26 m; 17.5 km distance) and the nearest rainfall station (Albergaria-a-Velha: 40°42′N, 8°29′W, 131 m; 4 km distance). The long-term mean annual temperature at the Estarreja station is 13.9 °C and the mean monthly temperatures range from 8.8 °C in December to 19.1 °C in July (DRA-Centro, 1998). The annual rainfall at the Albergaria-a-Velha station is, on average, 1229 mm and varies between 750 and 2022 mm (DRA-Centro, 1998). Fig. 1 also depicts the stations' seasonal variations in average monthly temperature and rainfall, and the monthly rainfall amounts at the study sites during the first year following wildfire. These latter data were obtained with a tipping-bucket rainfall gauge (Pronamic Professional Rain Gauge) linked to a Hobo Event Logger of Onset Computer Corporation, and were verified using the data from two totaliser rainfall gauges. All three gauges were installed at the foot of the study sites on September 24, 2005. These data were used in this paper to calculate the antecedent daily rainfall for the different field sampling days.

2.2. Rainfall simulation experiments

Between September 2005 and July 2007, a total of 46 rainfall simulation experiments (RSE's) were carried out in the field using two portable simulators as originally designed by Calvo et al. (1988) and later improved by Cerdà et al. (1997). One simulator was equipped with the original nozzle and was calibrated in the laboratory to produce artificial rain with an intensity of approximately 45 mm h^{-1}. The second simulator was equipped with a modified nozzle, using cone nozzle HARDI-1553-14 instead of HARDI-1553-10, to produce intensities of around 80 mm h^{-1}. The former intensity is comparable to the maximum hourly rainfall for a 100-year return period of the Aveiro rainfall station (Brandão et al., 2001). The latter is similar to the maximum hourly rainfall ever recorded in Portugal (Brandão et al., 2001) but a prior RSE study in Portuguese eucalypt forests like Leighton-Boyce et al. (2007) applied still higher intensities (100 mm h^{-1}) and found infiltration capacities exceeding this value. Hereafter, the two intensities will be referred to as "high" and "extreme", respectively. Other modifications to the original simulator design involved the use of a battery-driven pump system with pressure vat and of an approximately square plot (consisting of a square area of 0.50 m × 0.50 m and an outlet area of 0.03 m^2), both of which were introduced by De Alba (1997).

The 46 RSE's were carried out during four separate field campaigns in the first year after the wildfire, and two more campaigns in the second year (Table 2). Before every campaign (with the exception of the second) the two standard and two spare nozzles were (re-)calibrated in the laboratory. Each campaign involved four RSE's on both the ploughed and unploughed site, except in the case of the October 2006 campaign when only the high-intensity RSE's were carried out at the unploughed site due to failure of the extreme-intensity pump system. The four RSE's at a particular site were in general performed on the same day and within less than a week of those carried out at the other study site. Exceptions were the first campaign on the ploughed site and the October 2006 campaign, which took place on September 20 and 22, 2005, and October 12 and 31, 2006, respectively.

The four RSE's at each site and date were carried out using a pair-wise sampling design. High- and extreme-intensity RSE's were run almost

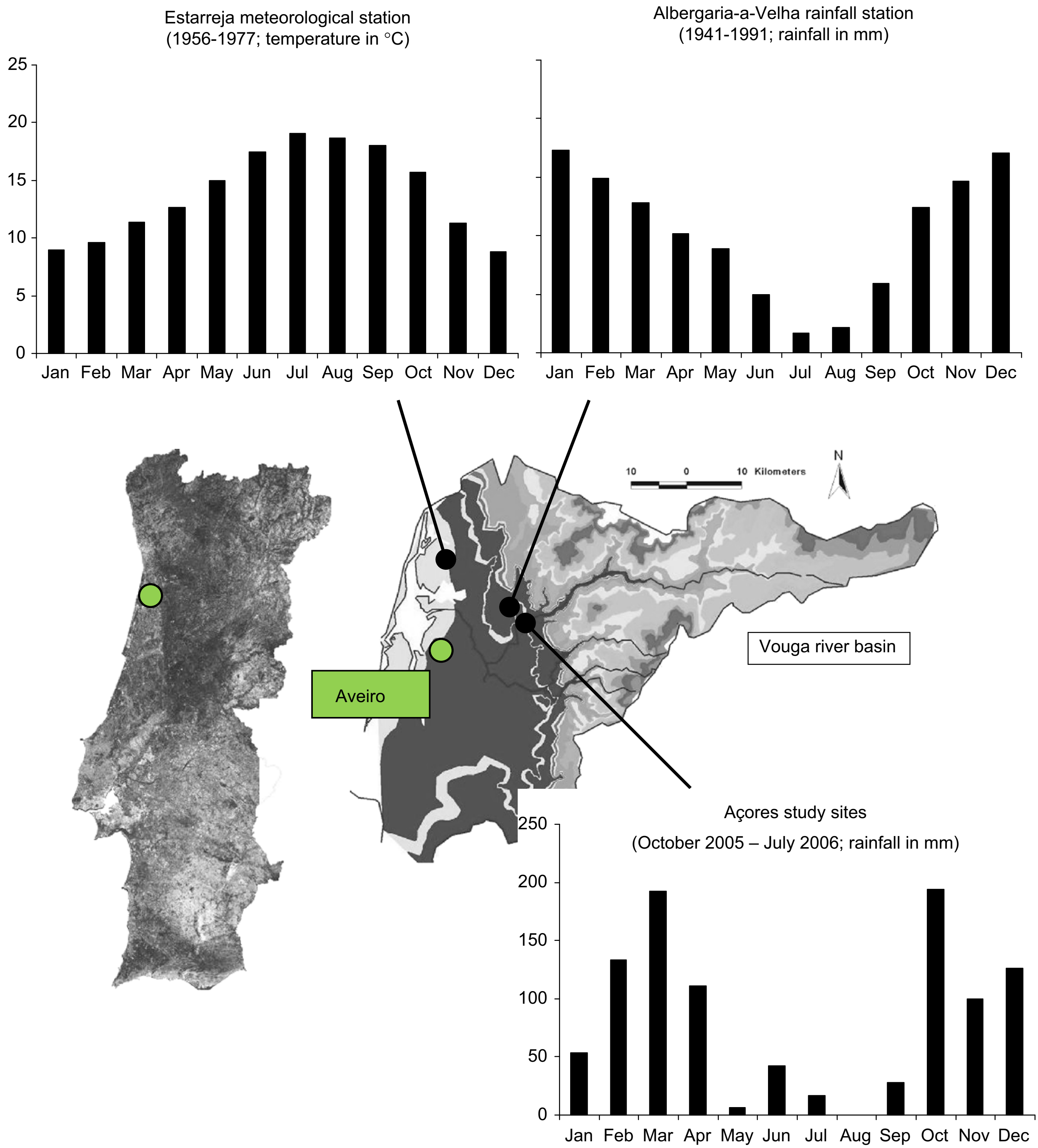

Fig. 1. Location of the study sites and the nearest weather stations, and their respective (average) monthly values.

simultaneously on two neighbouring plots located at about the same elevation on the slope but separated across the slope by 3–5 m. The two pairs of neighbouring plots on each site were placed randomly by installing them halfway the slope's upper and lower half. This was done in a horizontal section of the slope that was specifically reserved for the RSE's. The slope was further divided in a section that was equipped with erosion plots and a section that was used to describe topsoil characteristics at regular intervals (see Keizer et al., 2008). According to their spatial lay-out, the RSE-plots at each site were designated as follows: 1 and 2 were located on upper slope sections, 3 and 4 on the lower slope sections; 1 and 3 concerned high-intensity RSE's, 2 and 4 extreme-intensity RSE's. The prefixes "U" and "P" were used to indicate the plots on the unploughed and ploughed site, respectively.

The RSE's of the first campaign were immediately followed by destructive sampling of the plots as soon as the runoff had stopped. The RSE's of the second and subsequent campaigns, however, were carried out on permanent plots, with the repeat experiments on each plot involving the same intensity as established randomly in October 2006. Each pair of RSE's involved a third "control" plot for destructive measurements and sampling of the initial conditions, in particular

Table 1
General terrain characteristics and fire severity indicators at an unploughed and a ploughed eucalypt site.

Variable	Unploughed	Ploughed
Physiognomy		
Slope section length (m)	20–25	30–40
Slope angle (deg.)	20	15
Aspect	SE	NE
Fire severity indicators		
Eucalypt crown damage	Partial	Partial
Height of eucalypt stem scorching (m)	≤ 9	≤ 12
Combustion of litter/herbs layer	Total	Total
Combustion shrub layer	Partial	Partial
Ash colour	Black	Black

Table 2
Overview of high- and extreme-intensity RSE's ($n \times$ intensity in mm h^{-1}) and their average runoff and erosion results at an unploughed and a ploughed eucalypt stand during the first 2 years following a wildfire.

Campaign	Period	Unploughed		Ploughed	
		High	Extreme	High	Extreme
1	20–22–27/09/2005	2×46	2×84	2×46	2×84
2	10–15/11/2005	2×46	2×84	2×46	2×84
3	30/03–04/04/2006	2×48	2×80	2×48	2×80
4	20–25/07/2006	2×46	2×80	2×46	2×80
5	12–31/10/2006	2×47	2×81	2×47	–
6	03–09/07/2007	2×44	2×76	2×44	2×76
Variables					
Slope angle permanent plots (deg.)		23	23	17	17
Total simulated rainfall (mm)		277	485	277	404
Total runoff (mm)		150	265	94	154
Overall runoff coefficient (%)		54	55	34	38
Total soil loss (g m^{-2})		26	93	14	21
Total organic matter loss (g m^{-2})		18	57	10	14
Specific soil loss (g m^{-2} mm^{-1} runoff)		0.17	0.35	0.15	0.15
Specific o.m. loss (g m^{-2} mm^{-1} runoff)		0.12	0.21	0.11	0.09

regarding soil water repellency and moisture content at various depths. Non-destructive characterisation of the RSE-plots was done prior to all experiments and involved a standard procedure of quantifying the frequency of various cover classes by recording their presence/absence in the 5 cm × 5 cm cells of a 50 cm × 60 cm grid laid out over the plots. Photographs were taken and used to check the frequency estimates and convert them into decimal cover classes from 0 to 10.

The destructive sampling of the initial RSE-plots and control plots concerned first and foremost the moisture content and water repellency of the topsoil at 2–3 and 7–8 cm depth. This involved the same methods, equipment and water repellency severity ratings as described in Keizer et al. (2008). In a nutshell, soil moisture content was measured using an ML2 ThetaProbe™ connected to a HH2 ThetaMeter (Delta T-Devices Ltd.) or, in case of probe failure, gravimetrically and then converted based on Saxton et al. (1986) and Costa (1999). Water repellency severity was measured using the 'Molarity of an Ethanol Droplet' (MED) test (e.g. King, 1981; Doerr, 1998), by applying three droplets of increasing ethanol concentration and employing their median ethanol concentration (%vol) as test result. The following nine ethanol classes and corresponding ethanol concentrations were used: 0–0%; 1–1%; 2–3%; 3–5%; 4–8.5%; 5–13%; 6–18%; 7–24%; 8–$\geq$36%. Random roughness was determined using a pin profile metre and the PMPPROJ software (developed by J. Kilpelainen, Agricultural Research Centre, Jokioinen, Finland) for processing the photographs.

All RSE's were carried out using a pre-established protocol and standard field forms that were derived, with some modifications, from those employed in the MEDAFOR project (Shakesby et al., 2002). The protocol's principal elements were the application of artificial rain from a height of 2 m during 1 h, runoff measurements at 1-min intervals and the collection of up to five runoff samples (i.e. one from the start of the runoff till its approximate stabilisation; one from the end of the rainfall till the end of the runoff; three at the start, middle and end of the remaining period). The collected runoff samples were later analysed in the laboratory for their sediment and organic matter loads using the classical evaporation protocol (APHA, 1998) and loss-on-ignition at 550 °C. Soil texture classes were determined by the Soil Laboratory of the Coimbra Higher School of Agriculture, using a combination of mechanical sieving and the pipette method.

2.3. Data analysis

Data analysis was carried out using STATISTICA for Windows Version 9.0, by StatSoft Inc. Rank-based descriptive statistics and non-parametric statistical tests were preferred, in particular because of the limited number of samples and the resulting difficulties in verifying key assumptions underlying the parametric equivalents. The Mann-Whitney *U*-test and the Kruskal–Wallis test were employed to test overall differences, whereas the Wilcoxon's signed-ranks test and the Friedman test were used to assess differences in paired observations, either neighbouring plots or repeat-RSE's on the permanent plots. Besides differences between individual RSE's, also differences in average values of concurrent high-/extreme-intensity RSE's were included in the analyses for being less susceptible to possible noise due to spatial variability. In the case of the temporal patterns, only differences between consecutive campaigns were tested. This was done to restrict the number of multiple, unplanned comparisons to a minimum. Also the significance of the between-site differences of the individual RSE's was assessed using the standard type I error $\alpha=0.05$ and not using the comparison-wise type I error $\alpha'=0.025$ following the Dunn–Šidák method for 2 unplanned comparisons (Sokal and Rohlf, 1981).

3. Results and discussion

3.1. Overall runoff and erosion rates

Table 2 summarises the overall runoff and erosion figures obtained over the six field campaigns between September 2005 and July 2007. Direct comparison of the presented values is hampered by the lack of extreme-intensity data at the unploughed site for the October 2006 campaign. Nonetheless, the main differences observable in Table 2 are similar to those for the five common campaigns (explained below).

The two simulated rainfall intensities had a negligible effect on the relative amounts of overland flow generation at the two study sites; runoff coefficients were rather determined by site-specific differences. For the five "common" periods, the overall runoff coefficients amounted to 57–58% and 38–39% for the unploughed and ploughed site, respectively. In terms of absolute runoff amounts, the extreme-intensity RSE's at each site therefore produced, on average, about 70% more overland flow than the high-intensity RSE's on the same site. The extreme-intensity values for the five "common" campaigns were 231 and 154 mm for the unploughed and ploughed site, respectively; the corresponding high-intensity values were 133 and 91 mm.

Total losses of soil and organic matter were determined by a combined effect of site-specific factors and rainfall intensity. The losses at the unploughed site exceeded those at the ploughed site. For the five "common" campaigns, the total soil losses were 25 and 89 g m^{-2} *vs.* 14 and 21 g m^{-2}, respectively, and the corresponding total organic matter losses were 18 and 56 g m^{-2} *vs.* 10 and 14 g m^{-2}. The between-site differences for the separate rainfall intensities were more pronounced. The losses at the unploughed site were almost twice as high in the case of the high-intensity RSE's and more than four times as high in the case of the extreme-intensity RSE's. The intensity-related differences in total losses were bigger at the unploughed than ploughed site. The extreme-intensity RSE's produced, on average, roughly three times more soil and organic matter loss than the high-intensity RSE's at the unploughed site but only 40–50% higher losses at the ploughed site.

The intensity-related differences in total soil and organic matter losses can in the case of the unploughed site be partly attributed to higher specific losses. The specific losses were about twice as high for the extreme- than high-intensity RSE's. By contrast, at the ploughed site the specific losses were basically the same for the two intensities. The contribution of the specific losses to the between-site differences was also not consistent. They were of minor influence in the case of the high-intensity

RSE's, but contributed with roughly a factor two in the case of the extreme-intensity RSE's.

The present results were perhaps most surprising in that the ploughed site produced, on average, less runoff and lower total sediment losses than the unploughed site. In a nearby area, down slope rip-ploughing was found to substantially enhance overland flow responses and sediment loss rates during the first three years after ploughing (Shakesby et al., 1994; Walsh et al., 1995). These results are not directly comparable to those presented here, namely, they concerned much bigger plots (16 m^2) and lower, natural rainfall intensities. Even so, the overall sediment loss rates of the high-intensity RSE's of this study (0.09–0.16 g m^{-2} mm^{-1} rainfall) were much more similar to those reported by Shakesby et al. (1994) for "natural recovery" post-burn sites (0.05–0.10 g m^{-2} mm^{-1} rainfall) than for a recently rip-ploughed site do (3.27 g m^{-2} mm^{-1} rainfall; see also Terry (1996)).

The lower-than-expected sediment losses at the ploughed site could be related to the fact that ploughing took place several years before the wildfire. Shakesby et al. (1994) estimated that sediment losses decline rapidly following rip-ploughing. They attributed this to the formation of a protective stone lag, particularly in the early stages, and to the subsequent development of vegetation and litter cover. There was, however, no evidence that surface stone cover in the RSE-plots was noticeably higher at the ploughed than unploughed site. Walsh et al. (1995) further suggested that rip-ploughing ultimately decreased soil erodibility through selective removal of the fine soil fraction by initial erosion events. This fits in with the lower specific soil losses at the ploughed than unploughed site, especially in the case of the extreme-intensity RSE's. The topsoil (0–5 cm) at the ploughed site has, in fact, somewhat smaller clay and loam fractions than that at the unploughed site (median values of 3 samples: 7 and 20 *vs.* 13% and 24%, respectively). Nonetheless, the lower specific soil losses at the ploughed site could also be due to its smaller runoff amounts as well as to the expectedly lower flow velocities due to its less steep slope angle. Between-site differences are further analysed below.

The overall runoff and erosion values are not easily compared with those from literature, namely, the bulk of the field RSE studies following recent forest wildfires concerned singular moments in time (e.g. Sevink et al., 1989; Kutiel et al., 1995; Benavides-Solorio and MacDonald, 2001; Johansen et al., 2001; Rulli et al., 2006). Focusing on Portugal, only Leighton-Boyce et al. (2007) seem to have carried out RSE's in a recently burnt eucalypt plantation as well. In terms of rainfall intensity (100 mm h^{-1}) and pre-fire ploughing, their RSE's compare best with the extreme-intensity RSE's at the ploughed site. Compared with these RSE's, both the mean runoff coefficient and mean specific sediment loss of Leighton-Boyce et al. (2007) were roughly twice as high (70% and 0.90 g m^{-2} mm^{-1} runoff).

RSE data are also scarce for recently burnt stands of another common and fire-prone forest type in Portugal, that of Maritime Pine. Using basically the same experimental set-up as here, Coelho et al. (2004) and Ferreira et al. (2005a) found runoff coefficients of 55–65%, which is comparable to the overall figure for the high-intensity RSE's at the unploughed site. The specific sediment losses in Coelho et al. (2004), however, were 3–4 times higher (0.90–1.20 g m^{-2} mm^{-1} runoff) than the corresponding values of the present study. Walsh et al. (1998) reported lower runoff coefficients (19–25%) but this was 2 years after a wildfire and involved lower application rates (33–35 mm h^{-1}) as well as larger plots (1 m^2).

Outside Portugal, wildfire-affected eucalypt stands were studied in a particularly exhaustive manner in Australia by Sheridan et al. (2007). This included eight subsequent campaigns of field RSE's but, unlike in this study, using different plots during each campaign. With rainfall intensities of 100 mm h^{-1} applied (during 30 min) on unploughed soils, these RSE's are best compared with the extreme-intensity RSE's at the unploughed site. Over the first 2 years after fire, Sheridan et al. (2007) found a somewhat lower runoff coefficient (41%) than reported here but an almost six times higher specific sediment loss (3.26 g m^{-2} mm^{-1} runoff), possibly reflecting their larger plot size (3 m^2).

Organic matter constituted an important fraction of the sediment losses observed in the present study. It amounted, on average, to some 40% and varied little between the two sites and the two intensities (38–42%). This is held to reflect the export of litter and especially ash particles, since the organic matter content of the 0–5 cm topsoil at both sites was only some 10% (unploughed site = 10.3%; ploughed site = 9.0%; median value of three samples). Unfortunately, comparison with the other studies cited in this section is not possible, since they do not present separate data on organic matter losses.

3.2. Variation with rainfall intensity

Overall differences between the high- and extreme-intensity RSE's tended not to be statistically significant (Table 3). The absolute runoff amounts constituted an exception, with significant differences in three of the four tests. The extreme-intensity RSE's only did not produce significantly more runoff than the high-intensity RSE's in the case of the ploughed site. This can be attributed to a greater spatio-temporal variability in the site's hydrological response, namely, the difference in median runoff amounts is of the same of order of magnitude for the ploughed site as for the unploughed site (approximately 20 vs. 25 mm).

The effect of rainfall intensity was more apparent from the Wilcoxon's Test results, i.e. when eliminating the variability due to differences between the campaigns as well as between the plot pairs. Besides runoff amounts, total soil and organic matter losses revealed statistically significant differences. The significance of these differences and their sign can be perceived from Fig. 2. Thus, extreme-intensity RSE's tended to produce significantly stronger

Table 3
Statistical comparison of runoff and erosion by high- *vs.* extreme-intensity RSE's at an unploughed and a ploughed eucalypt stand. The comparison concerns the two study sites together ("U&P") as well as separately, and the site-wise average values ("mean") as well as the values of the individual RSE-pairs ("Indiv."). The statically significantly outcomes ($\alpha = 0.05$) of the MW *U*-test and Wilcoxon *S–R* test are indicated with "M" and "W".

Tests and variables	U&P Mean	U&P Indiv.	Unploughed Indiv.	Ploughed Indiv.
Total runoff (mm)	M/W	M/W	M/W	–
Overall runoff coefficient (%)	–	–	–	–
Total soil loss (g m^{-2})	W	M/W	W	–
Total organic matter loss (g m^{-2})	W	W	W	–
Specific soil loss (g m^{-2} mm^{-1} runoff)	W	W	–	–
Specific o.m. loss (g m^{-2} mm^{-1} runoff)	–	–	–	–

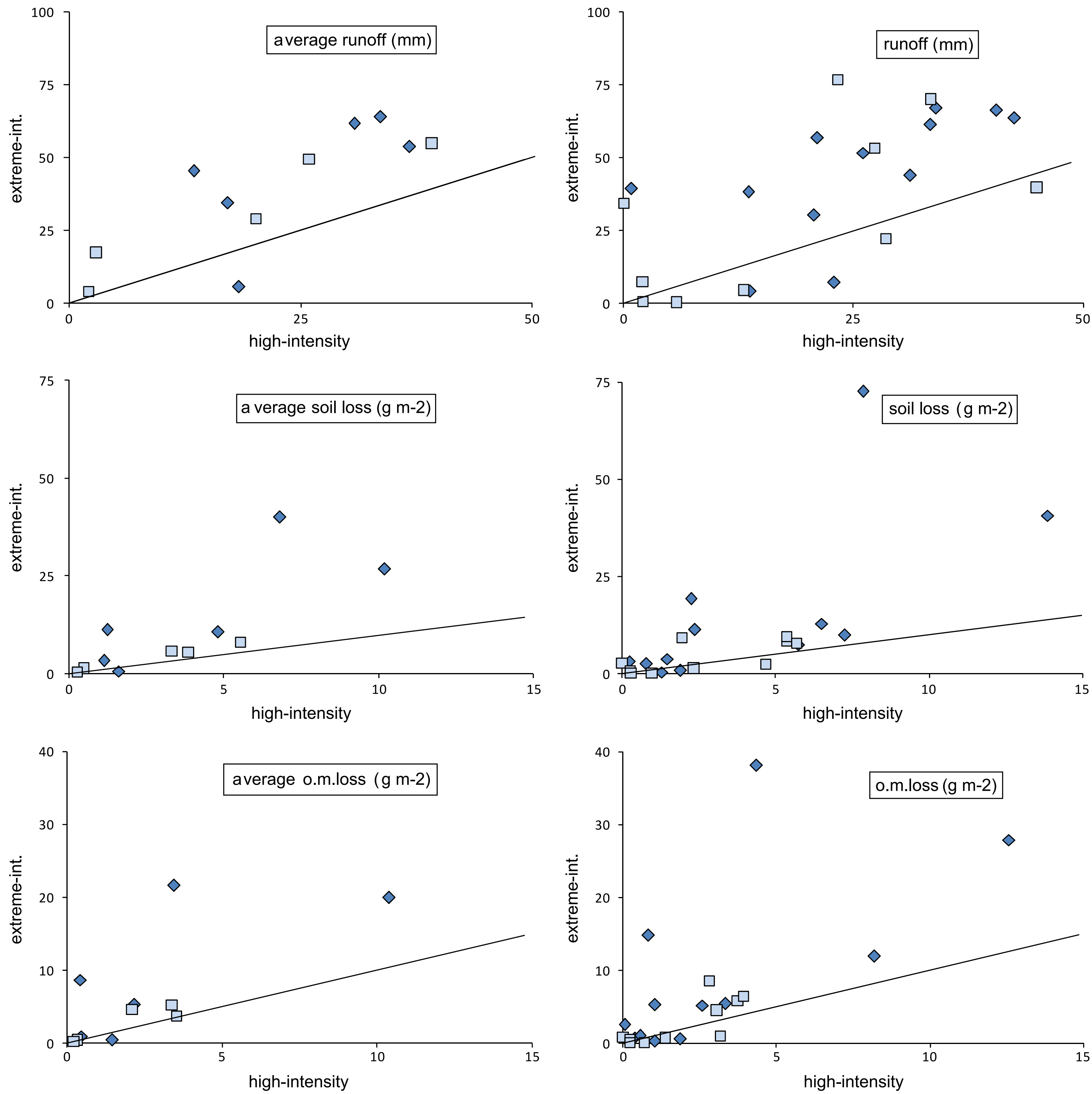

Fig. 2. Runoff and soil and organic matter losses of neighbouring pairs of high- and extreme-intensity RSE's at an unploughed (diamonds) and a ploughed (squares) eucalypt site.

runoff and erosion responses than the simultaneous high-intensity RSE's on the neighbouring plots. This especially applied to (i) absolute as opposed to relative measures; (ii) the two sites together and the unploughed site alone as opposed to the ploughed site alone. The runoff values at the ploughed site revealed a suspicious pattern in Fig. 2, with an equal number of points situated above and below the 1:1 line. Therefore, the Wilcoxon's tests were also applied to the site's separate plot pairs, even though the numbers of paired observations are small ($n=5$). For both plot pairs total runoff was significantly different. However, whilst total runoff was significantly higher for the extreme- than high-intensity RSE's in one case (plots P1 and P2 on the upper section of the slope), it was significantly lower in the other case (plots P3 and P4). In the case of the former plot pair, the extreme-intensity RSE's also produced significantly higher total soil and organic matter losses.

The deviant behaviour of especially one of the plot pairs on the ploughed site could be related to the pre-fire ploughing, leading to more heterogeneous micro-topographic and topsoil conditions in comparison to the undisturbed soil profiles of the neighbouring site. This could involve a combination of factors rather than a single factor *per se*. For example, the slope angle of the high-intensity plot on the lower slope section (P3: 20°) was slightly steeper than that of the adjacent extreme-intensity plot (P4: 18°)

and, at the same time, its random roughness was somewhat smaller (1.1 *vs.* 1.7). Also, spatial variability in topsoil water repellency (0–5 cm) during the first year following the wildfire tended to be more pronounced in the case of the ploughed than unploughed site (Keizer et al., 2008). Litter cover could play a role as well, since the P4 plot had a much higher litter cover than the P3 plot from the second campaign onwards (Fig. 6). This was due to the fall of leaves from scorched eucalypt crowns, which then slowly decomposed *in situ*. Shakesby et al. (1994) also mentioned this phenomenon in burnt eucalypt stands but expected its role in limiting erosion to be short lived. The role of such a litter cover could be direct – through interception storage and protection against rain drop impact – or indirect – by increasing the resistance to overland flow and/or by changing soil moisture as well as water repellency (e.g. Imeson et al., 1992; Lavee et al., 1995; Walsh et al., 1998; Doerr et al., 2000; Pannkuk and Roubichaud, 2003; Leighton-Boyce et al., 2007).

3.3. Temporal patterns

The timing of the RSE's had a significant influence on runoff response in general (Table 4). Overland flow generation varied significantly between the five and six campaigns: (i) in absolute as well as relative amounts; (ii) equally so for the average and individual values of the two sites together as for the values of the ploughed and unploughed site separately; (iii) in terms of both plot-specific and overall differences. The same applied to the total soil and organic matter losses. In the case of the specific losses, however, only the individual values of the two sites together and of the ploughed site separately varied significantly with time-since-fire.

Comparison of the consecutive campaigns revealed that significant changes in hydrological and erosion processes principally occurred between campaigns 2 (November 2005) and 3 (March/April 2006) as well as between campaigns 5 (October 2006) and 6 (July 2007) (Table 4). These last two campaigns differed significantly for all the variables studied here. Total runoff stood out amongst the various variables in that the differences between campaigns 2 and 3 as well as between campaigns 5 and 6 were only statistically significant on a plot-wise basis and not also in general. This probably reflected the significant differences in runoff amounts between the extreme- and high-intensity RSE's (see Table 3), adding to campaign-wise variability.

In close agreement with the above-mentioned statistical results, the temporal variation in runoff and erosion revealed two distinctive patterns (Fig. 3). First, the median values were clearly higher for the first two and the last campaigns than for the third to fifth campaigns. Second, median values of the first five campaigns were noticeably lower than that of the last campaign. The first pattern applied to the absolute and relative runoff amounts as well as to the absolute sediment losses, whilst the second pattern concerned the relative sediment losses. A consistent element in the first pattern was further that the median value of the fourth campaign (July 2006) was lower than those of the third and fifth campaigns).

The temporal patterns in soil water repellency and other potential explanatory variables are shown in Fig. 4. The significant decrease in overland flow and total sediment losses between 4 and 9 months after the wildfire agreed well with a pronounced drop-off at both sites in topsoil water repellency from extremely hydrophobic to hydrophilic. The significant increase in runoff and erosion between 16 and 24 months after the wildfire, however, was less consistent with differences in repellency. Whilst at the ploughed site median ethanol classes were higher in July 2007 than October 2006, at the unploughed site they were basically the same. The limited hydrological impact of the very strong repellency of the unploughed soil in October 2006 could be due to the antecedent rainfall (10 mm in the two preceding days), enhancing the spatial variability in repellency and, thereby, opportunities for re-infiltration of overland flow (e.g. Shakesby et al., 2000; Keizer et al., 2005a).

The results of the summer 2006 campaign also casted doubt on the role of soil water repellency, with the ploughed site presenting the most puzzling case. All four RSE's at this site then produced the least runoff, even though repellency was equally strong as during the first two campaigns and also rather homogeneous (range of ethanol classes: 6–8; $n=10$). In the case of the unploughed site, the reduced runoff production in July 2007 could be due to the moderate median repellency level as opposed to the very strong/extreme level during fall 2005 and summer 2007. The discrepancy in water repellency between the unploughed and ploughed site during the July 2006 campaign can be explained by the 15 mm of rainfall that fell on July 19, 2006,

Table 4
Statistical comparison of runoff and erosion for various RSE campaigns together as well as for consecutive RSE campaigns. The overall comparison concerned the two sites together ("U&P") as well as separately, and the site-wise average values ("mean") as well as the values of the individual RSE-pairs ("Indiv."). The statically significantly outcomes ($\alpha=0.05$) of the Kruskal–Wallis test, Friedman test, MW *U*-test and Wilcoxon *S–R* test are indicated with "K", "F", "M" and "W".

Data sets and variables *Campaigns together*	U&P		Unploughed	Ploughed
	Mean	**Indiv.**	**Indiv.**	**Indiv.**
Total runoff (mm)	K/F	K/F	K/F	K/F
Overall runoff coefficient (%)	K/F	K/F	K/F	K/F
Total soil loss (g m^{-2})	K/F	K/F	K/F	K/F
Total organic matter loss (g m^{-2})	K/F	K/F	K/F	K/F
Specific soil loss (g m^{-2} mm^{-1} runoff)		K/F	K/F	
Specific o.m. loss (g m^{-2} mm^{-1} runoff)		K/F	K/F	

Consecutive campaigns	**Campaign *i*/*i*+1**				
	1/2	**2/3**	**3/4**	**4/5**	**5/6**
Total runoff (mm)		W			
Overall runoff coefficient (%)		M/W			M/W
Total soil loss (g m^{-2})		M/W			M/W
Total organic matter loss (g m^{-2})		M/W			M/W
Specific soil loss (g m^{-2} mm^{-1} runoff)					M/W
Specific o.m. loss (g m^{-2} mm^{-1} runoff)				M/W	M/W

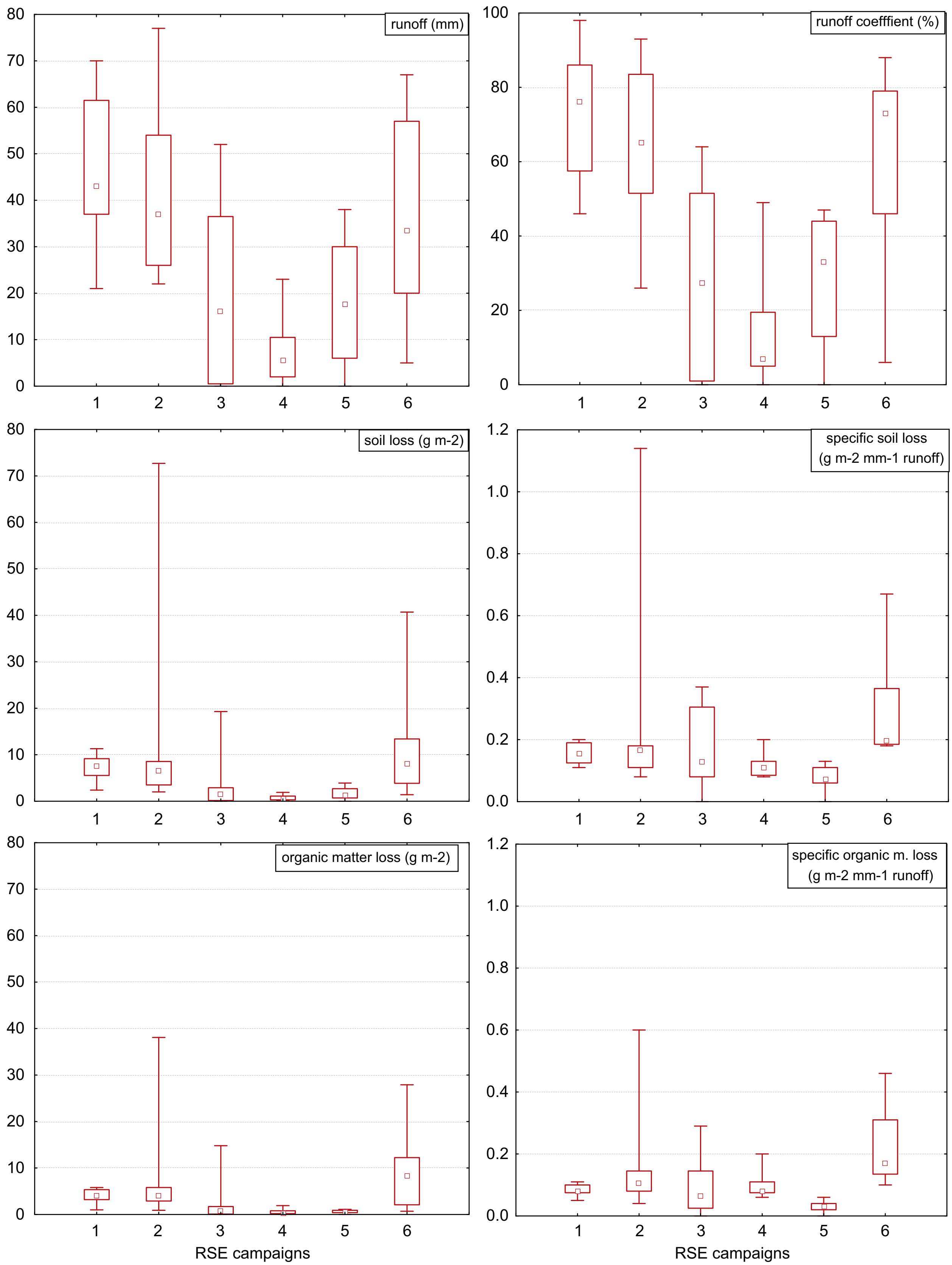

Fig. 3. Box-plots of runoff and soil and organic matter losses by individual RSE's at an unploughed and a ploughed eucalypt site for six field campaigns.

i.e. one *vs.* six days before the RSE's at the unploughed and ploughed site, respectively. On July 10 and July 24, 2006, repellency was very strong at both sites (Keizer et al., 2008).

The overall importance of vegetation recovery in limiting erosion during the study period was minor, as can be inferred from the comparatively high soil and organic matter losses of the

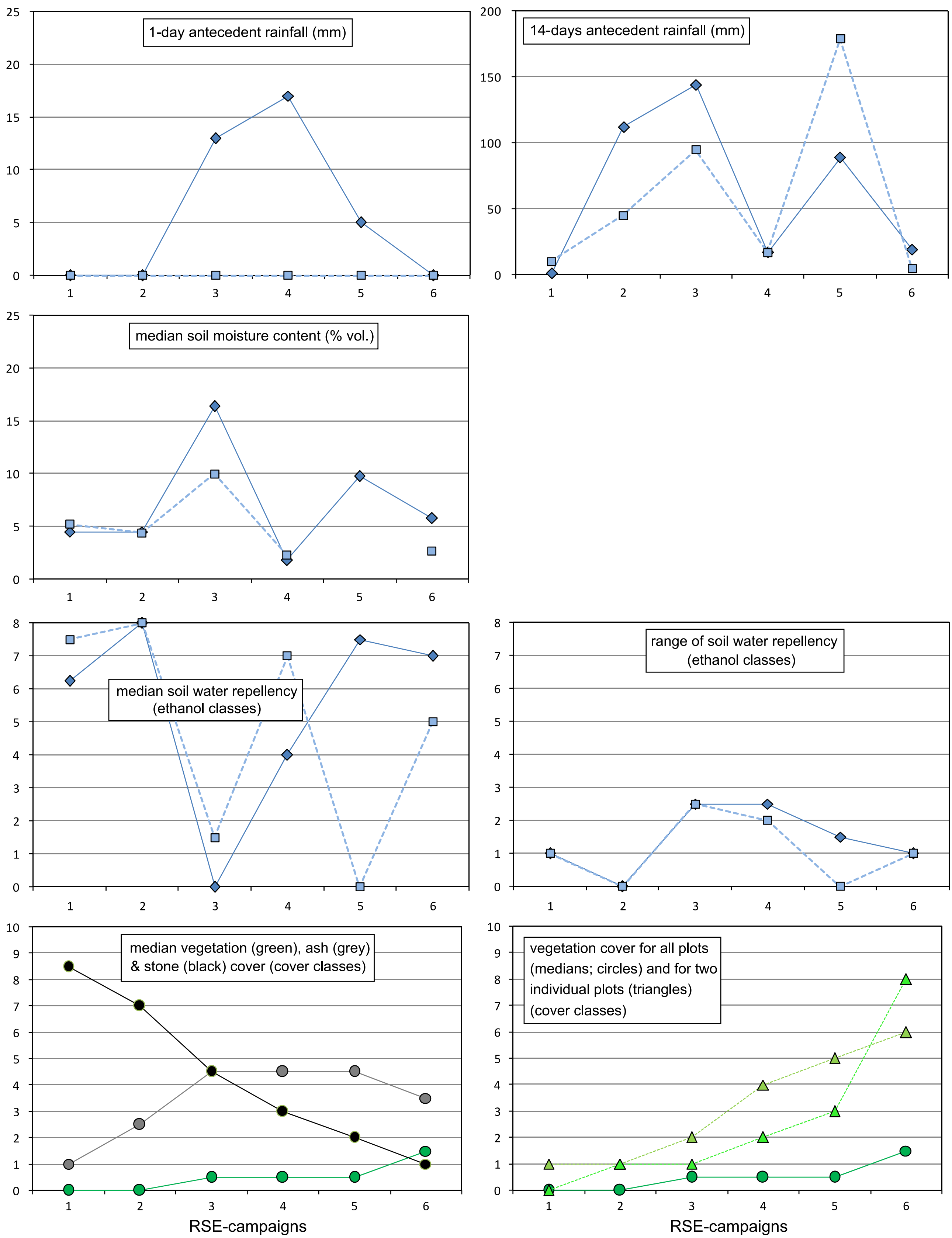

Fig. 4. Antecedent rainfall, initial soil moisture content and water repellency, and vegetation, ash and stone cover at an unploughed (diamonds) and a ploughed (squares) eucalypt site for six RSE campaigns.

last RSE campaign. Recovery of the ground vegetation was in fact limited during these 2 years following the wildfire (Fig. 4). By July 2006, vegetation cover was less than 20% in seven out of eight plots; by July 2007, it was less than 40% in all except the two plots depicted in Fig. 4. Shakesby et al. (1994) also indicated that ground vegetation in eucalypt stands recovered too slowly after fire to be effective within the first 2 years. The possible role of vegetation cover at the scale of individual plots is addressed next.

The RSE's by Sheridan et al. (2007) revealed a better overall agreement between the temporal patterns in runoff coefficient and soil water repellency than found here. Their highest runoff values were not restricted to the first few months after the wildfire but also occurred some 3 years later. Even so, differences in runoff could not be entirely attributed to water repellency, in particular the almost twice as high runoff coefficient 3 years compared to 1 month after fire under equally strongly repellent conditions. Clearly distinct from the current results was Sheridan's et al. (2007) finding of markedly higher sediment concentrations during the first year after fire. Such a decrease suggests a transition from transport- to sediment-limited conditions, as is also commonly observed in post-fire erosion plot studies under natural rainfall (see Shakesby and Doerr, 2006). Their specific sediment losses during the first post-fire year (2.26–7.19 g m^{-2} mm^{-1} runoff) clearly exceeded the present values. Their values for the subsequent 2 years (0.13–1.59 g m^{-2} mm^{-1} runoff), however, were comparable.

The only other study involving a time series of RSE's in wildfire-affected forests is that of Cerdà and Doerr (2005) in Aleppo Pine stands in eastern Spain. They employed the same simulator as in this study (application rate of 55 mm h^{-1}) and also permanent plots. During the first 3 years following fire, their RSE's produced higher runoff coefficients under wet than under dry conditions. This contrasting hydrological response could be explained by the low water repellency levels during this initial post-fire period, likely as a direct effect of fire. The erosion results of Cerdà and Doerr (2005) were also distinct from the present ones. The specific sediment losses dropped sharply from the first to the second year after fire and then more gradually afterwards. Only from the sixth year onwards the specific losses in Cerdà and Doerr (2005) fell below 0.40 g m^{-2} mm^{-1} runoff, thus becoming comparable to the bulk of the high-intensity values presented here. Their values for the first post-fire year (2.50–5.25 g m^{-2} mm^{-1} runoff) were not widely different from Sheridan's et al. (2007) above-mentioned figures for the first post-fire year, even though application rate and plot size were much smaller (55 vs. 100 mm h^{-1}; 0.25 vs. 3 m^2).

3.4. Spatial variability

Within-site differences. Overall differences between the same-intensity plots were not significant for any of the sites or variables (Table 5). This can be attributed to the above-mentioned, significant temporal variability between the various RSE campaigns. Campaign-specific differences, on the other hand, were significant in various instances, all of which involving extreme-intensity plots. The latter suggested that extreme events enhanced the inherent spatial variability in plot characteristics and, consequently, erosion processes. These significant differences, however, had different origins at the two sites. In the case of the ploughed site, the runoff response of the two extreme-intensity plots differed widely (Fig. 5). In turn, this discrepancy in runoff caused significant different total soil and organic matter losses, since the specific losses differed in the opposite sense. In the case of the unploughed site, by contrast, significant differences in specific soil losses contributed markedly to the significant differences in total soil losses.

As discussed before, the significantly lower amount of overland flow generated at one of the extreme-intensity plots at the ploughed site (plot P4) could be explained by its high litter cover (Fig. 6), possibly in combination with other factors. The significantly higher specific soil losses at plot U4 at the unploughed site were more difficult to explain, also because plot-specific data related to soil erodibility were not available. Post-fire vegetation recovery could play a role, since it was basically lacking at plot U4 but pronounced at plot U2 (Fig. 6). It would especially help explain why the plots' specific losses differed considerably less in July 2007 than in November 2005 (with a factor 3 and 6, respectively).

In particular during the campaigns of November 2005 and July 2007, the specific sediment losses recorded at plot U4 stood out amongst the present values. Compared to other studies, however, these values (1.7 and 1.1 g m^{-2} mm^{-1} runoff) were hardly suspicious. Leighton-Boyce et al. (2007) reported a mean value of 2.3 g m^{-2} mm^{-1} runoff for an unburnt eucalypt site where the litter was removed prior to the RSE's. Specific sediment losses in

Table 5
Statistical comparison of within-site and between-site variation in runoff and erosion by high- and extreme-intensity RSE's. The within-site comparison concerned the same-intensity plots at each study site; the between-site comparison concerned the same-intensity plots at different sites, either the site-wise average values ("mean") or the values of the individual RSE's. The statically significantly outcomes ($\alpha = 0.05$) of the MW *U*-test and Wilcoxon *S*–*R* test are indicated with "M" and "W" or, in the case of the between-site comparison of individual plots, with the codes of the unploughed plots (U1–U4) that are significantly different from the ploughed plots (P1–P4).

Variability and variables *With-in site*	**Unploughed**		**Ploughed**	
	High	**Extreme**	**High**	**Extreme**
Total runoff (mm)				W
Overall runoff coefficient (%)				W
Total soil loss (g m^{-2})		W		W
Total organic matter loss (g m^{-2})				W
Specific soil loss (g m^{-2} mm^{-1} runoff)		W		
Specific o.m. loss (g m^{-2} mm^{-1} runoff)				

Between-site	**Means**		**Individual plots**			
	High	**Extr.**	**High**		**Extreme**	
	Ploughed		**P1**	**P3**	**P2**	**P4**
Total runoff (mm)	W	W	U1		U4	U4
Overall runoff coefficient (%)	W	W	U1		U4	U4
Total soil loss (g m^{-2})		W	U1		U4	U4
Total organic matter loss (g m^{-2})		W			U4	U4
Specific soil loss (g m^{-2} mm^{-1} runoff)						U2
Specific o.m. loss (g m^{-2} mm^{-1} runoff)						U2

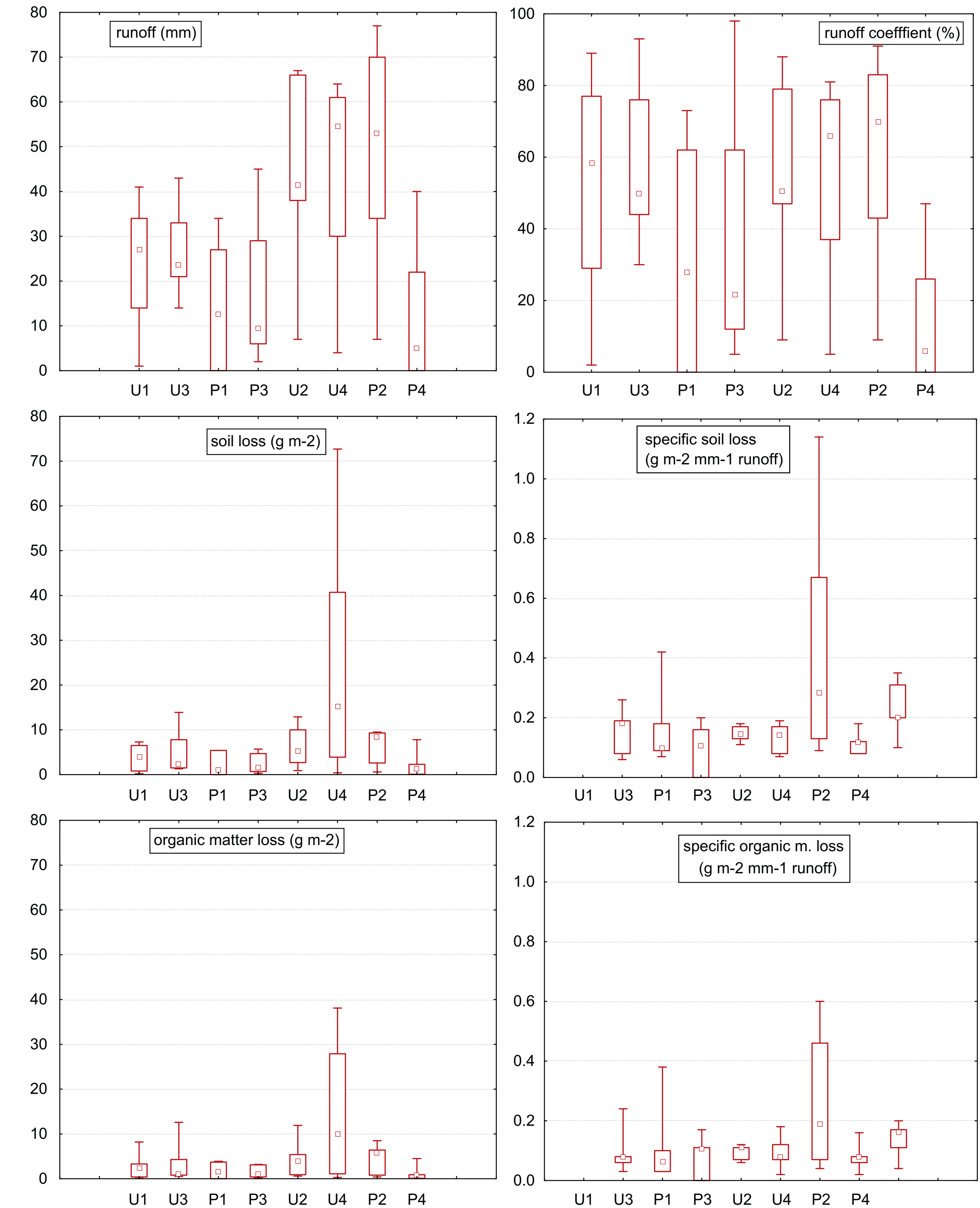

Fig. 5. Box-plots of runoff and soil and organic matter losses over various RSE campaigns for four high- ("1" and "3") and four extreme-intensity ("2" and "4") plots at an unploughed ("U") and a ploughed ("P") eucalypt site.

Cerdà and Doerr (2005) and Sheridan et al. (2007) equally exceeded 2 g m^{-2} mm^{-1} runoff. Also the present spatial variability in specific sediment losses in concurrent RSE's was not extraordinary in comparison to these latter two studies (Cerdà and Doerr, 2005: 2.50–4.46 g m^{-2} mm^{-1} runoff; Sheridan et al., 2007: 7.2–24.3 g m^{-2} mm^{-1} runoff).

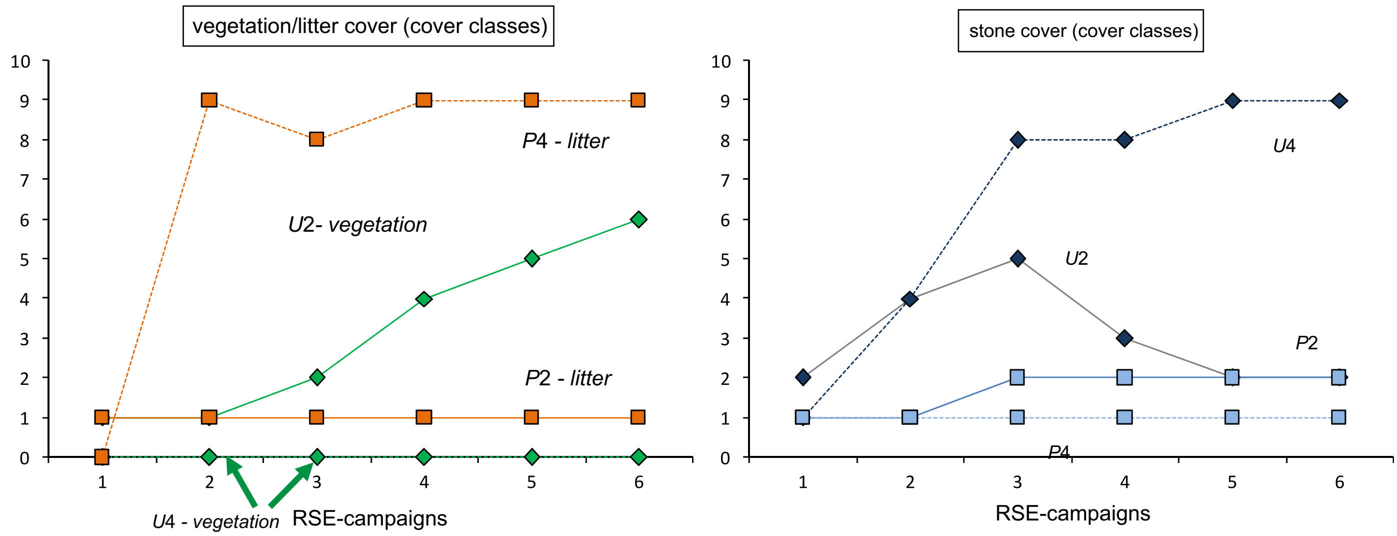

Fig. 6. Vegetation/litter, and stone cover of four extreme-intensity ("2" and "4") plots at an unploughed ("U") and a ploughed ("P") eucalypt site for six RSE campaigns.

The credibility of the relatively high losses at plot U4 was further corroborated by the strong increase in the plot's stone cover (Fig. 6). It remained unclear, however, if this stone lag already existed before the wildfire, becoming increasingly exposed by the subsequent removal of the ash layer and the lack of vegetation recovery, or whether it developed during the study period. The former explanation is perhaps most likely, namely, Shakesby et al. (1993) and Terry (1996) reported a much higher specific sediment loss (11.9 g m^{-2} mm^{-1} runoff) for the initial phase of stone lag formation in an eucalypt stand.

Between-site differences. The unploughed site revealed a significantly stronger average runoff response than the ploughed site (Table 5). This was true for both the absolute and relative runoff amounts and for both the high- and extreme-intensity RSE's, as is also easily perceived from Fig. 7. By contrast, significant differences in average sediment losses were restricted to the total soil and organic matter losses of the extreme-intensity RSE's, again with the values at the unploughed site being highest. Nonetheless, also the high-intensity RSE's revealed some tendency towards higher average soil losses at the unploughed site, namely, the values at the unploughed site were highest in five out of the six RSE campaigns.

Although the Wilcoxon's test results for the individual plots were indicative only, they allowed further insight in the average between-site differences (Table 5). This especially applied to the extreme-intensity RSE's, namely, the significant difference in the average extreme-intensity values was due to pronounced spatial variation at the ploughed site and, more specifically, the deviant behaviour of plot P4, as also readily appreciated in Fig. 5. Plot P4 not only produced, as mentioned above, consistently less sediment and/or runoff than the other extreme-intensity plot at the ploughed site and even the neighbouring high-intensity plot but also then the two extreme-intensity plots at the unploughed site. Thus, the extreme-intensity results of this study were strongly influenced by a highly localised and rather accidental factor like litter fall from scorched crowns.

4. Conclusions

The main conclusions from this study include the following:

- Extreme-intensity RSE's (80–85 mm h^{-1}) tended to generate larger amounts of runoff and, thereby, higher losses of soil and organic matter than high-intensity RSE's (45–50 mm h^{-1}); however, this tendency was not invariable either in space or, at a certain location, through time.
- Within-site variability in runoff and erosion response was more pronounced in the case of the extreme- than high-intensity RSE's, so that their modelling will require greater efforts in terms of model calibration and/or obtaining plot-specific information.
- Runoff and associated sediment losses varied significantly with time-after-fire; however, this temporal pattern did not correspond to a simple decrease with time but had a marked seasonal component, which broadly agreed with the role of topsoil water repellency in enhancing overland flow generation under dry antecedent weather conditions.
- The risk of enhanced runoff generation and erosion in recently burnt eucalypt stands does not necessarily disappear with the first significant rains after the wildfire but can persist through most of the first autumn and also re-appear after subsequent dry spells as long as 2 years later; this could be attributed to the typically pronounced water repellency of eucalypt forest soils combined with an often slow post-fire vegetation recovery.
- Contrary to expected, the unploughed site produced more runoff and erosion than the adjacent unploughed site. Besides soil properties altered by ploughing, the difference in slope angle between the two sites could play a role. These possible explanations will be further explored using the MEFIDIS erosion model as research tool.
- The sediment losses at the two study sites were low compared to those obtained with similar methodologies (i.e. field rainfall simulation experiments on small plots) following wildfires in other parts of the world. Nonetheless, they need to be evaluated against the typically shallow soil depths on the steep hill slopes in the study area, with the elevated organic matter fractions in the observed sediment losses requiring special attention.

Acknowledgments

We gratefully acknowledge the help of Raquel Ferreira, Mart Houmann, Mark Lagewaard, Angela García-Monge, David Herrera

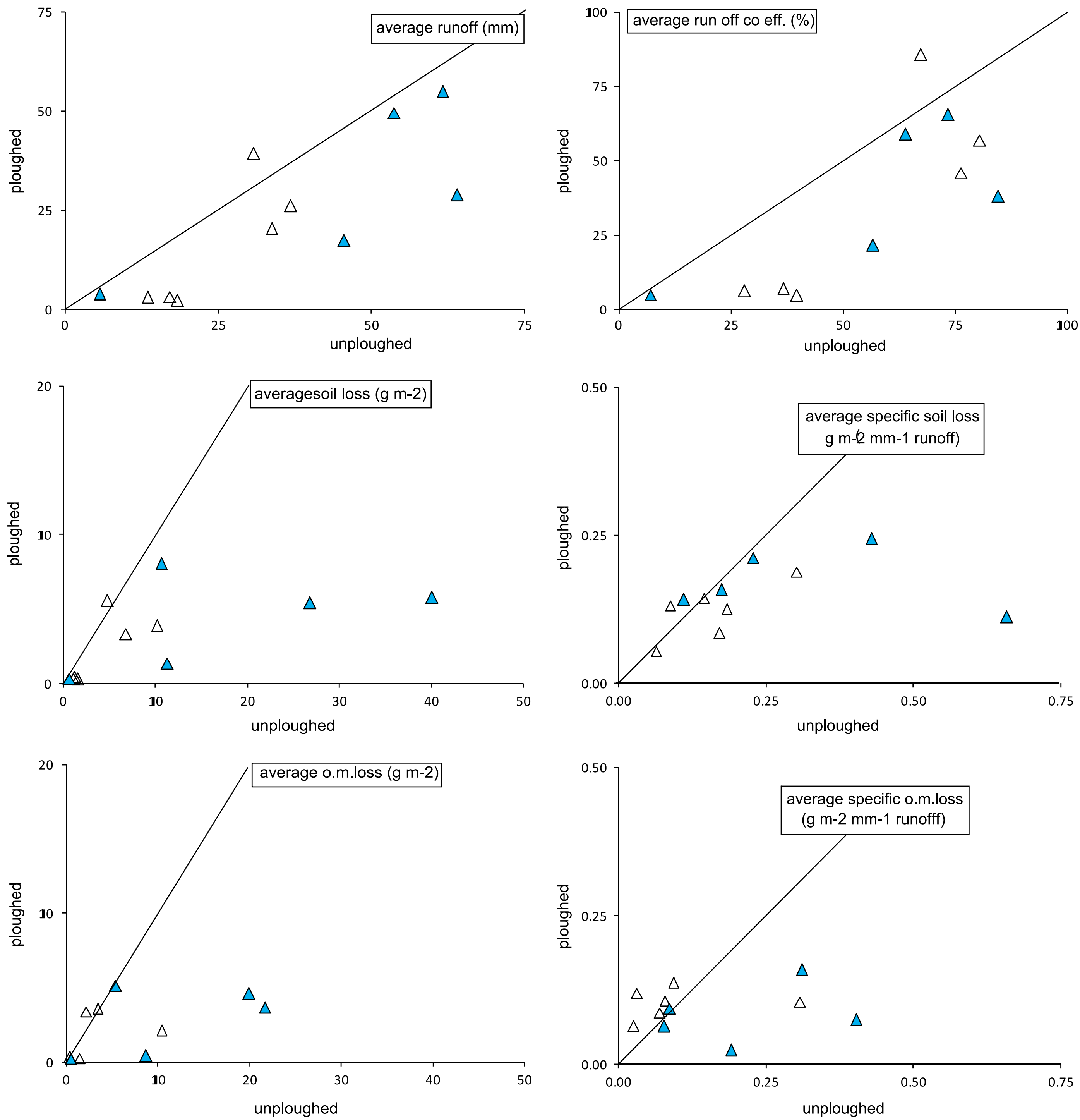

Fig. 7. Average absolute and relative amounts of runoff and soil and organic matter losses by high- (open triangles) and extreme-intensity (closed triangles) RSE's at an unploughed *vs.* a ploughed eucalypt site.

and Ana Sofia Santos with the field data collection and/or laboratory analysis of the runoff samples; Virgínia M.F.G. Pereira with the soil profile descriptions; Jorge Lucena, Carmen Magalhães and Joaquim Sande Silva for the laboratory analyses of the soil samples.

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Chapter 3: Assessing the role of pre-fire ground preparation operations and soil water repellency in post-fire runoff and inter-rill erosion by repeated rainfall simulation experiments in Portuguese eucalypt plantations

Catena 108 (2013) 69–83

Contents lists available at SciVerse ScienceDirect

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Assessing the role of pre-fire ground preparation operations and soil water repellency in post-fire runoff and inter-rill erosion by repeated rainfall simulation experiments in Portuguese eucalypt plantations

Maruxa C. Malvar [a,*], Martinho A.S. Martins [a], João P. Nunes [a], Peter R. Robichaud [b], J. Jacob Keizer [a]

[a] Centro de Estudos do Ambiente e do Mar (CESAM), Departamento de Ambiente e Ordenamento, Universidade de Aveiro, 3810-193 Aveiro, Portugal
[b] US Department of Agriculture, Forest Service, Rocky Mountain Research Station, 1221 South Main Street, Moscow, ID 83843, USA

ARTICLE INFO

Keywords:
Wildfire
Eucalypt plantations
Soil water repellency
Field rainfall simulation experiments
Runoff
Inter-rill erosion

ABSTRACT

This study addressed the impacts of contrasting pre-fire ground preparation operations on post-fire runoff and inter-rill erosion in six eucalypt plantations in north-central Portugal, with a special emphasis on the role of soil water repellency in the seasonal patterns of overland flow generation. To this end, a down slope ploughed, a contour ploughed and a terraced site were compared with three unploughed sites. Runoff and erosion data were collected in the field by carrying out rainfall simulation experiments (RSEs) with two intensities (45–50 and 80–85 mm h^{-1}) at six occasions during the first one to two years following wildfires in 2005 and 2006.

Overall runoff coefficients varied markedly amongst the six study sites and between the two intensities (7 to 55%). While runoff figures were comparable to those of prior RSE studies in recently burnt areas, overall sediment losses were comparatively low (7–155 g m^{-2}) but contained a substantial organic matter fraction (29–74%). Apparently, the inter-rill erosion rates were essentially sediment-limited, fitting in with the long history of intensive land use that is typical in the Mediterranean Basin. The hydrological and erosion impacts of the three pre-fire ground preparation operations were minor, probably because these operations took place several years before the latest wildfire. Overall, the two rainfall intensities produced the expected differences but this effect was only statistically significant for simultaneous RSEs. Furthermore, the effect of rainfall intensity varied markedly between the study sites and, occasionally, between the two plot pairs at the same site. This impeded an erosion risk ranking of the six study sites that was consistent for both rainfall intensities. Runoff and erosion rates did not decrease in a simple or pronounced manner with time-since-fire. These temporal patterns could in part be attributed to changes in soil water repellency but other factors were involved as well. Removal of the protective soil cover by litter in particular appeared to play a key role in the increase in sediment losses following logging and wood extraction.

1. Introduction

Wildfires are a common phenomenon in present-day Portugal and have affected an average of 100,000 ha of rural lands per year over the past three decades (Pereira et al., 2005). Two key factors behind the elevated wildfire incidence in Portugal are land abandonment and widespread planting of highly flammable pines and eucalypts (Carmo et al., 2011; Moreira et al., 2001). Due to the structural nature of these underlying causes, combined with an increase in meteorological conditions propitious to wildfire (longer and more frequent drought periods), wildfire occurrence in Portugal is also not expected to decrease in the foreseeable future (Pereira et al., 2006).

Wildfires can produce marked changes in hydrological and erosion processes (Shakesby and Doerr, 2006). Fire-enhanced runoff and erosion rates are attributed to the (partial) removal of the protective vegetation and litter cover, and to heating-induced alterations in soil properties controlling runoff generation and soil erodibility such as soil water repellency and aggregate stability, respectively (Mataix-Solera et al., 2011; Shakesby, 2011; Shakesby and Doerr, 2006; Varela et al., 2010). Strong increases in runoff and erosion following wildfire have also been reported for the two principal forest types in north-central Portugal, i.e. Maritime Pine and eucalypt plantations (e.g. Coelho et al., 2004; Ferreira et al., 1997; Shakesby et al., 1994). Eucalypt plantations are typically associated with elevated levels of soil water repellency (Doerr et al., 1998, 2000; Ferreira et al., 2008; Keizer et al., 2005b, 2008; Scott, 2000), and their crucial importance for post-fire runoff generation was demonstrated by Leighton-Boyce et al. (2007).

Post-fire forestry practices can contribute markedly to an enhanced hydrological and erosion response of recently burnt areas (Fernández

* Corresponding author at: Centro de Estudos do Ambiente e do Mar (CESAM), Departamento de Ambiente e Ordenamento, Universidade de Aveiro, 3810-193 Aveiro, Portugal. Tel.: +351 234370200; fax: +351 234370309.
E-mail address: maruxa@ua.pt (M.C. Malvar).

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http://dx.doi.org/10.1016/j.catena.2012.11.004

et al., 2007; Shakesby, 2011). In the study region, rip-ploughing in down slope direction to prepare eucalypt planting increased sediment losses to rates well beyond those immediately after fire (Shakesby et al., 1996, 2002; Walsh et al., 1995). Contour ploughing and terracing are also regularly employed in recently burnt areas in the study region, but their erosion implications remain to be studied. The role of pre-fire ground preparation techniques (i.e. when ploughing and terracing took place before the latest wildfire) has equally received little research attention, in spite forest lands in north-central Portugal — as is typical for many Mediterranean landscapes (Shakesby, 2011) — are nowadays an intricate mosaic of terraced, ploughed and unploughed terrains. Malvar et al. (2011) compared an eucalypt plantation that had been ploughed in down slope direction several years before a wildfire with an adjacent unploughed eucalypt plantation, finding no marked differences in immediate post-fire erosion rates.

While there is thus a strong need for an ERMIT-like tool (Robichaud et al., 2007) for assessing soil erosion risk in recently burnt areas in Portugal, its development is constrained by a lack of data for model parameterization and assessment. In the EROSFIRE project, field rainfall simulation experiments (RSEs) were selected to overcome some of these data constraints, focussing on the comparison of different pre-fire ground preparation techniques. RSEs have well-known limitations in terms of reproducing natural rainfall events and erosion processes beyond small spatial scales (e.g. Rickson, 2001). However, they avoid the confounding effects of seasonal and inter-annual variations in rainfall that are typical for erosion plot data (Cerdà and Doerr, 2005; Shakesby et al., 1993; Spigel and Robichaud, 2007) and, thus, facilitate the comparison of results obtained at different moments in time after a certain wildfire as well as in study areas burnt by different wildfires (e.g. Cerdà, 1998). Seasonal differences in erosion deserve special attention when studying eucalypt plantations, because of the supposed role of soil water repellency in runoff generation (Doerr et al., 2006; Ferreira et al., 2000; Keizer et al., 2005a; Sheridan et al., 2007), on the one hand, and, on the other, the well-known variation in repellency with dry and wet seasons (Doerr et al., 2000; Keizer et al., 2005b; Leighton-Boyce et al., 2005). RSEs have been widely used in post-fire erosion studies (e.g. Benavides-Solorio and MacDonald, 2001; Coelho et al., 2004; Kutiel et al., 1995; Leighton-Boyce et al., 2007; Sevink et al., 1989) but only Cerdà and Doerr (2005), Sheridan et al. (2007) and Malvar et al. (2011) did so at more than a single moment in time after fire.

The present study was an extension of Malvar et al. (2011) in two manners. It included pre-fire contour ploughing and terracing, two further pre-ground preparation operations that, unlike down slope ploughing, are well-established soil conservation practices. Also, it included two additional unploughed eucalypt plantations that were burnt by a different wildfire and one of which was logged during the study period (by chance). The specific objectives of the present study were to assess and evaluate how post-fire runoff and erosion rates: (i) differed amongst eucalypt plantations that had and had not suffered contrasting ground preparation operations before the latest wildfire; (ii) varied with time-since-fire and, in particular, with temporal patterns in soil water repellency, vegetation recovery and post-fire forestry operations; and (iii) differed between high- and extreme-intensity simulated rainfall events (45–50 vs. 80–85 mm h^{-1}).

2. Materials and methods

2.1. Study area and sites

Within the Aveiro District of north-central Portugal, the Açores and Jafafe study locations were selected following a wildfire in July 2005, and the Soutelo study location following a wildfire in August 2006 (Fig. 1). Soutelo was the nearest 2006-burnt location to Açores and Jafafe with the same geology (the distance is some 9 km towards east). A total of six hillslopes — two per study location — were selected to compare eucalypt plantations (*Eucalyptus globulus* Ait.) with and without ground preparation techniques carried out before the latest wildfire (Table 1). The three unploughed study sites were designated as UP05_A1 (UnPloughed, 2005-burnt, Açores1), and UP06_S1 and UP06_S2 (2006-burnt, Soutelo1 and Soutelo2); the three intervened sites as DP05_A2 (Down slope Ploughed, Açores2), CP05_J1 (Contour Ploughed, Jafafe1) and ST05_J2 (Slope Terraced — i.e. the terraces were not constructed in perpendicular direction to the main slope angle but at a considerable angle — Jafafe2). Judging by the remaining eucalypt stumps, the ground preparation practices at all three sites were carried out several years before the wildfire in 2005 but precise estimates could not be obtained. Although logging immediately after wildfire was commonly observed, only the UP06_S2 was logged during the study period (in February 2007).

A general characterisation of the study sites was carried out as soon as possible after their selection (Table 1). This involved a description of terrain physiognomy, the assessment of fire severity using five simple indices recorded at five points along a transect from the base to the top of each slope, the description and sampling of two soil profiles at the base and halfway each slope, and the laboratory analysis of these soil samples with respect to bulk density (Porta et al., 2003), granulometric composition (Guitian and Carballas, 1976) and organic matter content (Botelho da Costa, 2004). Wildfire severity was classified as moderate at all sites due to the partial consumption of eucalypt canopies and shrub twigs, the total consumption of the litter layer and the presence of black ashes (Shakesby and Doerr, 2006). The soils at the two Açores sites were identified in the field as Umbric Leptosols and those at the remaining sites as Leptic Umbrisols (WRB, 2006). All soils were developed from pre-Ordovician schists of the Hesperic Massif (Ferreira and de Brum, 1978; Pereira and FitzPatrick, 1995), and their upper 20 cm had a coarse texture varying between sandy loam and clay loam, and a high organic matter content ranging from 5 to 11%.

The climate at the study sites is Mediterranean with ocean influence, and can be described as humid meso-thermal with prolonged dry and warm summers (Köppen-Csb; DRA-Centro, 2001). The long-term mean annual rainfall at the nearest rainfall station (Albergaria-a-Velha, 4 km north of the Açores sites; 1941–1991) was 1229 mm but annual rainfall varied markedly from 750 to 2022 mm. The long-term mean annual temperature at the nearest climate station (Estarreja, 17.5 km north-east of the Açores sites; 1956–1977), with monthly mean temperatures ranging from 8.8 °C in December to 19.1 °C in July. The rainfall during the study period was measured by installing at each study location a tipping-bucket rainfall gauge (Pronamic Professional Rain Gauge) linked to a Hobo Event Logger (Onset Corporation) as well as one or more storage gauges for validation purposes.

2.2. Experimental design

The present experimental design differed from that of the bulk of post-fire erosion studies employing field rainfall simulation experiments (RSEs) in two respects, by repeating the RSEs at five or six occasions on the same, permanent plots and by simultaneously carrying out high- and extreme-intensity RSEs (45–50 vs. 80–85 mm h^{-1}) on adjacent, paired plots. At each study site, two pairs of permanent plots were installed halfway in the lower and upper section of the slope, and the two plots of each pair were randomly assigned the — fixed — intensity to be applied throughout the study period. In the case of the 2005-burnt sites, the permanent plots were installed during the second and not the first campaign to allow for destructive soil measurements and sampling within this first set of plots (immediately following the end of the RSEs). In addition to each pair of RSE plots, a third plot with the same dimensions was used for measuring initial soil conditions, with a special interest in topsoil water repellency. Because of the destructive nature of these measurements, the control plots were relocated between subsequent field campaigns but always such that they were at similar distances to the two associated RSE plots (generally at 3–5 m).

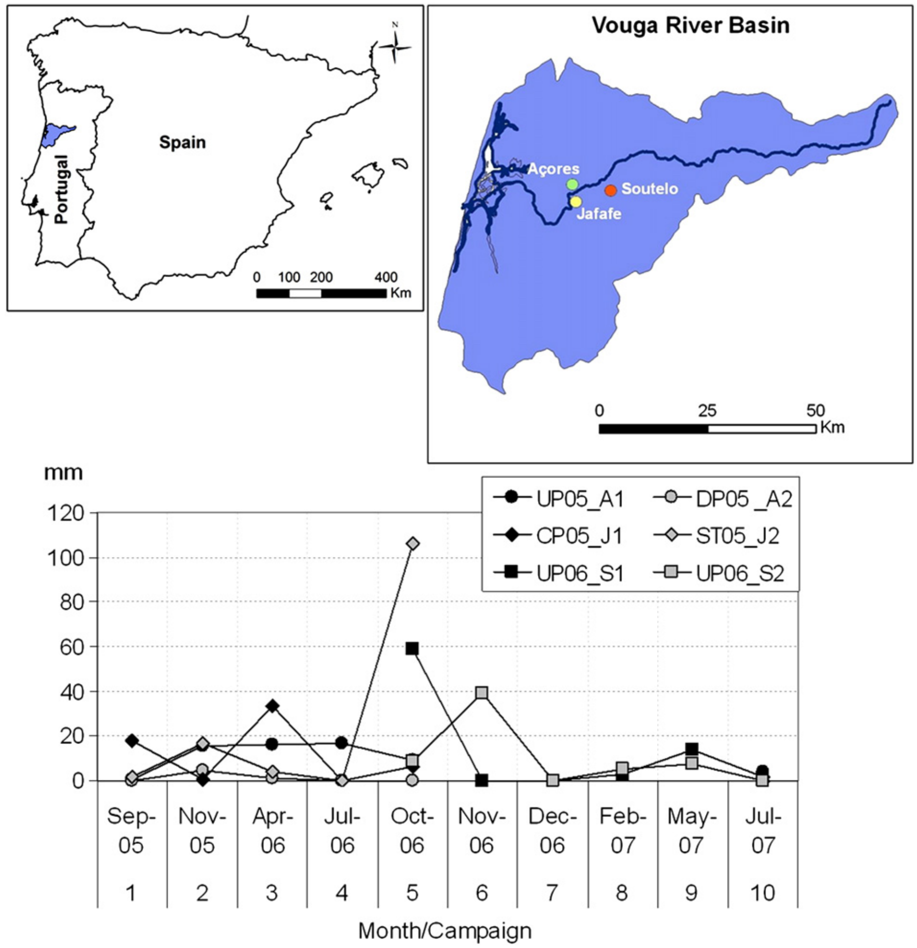

Fig. 1. Location of the three study sites and 4-day antecedent rainfall prior to the first rainfall simulation experiment at the six study sites (see Table 1 for site codes and Table 2 for timing of first experiments).

In total, 10 field campaigns were carried out between September 2005 and July 2007 (Table 2). The six campaigns at the 2005-burnt sites concerned the first two years after fire, whereas the six campaigns at the 2006-burnt sites had to be limited to the first year after fire (due to the project's end). At all study sites the first RSE campaign was carried out within the first two months after the wildfire but marked differences in antecedent rainfall (30–120 mm) could not be avoided (Fig. 1). From the total of 144 RSEs that were originally foreseen, 12 could not be carried out due to occasional malfunctioning of the extreme-intensity simulator in particular.

2.3. Rainfall simulation experiments

The RSEs were carried out with two portable rainfall simulators following the design by Cerdà et al. (1997) and with modifications by De Alba (1997), including a square plot of 0.28 m^2. The high (45–50 mm h^{-1}) and extreme intensities (80–85 mm^{-1}) were obtained using two distinct nozzles, the HARDI-1553-10 and -14, respectively. The two intensities were chosen to represent the maximum hourly rainfall at the Aveiro rainfall station for a 100-year return period and the maximum hourly rainfall ever recorded in Portugal (Brandão et al., 2001). The two default nozzles and two spare nozzles were (re-)calibrated in the laboratory before basically every field campaign. This involved calibrating the rainfall intensity as well as its homogeneity using a minimum threshold of 75% for the Christiansen uniformity coefficient (Christiansen, 1941 *in* Stewart and Howell, 2003).

In the field, the RSEs were performed according to a fixed protocol (Shakesby et al., 2002). Prior to applying the artificial rain, the cover of the plots was described by recording the presence–absence of various cover classes (stones, bare soil, litter, vegetation) in each of the 5 cm × 5 cm cells of a 50 cm × 60 cm grid laid out over the plot. The simulations themselves involved the application of the selected intensity during 1 h, the measurement of runoff at 1-minute intervals, and collection of up to five runoff samples (one from the start of the runoff until its approximate stabilization, one from the end of the rainfall until the end of the runoff and three at the start, middle and end of the remaining period). These runoff samples were then later analysed in the laboratory using the classical evaporation method (APHA, 1998) and the loss-on-ignition method (Botelho da Costa, 2004) to determine their sediment and organic matter concentrations. Random roughness of the RSE plots was measured using a pin profile meter and the PMPPROJ software (developed by J. Kilpelainen, Agricultural Research Centre, Jokioinen, Finland). This was done at a single occasion at the end of the RSE campaigns, and involved placing the meter at three fixed positions within each RSE plot (at one, two and three quarters along the plot's length).

2.4. Soil water repellency, moisture and resistance measurements

At five fixed points within the control plots, soil water repellency was measured in situ at the soil surface as well as between 2–3 and 7–8 cm depth (see Keizer et al. (2008) for further details). This was done using the "Molarity of Ethanol Droplet" (MED) test, as specified in Doerr (1998) and slightly modified in our prior work (Keizer et al.

Table 1
General site and soil characteristics as well as fire severity indicators for the six study sites.

Fire	2005				2006	
Location	Açores	Açores	Jafafe	Jafafe	Soutelo	Soutelo
Site code	UP05_A1	DP05 _A2	CP05_J1	ST05_J2	UP06_S1	UP06_S2
Coordinates	40°40′46.62″N 8°26′54.80″W	40°40′45.32″N 8°26′55.85″W	40°40′22.88″N 8°26′41.56″W	40°40′23.66″N 8°26′36.39″W	40°40′53.59″N 8°20′43.82″W	40°40′54.24″N 8°20′45.88″W
Physiognomy						
Slope section length (m)	20–25	30–40	45–50	55–76	28–40	18–45
Slope angle (°)	20	15	14	17	16	22
Aspect	SE	NE	NW	NE	NW	NW
Land management						
Ground preparation operations	Unploughed	Ploughed down-slope	Contour ploughed	Incline terracing	Unploughed	Unploughed
Post-fire operations	–	–	–	–	–	Logging
Fire severity indicators						
Eucalypt crown damage	Partial	Partial	Partial	Partial	Partial	Partial
Height burned stems (m)	9	12	12	6	4	4
Combustion of litter/herb layer	Total	Total	Total	Total	Total	Total
Combustion of shrub layer	Partial	Partial	Partial	Partial	Partial	Partial
Ash colour	Black	Black	Black	Black	Black	Black
Soil characteristics						
Soil type	Umbric Leptosol	Umbric Leptosol	Leptic Umbrisol	Leptic Umbrisol	Leptic Umbrisol	Leptic Umbrisol
Soil depth range (cm)	20–40	20–35	20–60	30–60	35–45	40–65
Bulk density (g cm^{-3}; 0–20 cm; n = 10–14)	0.83	0.93	0.88	0.83	0.86	0.8
Soil texture (0–5 cm; n = 4)	Sandy clay loam	Clay loam	Sandy clay loam	Sandy clay loam	Sandy loam	Sandy loam
Organic matter (%)	11	10	11	10	5	7
Clay (%)	25	31	23	30	15	20
Silt (%)	25	36	7	15	23	24
Sand (%)	50	33	70	55	62	56

(2005a, 2005b, 2008). Three droplets of increasing ethanol concentration classes (decreasing surface tension) (0, 0%; 1, 1%; 3, 3%; 3, 5%; 4, 8.5%; 5, 13%; 6, 18%; 7, 24%; and 8, 36% or > 36%) were applied to fresh parts of the soil until infiltration of at least two of three droplets of the same concentration that occurred within 5 s. The median ethanol concentration was then used as test result.

Following the repellency measurements, readings of volumetric soil moisture content were made at the same five sampling points and the two sampling depths (2–3 and 7–8 cm) using an ML2 Theta Probe TM (Delta T-Devices Ltd.) inserted horizontally into the soil. In the case of probe failure, a soil sample was collected and its moisture content determined gravimetrically, as further detailed in Keizer et al. (2008).

Prior to the repellency and moisture measurements, the resistance of the soil surface to shear stress and penetration was measured at the same five points within the plots, using a pocket vane tester and a penetrometer.

2.5. Data analysis

Data analysis was carried out using the SAS 9.2 software package (SAS Institute, Inc., 2008). Rank-based and non-parametric tests were preferred, also because of the small number of observations (Ott and Longnecker, 2001). Testing focused on the differences between the two rainfall intensities, the differences within and between the study sites, and the differences between the successive field campaigns. The Mann–Whitney *U*-test (MWU-t) and the Kruskal–Wallis test were used to assess overall differences between two and more than two groups of observations, respectively. The Wilcoxon's signed-ranks test (WSR-T) was employed to evaluate difference between paired observations or two

Table 2
Overview of the rainfall simulation experiments carried out at the six study sites (see Table 1 for site codes) during the approximately 2-year study period.

Fire		2005								2006			
Site code		UP05_A1		DP05 _A2		CP05_J1		ST05_J2		UP06_S1		UP06_S2	
Intensity		High	Extreme	High	Extreme	High	Extreme	High	Extreme	High	Extreme	High	Extreme
Campaign	Period	(n×mm/h)	(n×mm/h)	(n×mm/h)	(n×mm/h)	(n×mm/h)	(n×mm/h)	(n×mm/h)	(n×mm/h)	(n×mm/h)	(n×mm/h)	(n×mm/h)	(n×mm/h)
1	Sep05	2×46	2×84	2×46	2×84	1×46	1×84	2×46	2×84				
2	Nov05	2×46	2×84	2×46	2×84	2×46	2×85	1×46	1×85				
3	Apr06	2×48	2×80	2×48	2×80	2×48	2×80	2×46	2×80				
4	Jul06	2×46	2×80	2×46	2×80	2×46	2×80	2×46	2×80				
5	Oct06	2×47	2×82	2×47	–	2×47	2×88	2×47	–	2×47	2×82	2×47	2×82
6	Nov06									2×47	–	2×47	–
7	Dec06									2×47	2×82	2×47	2×82
8	Feb07									2×47	2×83	2×47	2×83
9	May07									2×44	2×76	2×44	2×76
10	Jul07	2×45	2×76	2×45	2×76	2×45	2×76	2×45	2×76	2×44	2×76	2×44	2×76
Total		12	12	12	10	11	11	11	9	12	10	12	10

sets of repeated observations, and the Friedman test to compare three of more sets of repeated observations. The Spearman rank correlation coefficient (ρ) was used to explore the relationships of runoff and erosion rates with soil cover and soil resistance.

3. Results

3.1. Overall runoff and inter-rill erosion rates

The hydrological and soil erosion response at the six study sites was summarized for the six field campaigns together in Table 3. The high- and extreme-intensity RSEs produced different rankings of the six eucalypt plantations in terms of overall runoff coefficients. The rankings contrasted most pronouncedly for CP05_J1 and UP06_S2. At CP05_J1 the overall runoff coefficient of the high-intensity RSEs was twice as high as that of the extreme-intensity RSEs, whereas the opposite was true for UP06_S2. If the risk of post-fire runoff generation at the different study sites is evaluated using the maximum runoff coefficient of the two intensities, the resulting ranking was surprising in two respects. First, the risk was highest at the contour-ploughed CP05_J1 as well as at two of the three unploughed sites (UP05_A1 and UP06_S2); second, the risk at the third unploughed site (UP06_S1) was lowest.

Total soil and total organic matter losses at the micro-plot scale depended strongly on overland flow generation (Fig. 2). For the entire set of 24 micro-plots, both losses were significantly and strongly correlated with total runoff (Spearman rank correlation coefficient = 0.92–0.94; ps < 0.01). Correlation coefficients were similar when analysing the high- and extreme-intensity RSEs separately (Fig. 2). Consequently, the high- and extreme-intensity RSEs also did not produce entirely consistent rankings of the six eucalypt plantation in terms of overall inter-rill erosion rates. Likewise, erosion risk assessment based on the highest losses of the two intensities was surprising in that the risk was clearly highest at two of the three unploughed sites (UP05_A1 and UP06_S2) and, at the same time, lowest at the third unploughed site (UP06_S1).

As suggested by the strong correlations between erosion and runoff rates, the specific soil and organic matter losses revealed mostly minor differences (Fig. 2). The bulk of the values ranged from 0.14 to 0.22 g of soil m^{-2} mm^{-1} runoff and from 0.08 to 0.13 g of organic matter m^{-2} mm^{-1} runoff. Comparatively high specific losses were produced by the extreme-intensity RSEs at the unploughed UP05_A1 and UP06_S2 sites, which in part explained the high total losses of these RSEs. In the case of the UP06_S2 site, these high values were largely due to a roughly 10-fold increase in specific losses following manual logging (with a chain saw) and mechanised wood extraction. No such increase was observed for the high-intensity RSEs at the UP06_S2 site.

3.2. Variation with rainfall intensity

The data set as a whole revealed that the high- and extreme-intensity RSEs produced significantly different responses in runoff and inter-rill erosion (Table 4). This was true for the individual RSEs as well as for the average responses of the simultaneous RSEs. The significant role of application rate was, however, location- and RSE campaign-specific, as indicated by the fact that significant differences were restricted to the Wilcoxon's signed ranks test. Thus, there was an overall tendency for extreme-intensity RSEs to produce significantly larger quantities of overland flow and significantly greater total as well as specific soil and organic matter losses than the high-intensity RSEs carried out at the location (plot pair or study site) and same time.

The role of rainfall intensity was less straightforward at the level of the individual study sites (Table 4; Fig. 3). Significant differences between the paired RSEs were basically limited to four of the six study sites, i.e. the terraced and the three unploughed sites. In agreement with the overall pattern for the entire data set, the extreme-intensity RSEs produced significantly higher runoff and inter-rill erosion rates than the high-intensity RSEs at UP05_A1, UP06_S2 and ST_05_J2. The opposite, however, was true at UP06_S01. From the two remaining sites, CP05_J1 revealed a similar tendency as UP06_S1 whereas DP05_A2 lacked an apparent pattern, with its paired observations almost evenly distributed above/below the 1:1 line or coinciding with it.

The unexpected and unclear differences at UP06_S1, CP05_J1 and DP05_A2 were further explored by comparing the results for the two plot pairs separately, both graphically (Fig. 4) and statistically (Wilcoxon's signed-ranks test). In the case of the down slope ploughed DP05_A2 site, the extreme-intensity RSEs produced significantly more runoff than the high-intensity RSEs at the upper slope section but significantly less at the lower slope section. Also one of the plot pairs at CP05_J1 as well as at UP06_S1 revealed consistently lower runoff quantities for the extreme- than high-intensity RSEs, while the other plot pair revealed at least a tendency to the same effect. As illustrated in Fig. 4, consistent differences between neighbouring plots were not limited to time-invariant properties such as micro-topography but also included protective litter and/or vegetation cover. This resulted from highly localized litter fall from scorched tree canopies as well as the generally sparse recovery of the spontaneous vegetation.

3.3. Spatial variability

3.3.1. Within-site variability

The RSEs did not tend to produce significantly different runoff and inter-rill erosion responses at the two plots subjected to the same application rates at each study site (Table 5). The extreme-intensity RSEs at the down slope ploughed DP05_A2 and unploughed UP06_S2 sites

Table 3
Overall values of simulated rainfall, runoff and inter-rill erosion produced by high- and extreme-intensity rainfall simulation experiments at the six study sites (see Table 1 for site codes) over the entire study period, showing the average values of the two micro-plots at each site.

Fire	2005								2006			
Site code	UP05_A1		DP05 _A2		CP05_J1		ST05_J2		UP06_S1		UP06_S2	
Rainfall intensity	High	Extreme	High	Extreme	High	Extreme	High	Extreme	High	Extreme	High	Extreme
Number RSEs	12	12	12	10	11	11	11	9	12	10	12	10
Mean slope angle (°) (permanent plots)	23	23	17	17	14	14	24	19	22	18	19	20
Total simulated rainfall (mm)	277	486	277	404	254	449	253	365	275	398	276	398
Total runoff (mm)	150	265	94	154	124	69	53	134	68	26	47	208
Runoff coefficient (%)	54	55	34	38	49	15	21	37	25	7	17	52
Total soil loss (g m^{-2})	26	93	14	21	26	10	11	25	12	5	9	109
Total organic matter loss (g m^{-2})	18	57	10	14	13	9	5	15	6	2	4	46
Specific soil loss (g m^{-2} mm^{-1}runoff)	0.17	0.35	0.15	0.15	0.21	0.14	0.21	0.19	0.18	0.21	0.19	0.52
Specific organic matter loss (g m^{-2} mm^{-1}runoff)	0.12	0.21	0.11	0.09	0.11	0.13	0.09	0.11	0.1	0.08	0.09	0.22
Specific soil loss (g m^{-2} mm^{-1}rain)	0.09	0.19	0.05	0.05	0.1	0.02	0.04	0.07	0.04	0.01	0.03	0.27
Specific organic matter loss (g m^{-2} mm^{-1}rain)	0.07	0.12	0.03	0.03	0.05	0.02	0.02	0.04	0.02	0.01	0.02	0.12

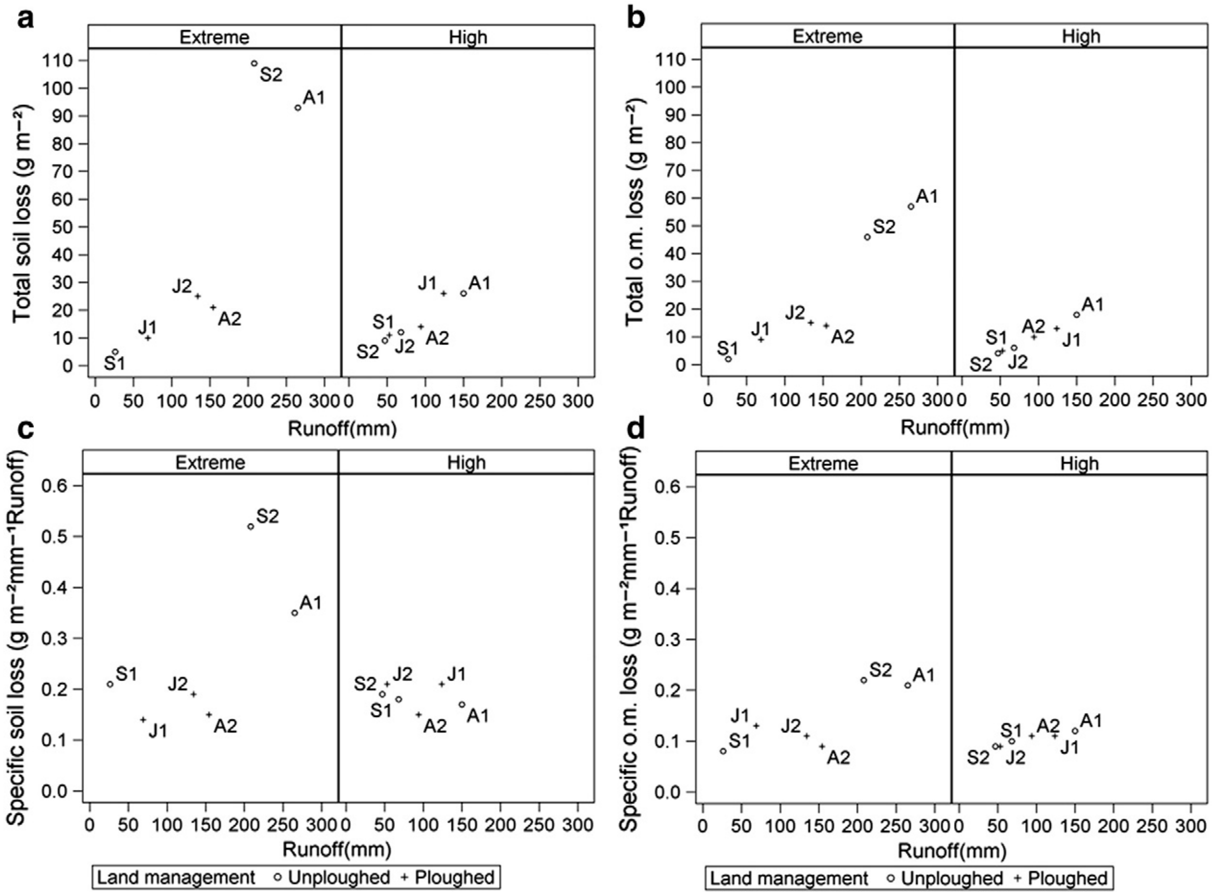

Fig. 2. Scatter plots of runoff volumes against total and specific losses of soil and organic matter (o.m.) for the two simulated rainfall intensities, showing the average values of the six study sites over the entire study period. The sites are indicated with the last two letters of their codes (see Table 1), and are grouped in unploughed and ploughed (including terraced) sites.

were an exception, with significant differences that were campaign-specific as indicated by the Wilcoxon's signed-ranks test. In the case of the down slope ploughed site (DP05_A2), the significant differences at DP05_A2 were consistent with differences in protective vegetation and especially litter cover throughout the six campaigns (Fig. 4). Those at UP06_S1, however, lacked an obvious relationship with the available plot data. For example, the runoff differences in May 2007 agreed with the differences in median levels of soil water repellency (extreme-ethanol class 8 vs. strong-ethanol class 5) but the runoff differences of the other campaigns did not.

3.3.2. Between-site variability

The same-intensity RSEs produced various significant runoff and erosion differences amongst the 2005-burnt eucalypt plantations (Table 6). Significant differences were more common for the individual RSEs than for the sites' average responses, for runoff than soil and especially organic matter losses, and for total than specific soil losses. Furthermore, many significant differences were strictly campaign-specific as indicated by the discrepancies in the results of the Wilcoxon's signed-ranks test and Mann–Whitney *U*-test. The significant differences produced by the high-intensity RSEs coincided with those of the extreme-intensity RSEs in three out of the six cases. In one of these cases, however, the two application rates resulted in opposite differences. The high-intensity RSEs produced significantly more runoff and greater soil losses at the contour-ploughed CP05_J1 site than at the terraced ST05_J2, whereas the opposite was true for the extreme-intensity RSEs (Fig. 5). The latter reflected the fact that one of the extreme-intensity plots at CP05_J1 stood out for produced exceptionally

Table 4
Statistical comparison of runoff and inter-rill erosion rates produced by the high- vs. extreme-intensity rainfall simulation experiments, for the 2005- and 2006-burnt sites together and separately (see Table 1 for site codes) as well as for the individual experiments and their mean values per site. Statistically significant differences are indicated with the first letter of the statistical test (Mann–Whitney *U*-test/Wilcoxon signed ranks test), followed by the p-value.

Fire	2005 and 2006		2005				2006	
Site code	all sites		UP05_A1	DP05 _A2	CP05_J1	ST05_J2	UP06_S1	UP06_S2
Mean/individual values	Mean	Individual	Individual	Individual	Individual	Individual	Individual	Individual
Total runoff	W = 0.01	W < 0.01	M = 0.01/W < 0.01			W = 0.01	M = 0.01	M < 0.01/W < 0.01
Runoff coefficient					M = 0.01/W < 0.01		M < 0.01/W = 0.04	M = 0.01/W < 0.01
Total soil loss	W = 0.01	W < 0.01	W < 0.01			W = 0.01		M = 0.01/W < 0.01
Total organic matter loss	W = 0.02	W < 0.01	W < 0.01			W = 0.02	W = 0.03	M = 0.02/W < 0.01
Specific soil loss per mm runoff	W < 0.01	W = 0.04						
Specific organic matter per mm runoff	W = 0.02							W = 0.04

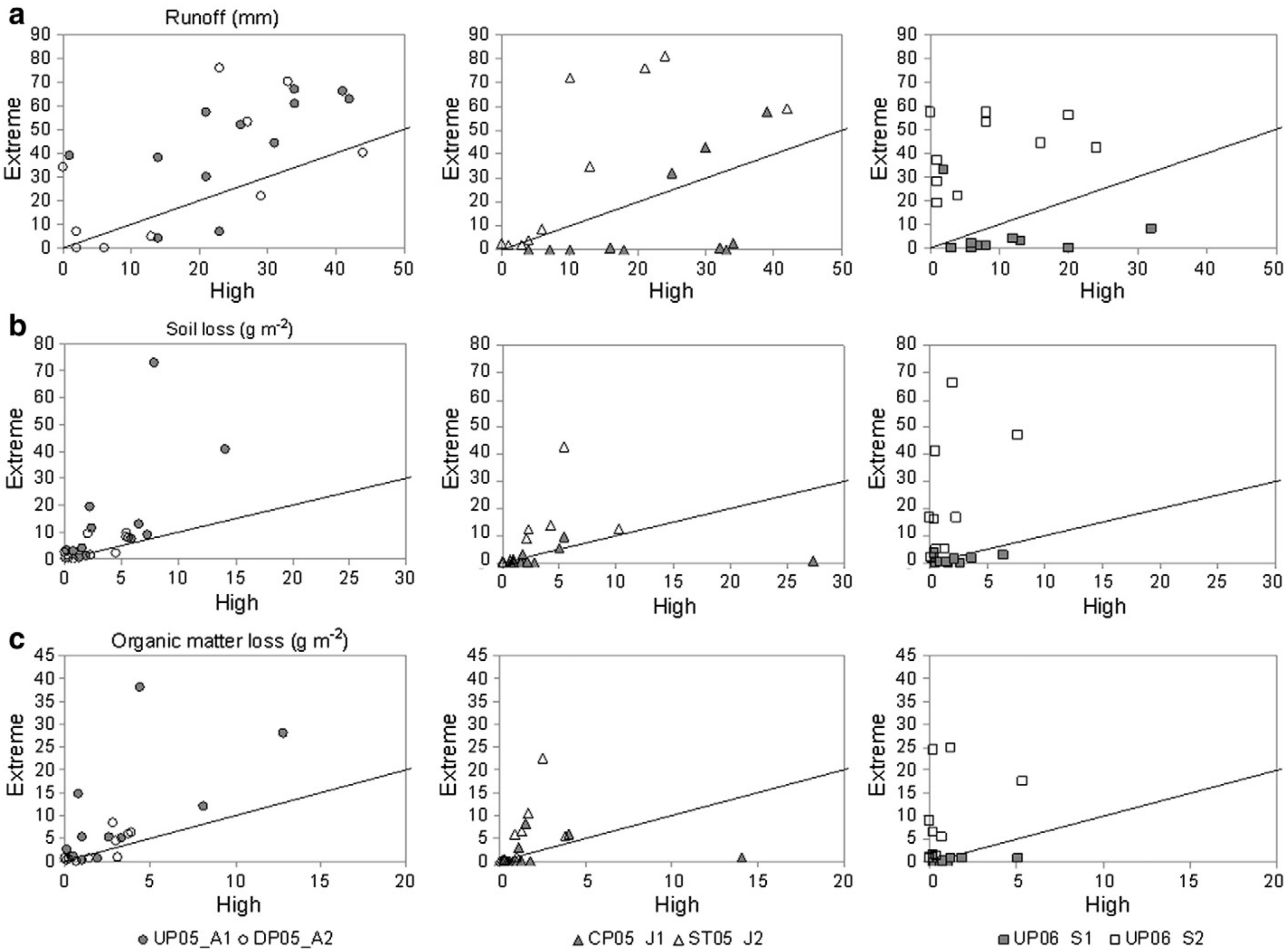

Fig. 3. Scatter plots of runoff, soil and organic matter losses for the pairs of simultaneous, high- and extreme-intensity rainfall simulation experiments at the six study sites (see Table 1 for the site codes). The sites are organized according to the three study locations (left — Açores; middle — Jafafe; right — Soutelo), and the 1:1 line is added to facilitate the appreciation of consistent differences.

little runoff throughout the study period, possibly also due to the plot's marked litter cover (Fig. 4).

Significant differences between the two 2006-burnt sites were restricted to the extreme-intensity RSEs (Table 6). They were consistent for the individual RSEs and their average responses, as well as consistent throughout the first year after fire and not just campaign-specific. They did, however, reflect somewhat deviant behaviour of the extreme-intensity plots at UP06_S1. These plots mostly produced less runoff and erosion than the paired high-intensity plots, due to factors unrelated to vegetation-litter cover (Figs. 4, 5).

3.4. Temporal patterns

Runoff generation and inter-rill erosion at the 2005-burnt sites varied significantly amongst the six field campaigns (Table 7). Significant variation existed in total as well as specific runoff and erosion rates, for the individual RSEs as well as their site-wise mean values, and in terms of overall differences (Kruskal–Wallis test) as well as specific differences between repeated observations (Friedman test). In the case of the 2006-burnt sites, however, significant differences amongst the six campaigns were largely restricted to the erosion rates, the individual RSEs and the repeated observations.

A sharp contrast between the 2005- and 2006-burnt study sites was also evident from the test results for the pairs of consecutive campaigns (Table 7). The 2005-burnt sites revealed significant overall (Mann–Whitney *U*-test) as well as plot-specific (Wilcoxon's signed-ranks test) differences in two instances and these differences concerned basically all parameters. Runoff and erosion rates decreased significantly from the 2nd to the 3rd campaign and increased significantly from the 5th to the 6th campaign (Fig. 6). The 2006-burnt sites also revealed the majority of significant differences in two instances but these differences were plot-specific and especially concerned total losses in soil and organic matter. The plots produced significantly smaller losses in February 2007 than in both December 2006 and May 2007. The increase in erosion rates between February and May 2007 was not restricted to the site that was logged in that period (UP06_S2). Total losses of soil and organic matter of the 132 RSEs were strongly correlated with runoff volumes (Spearman's rank correlation coefficient = 0.93–0.94; $p<0.01$). Further analysis of the above-mentioned significant differences between consecutive campaigns therefore focussed on overland flow generation and, in particular, on the role therein of soil water repellency. Changes in water repellency at the 2005-burnt sites agreed well with both the decrease in runoff between November 2005 and April 2006, and its increase between October 2006 and July 2007. This was true for changes in median repellency levels as well as for changes in the frequency of extreme repellency (ethanol class > 7; Fig. 7). The remarkably low runoff in July 2006, however, fitted in poorly with the very strong median repellency level (ethanol class 7) but not

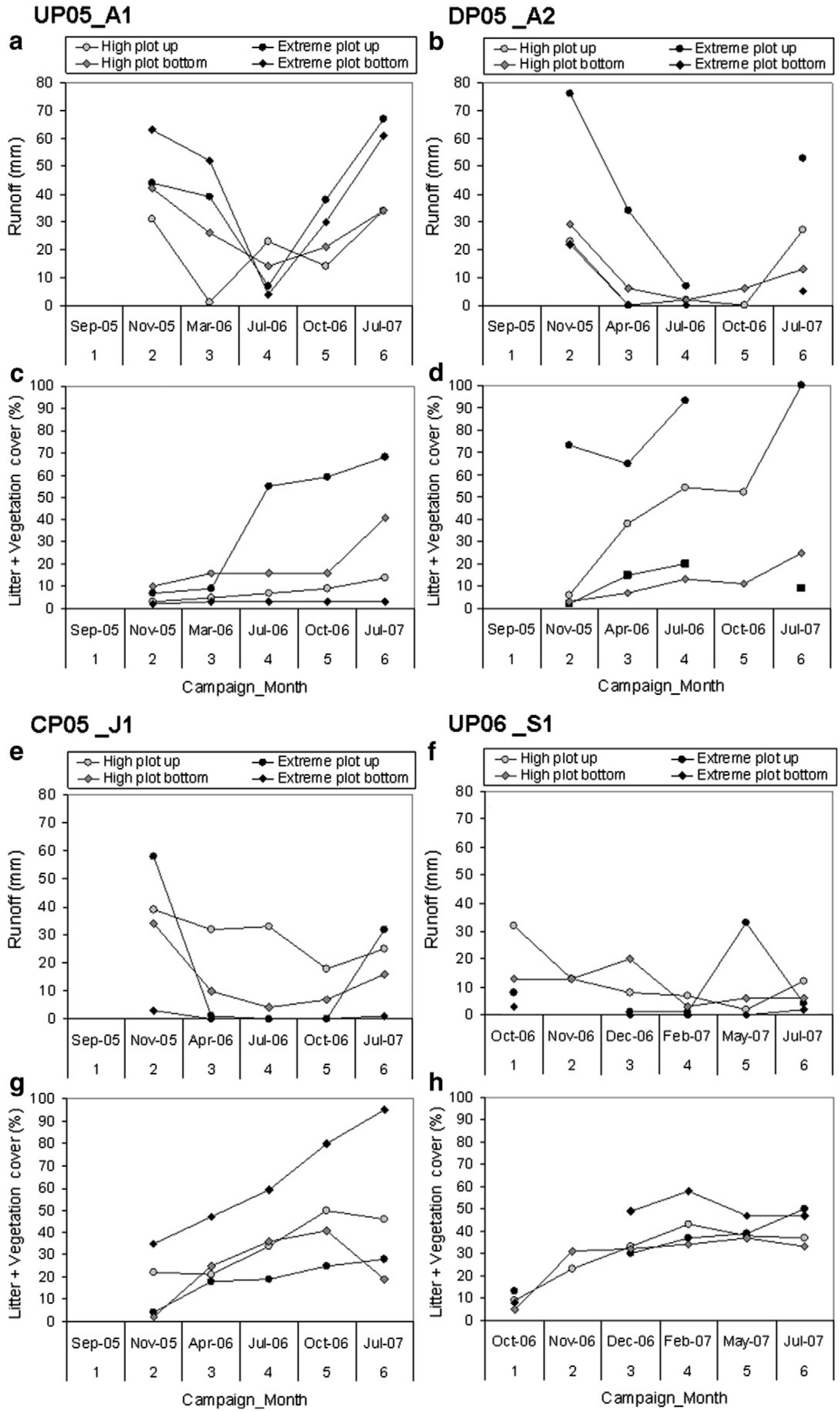

Fig. 4. Runoff produced by the four permanent plots (a, b, e, f) at four selected study sites (see Table 1 for codes) and corresponding total covers of litter and vegetation (c, d, g, h). Not shown are the results for the first field campaign at the 2005-burnt sites (since these plots were sampled and, thus, destroyed immediately after the rainfall simulations), while the missing values due to technical problems are not represented (giving rise to unconnected data points).

Table 5
Statistical comparison of within-site differences in runoff and inter-rill erosion produced by the high-/extreme-intensity rainfall simulation experiments at each of the six study sites (see Table 1 for site codes). Statistically significant differences are indicated with the first letter of the statistical test (Mann–Whitney *U*-test/Wilcoxon signed ranks test), followed by the p-value.

Rainfall intensity	High						Extreme					
Site code	UP05_A1	DP05 _A2	CP05 _J1	ST05_J2	UP06 _S1	UP06 _S2	UP05_A1	DP05 _A2	CP05 _J1	ST05_J2	UP06 _S1	UP06 _S2
Total runoff								W = 0.04			W = 0.04	
Runoff coefficient								W = 0.04			W = 0.04	
Total soil loss						M = 0.04	W = 0.04	W = 0.04			W = 0.04	
Total organic matter loss								W = 0.04			W = 0.04	
Specific soil loss per mm runoff			M = 0.01				W = 0.04					
Specific organic matter per mm runoff												

Table 6
Statistical comparison of between-site differences in runoff and inter-rill erosion produced by the high- and extreme-intensity rainfall simulation experiments, for the 2005- and 2006-burnt sites separately (the sites are indicated with the last two letters of the codes given in Table 1) and for both the individual experiments and their mean values per site. Statistically significant differences are indicated with the first letter of the statistical test (Mann Whitney *U*-test/Wilcoxon signed ranks test), followed by the p-value.

Rainfall intensity	High							Extreme						
Fire	2005						2006	2005						2006
Sites	A1 vs. A2	A1 vs. J1	A1 vs. J2	A2 vs. J1	A2 vs. J2	J1 vs. J2	S1 vs. S2	A1 vs. A2	A1 vs. J1	A1 vs. J2	A2 vs. J1	A2 vs. J2	J1 vs. J2	S1 vs. S2
Mean values														
Total runoff	W = 0.04		M = 0.02/ W = 0.03			M = 0.03/ W = 0.03		W = 0.04	M = 0.03/ W = 0.03					M = 0.01/ W<0.01
Runoff coefficient	W = 0.04		M = 0.02/ W = 0.03			M = 0.03/ W = 0.03		W = 0.04	M = 0.03/ W = 0.03					M = 0.01/ M<0.01
Total soil loss								W = 0.04	M = 0.03/ W = 0.03					M = 0.02/ M<0.01
Total organic matter loss								W = 0.04						M = 0.01/ M<0.01
Specific soil loss per mm runoff														
Specific organic matter per mm runoff														
Individual experiments														
Total runoff	W = 0.03		M<0.01/ W = 0.01	W = 0.03	W = 0.04	M = 0.01/ W<0.01		W = 0.04	M<0.01/ W<0.01		W = 0.03		M = 0.01/ W = 0.03	M<0.01/ W<0.01
Runoff coefficient	W = 0.03		M = 0.01/ W = 0.01	W = 0.04	W = 0.03	M = 0.01/ W<0.01		W = 0.04	M<0.01/ W<0.01		W = 0.03		M = 0.01/ W = 0.03	M<0.01/ W<0.01
Total soil loss	W = 0.01					W = 0.01		W = 0.01	M<0.01/ W = 0.01				M = 0.01/ W = 0.04	M<0.01/ W<0.01
Total organic matter loss					W = 0.01			W = 0.04	M<0.01/ W = 0.03					M<0.01/ W<0.01
Specific soil loss per mm runoff									W<0.01					
Specific organic matter per mm runoff									W = 0.03					

with the low frequency of extreme repellency (0–30%). In the case of the 2006-burnt sites, the significant decrease in runoff between December 2006 and February 2007 seemed unrelated to soil water repellency since the median ethanol class was 0 at both occasions. The subsequent increase in runoff, on the other hand, coincided with a pronounced rise in repellency severity, both in terms of median ethanol classes and frequency of extreme repellency.

The role of the three ground cover classes and the two soil erodibility parameters was tested as well (Table 8). Runoff volumes and total losses could be explained best by differences in litter cover in particular, whereas specific losses were most closely associated to variations in resistance to especially shear stress. Litter covers above 35–40% effectively reduced inter-rill erosion rates (Fig. 8). Contrary to litter cover, ash cover seemed to enhance overland flow generation and the associated losses. The limited role of vegetation cover reflected a slow and spatially heterogeneous post-fire recovery, as well-illustrated by the fact that only 2 out of 24 plots had attained a vegetation cover of over 30% one year after the wildfire.

4. Discussion

4.1. Overall runoff and inter-rill erosion rates

The observed runoff and inter-rill erosion rates suggested that pre-fire ground preparation practices were not a key factor in post-fire erosion risk. This not only applied in relation to down slope ploughing, confirming the findings by Malvar et al. (2011), but also to contour ploughing and the construction of sloping terraces. Specific soil loss rates tended to vary little with either runoff volumes or the two rainfall intensities, suggesting that inter-rill erosion at the six study sites was by and large sediment-limited. Even so, the results at the UP05_A1 and UP06_S2 sites indicated that extreme rainfall events can provoke comparatively high specific soil losses at recently burnt eucalypt plantations with relatively undisturbed soil profiles and, supposedly, greater sediment availability.

Comparison of the overall runoff and erosion rates of this study with those of prior RSE studies was not straightforward, mainly because the

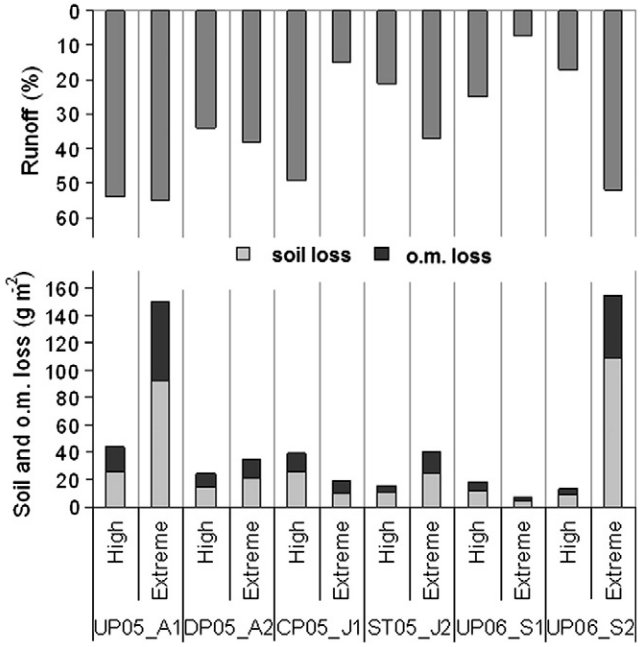

Fig. 5. Runoff coefficients and soil and organic matter (o.m.) losses for the two simulated rainfall intensities, showing the average values of the six study sites (see Table 1 for codes) over the entire study period.

bulk of the prior studies concerned singular moments in time after fire. In the case of Portugal, this was well illustrated by e.g. Coelho et al. (2004), Ferreira et al. (2005a, 2005b), Leighton-Boyce et al. (2007) and Walsh et al. (1998). The overall figures at the Jafafe and Soutelo sites did not differ markedly from those at the Açores sites, confirming the principal points that emerged from the comprehensive comparison with literature in Malvar et al. (2011). They were that, while the observed runoff coefficients were comparable to those from prior RSE studies in recently burnt areas, the specific soil losses were generally lower than those reported earlier, particularly outside Portugal. The elevated organic matter content of the eroded sediments, especially compared to the topsoil, was also confirmed by the Jafafe and Soutelo results. This preferential removal of a mixture of partially combusted plant material, black ashes and charcoal with soil organic matter, was not reported by existing RSE studies, as they typically seemed to lack information on organic matter losses. Thomas et al. (1999) and Fernández et al. (2007), however, also found high organic matter fractions (25–80%) in sediments eroded under natural rainfall conditions from recently burnt pine and eucalypt stands in north-central Portugal and north-west Spain.

4.2. Effects of rainfall intensity

The two rainfall intensities applied in this study had noticeable effects on runoff volumes and inter-rill sediment losses. These effects, however, depended strongly on time-invariant plot- and site-specific properties as well as on changes in soil conditions with time-since-fire. Overall, the role of rainfall intensity was less well-defined at the two ploughed sites than at the other four sites. This could involve a chance factor, reflecting the increased spatial heterogeneity in micro-topographic and/or topsoil characteristics produced by ploughing. Such a random effect was most clearly suggested for the down slope ploughed site (DP05_A2), as the two plot pairs revealed contrasting differences between the two intensities.

Table 7
Statistical comparison of the differences in runoff and inter-rill erosion amongst all six field campaigns as well as between the consecutive campaigns, for the 2005- and 2006-burnt sites separately (the locations and sites are indicated with the penultimate and last two letters, respectively of the codes given in Table 1) and for both the individual experiments and their mean values per site. Statistically significant differences are indicated with the first letter of the statistical test (Kruskal–Wallis/Friedman tests), followed by the p-value.

Mean/individual values	Mean values		Individual simulations							
Fire	2005	2006	2005					2006		
Location/sites	A and J	S1 and S2	A and J	A1	A2	J1	J2	S1 and S2	S1	S2
Total runoff	K<0.01/ F<0.01		K<0.01/ F<0.01	K<0.01/ F=0.01	K=0.02/ F<0.01	F=0.01	K<0.01/ F<0.01			
Runoff coefficient	K<0.01/ F<0.01		K<0.01/ F<0.01	K<0.01/ F<0.01	K=0.01/ F<0.01	F=0.01	K<0.01/ F<0.01			
Total soil loss	K<0.01/ F<0.01		K<0.01/ F<0.01	K=0.01/ F<0.01	K=0.01/ F=0.01	K=0.04/ F=0.01	K<0.01/ F<0.01	F=0.02		
Total organic matter loss	K<0.01/ F<0.01		K<0.01/ F<0.01	K=0.01/ F<0.01	K>0.01/ F=0.01	K=0.02/ F=0.01	K<0.01/ F<0.01	F<0.01	F=0.04	F=0.02
Specific soil loss per mm runoff	K<0.01/ F<0.01		K<0.01/ F<0.01	K=0.01/ F=0.01			K=0.01/ F=0.03	F=0.02	F=0.03	
Specific organic matter per mm runoff	K<0.01/ F<0.01		K<0.01/ F<0.01	K<0.01/ F<0.01		K=0.03/ F=0.04		K=0.01/ F=0.01	K=0.02/ F=0.02	K=0.02
Fire	2005					2006				
Campaigns	1/2	2/3	3/4	4/5	5/6	1/2	2/3	3/4	4/5	5/6
Dates	Sep05– Nov05	Nov05– Apr06	Apr06– Jul06	Jul06– Oct06	Oct06– Jul07	Oct06– Nov06	Nov06– Dec06	Dec06– Feb07	Feb07– May07	May07– Jul07
Total runoff		M=0.02/ W<0.01	W=0.02		M=0.02/ W<0.01			W=0.03		
Runoff coefficient		M<0.01/ W<0.01			M=0.01/ W<0.01			W=0.03		
Total soil loss		M<0.01/ W<0.01	W=0.01		M<0.01/ W<0.01			W=0.01	W=0.04	
Total organic matter loss		M<0.01/ W<0.01			M<0.01/ W<0.01	M=0.04		W=0.03	W=0.03	
Specific soil loss per mm runoff			M=0.02		M<0.01/ W<0.01					
Specific organic matter per mm runoff		M<0.01/ W<0.01			M<0.01/ W<0.01				W=0.04	

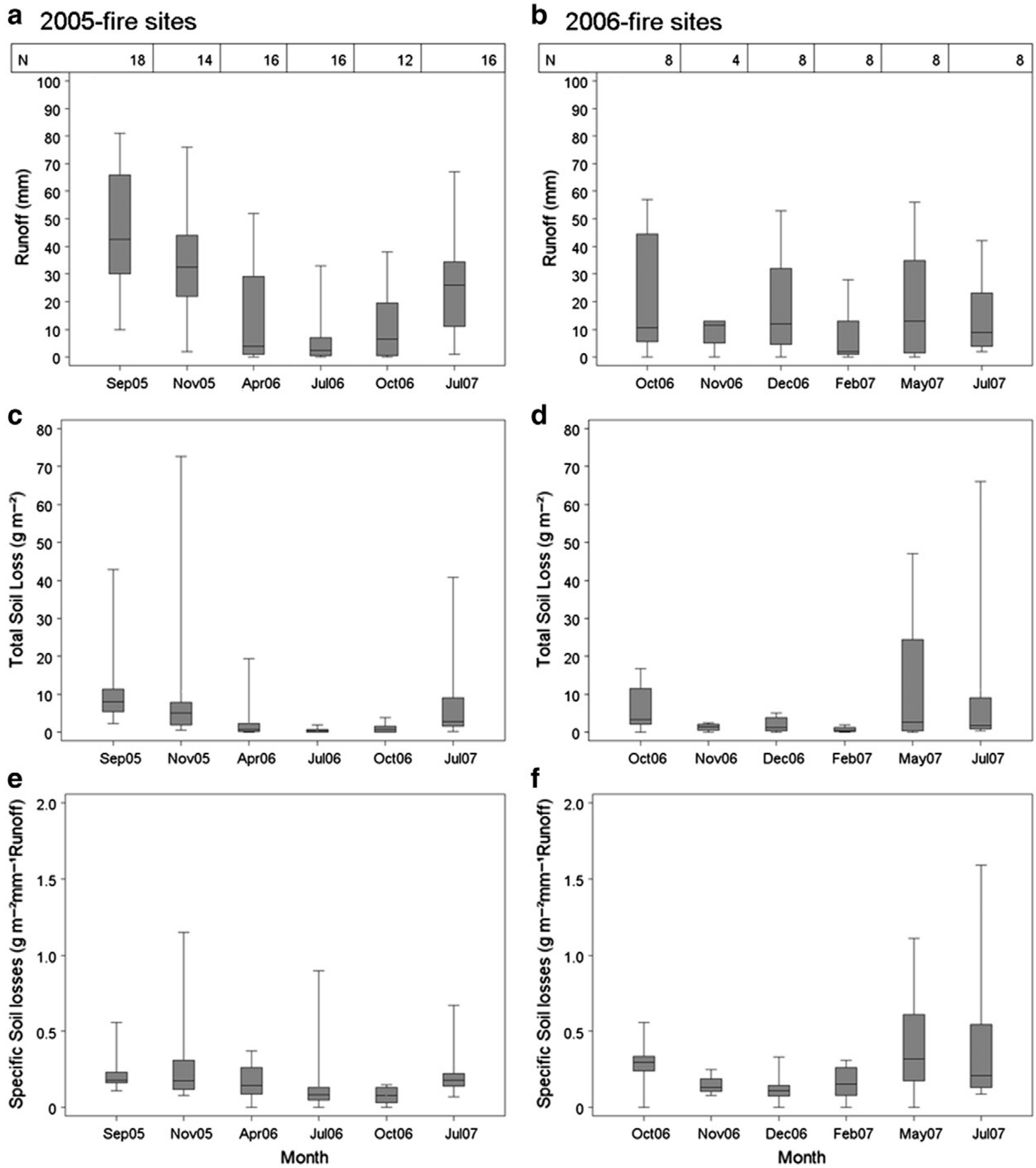

Fig. 6. Box plots of runoff (a, b) and total (c, d) and specific (e, f) soil losses produced by the individual rainfall simulation experiments during the six subsequent field campaigns at the 2005-burnt (left) and 2006-burnt (right) sites.

Runoff and erosion rates have been found to increase with rainfall intensity but not always in a simple manner or in a general sense (Arnaez et al., 2007; Parsons and Stone, 2006; Tejada and Gonzalez, 2007). Thus, although perhaps surprising, the present results were not extraordinary in that the extreme-intensity RSEs produced significantly more overland flow and erosion than the high-intensity RSEs at three study sites and, at the same time, significantly less at another site. There was a tendency for a clearer role of rainfall intensity on erosion than runoff rates, in agreement with RSE studies comparing constant vs. variable application rates s (Dunkerley, 2008; Frauenfeld and Truman, 2004; Parsons and Stone, 2006; Truman et al., 2007).

The complex role of rainfall intensity could be due to an increase in steady-state infiltration rate with increasing rainfall intensity, as found by Hawkings (1982 *in* Paige et al., 2002) Flanagan and Nearing (1995 *in* Paige et al., 2002) and Holden and Burt (2002). The authors attributed such an increase to the phenomenon of "partial area contribution", in which higher rainfall intensities simply produce greater fluxes of infiltration into those plot parts where infiltration capacities exceed the simulated rainfall intensities. This phenomenon could be especially relevant in water repellent soils in recently burnt areas. The ponded hydraulic conductivity of a burnt forest in Australia revealed a very pronounced spatial variability, due to the presence of macro-pores in a soil matrix that was otherwise water repellent (Nyman et al., 2010). Ferreira et al. (2005a) and Shakesby and Doerr (2006) likewise stressed the importance of spatial patterns in infiltration rates, particularly due to soil water repellency, for overland flow

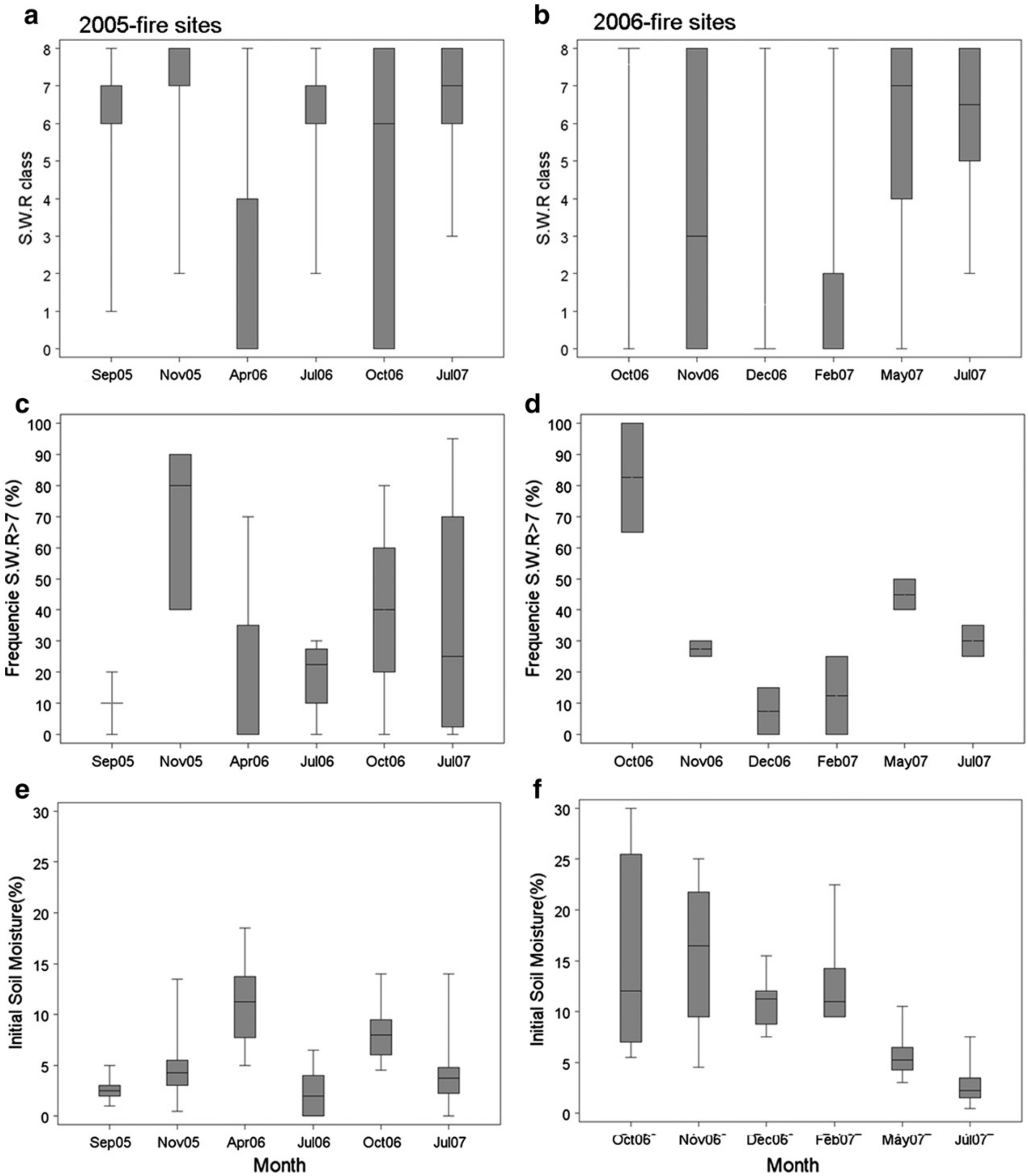

Fig. 7. Box plots of initial soil water repellency in terms of ethanol classes (a, b) and frequency of ethanol class >7 (c, d) as well as initial volumetric soil moisture content (e, f) during the six subsequent field campaigns at the 2005-burnt (left) and 2006-burnt (right) sites.

generation in recently burnt areas. Possibly, technical limitations might have confounded the role of rainfall intensity in at least some of the paired experiments. The extreme-intensity nozzles were more difficult to calibrate than the high-intensity nozzles, especially in terms of the uniformity threshold and in spite of the somewhat limited sensitivity of the Christiansen coefficient (Lascelles et al., 2000). Furthermore, the extreme-intensity nozzles were found to produce less constant soil moisture readings during the field experiments than the high-intensity nozzles, suggesting less constant extreme- than high-intensity application rates.

4.3. Within- and between-site spatial variability

Significant within-site differences between the plots subjected to the same intensities were by and large limited to the extreme-intensity RSEs. Apparently, the typically elevated spatial variability in soil erosion data (e.g. Nearing et al., 1999; Sheridan et al., 2007) was masked by applying 45–50 mm h^{-1} as opposed to 80–85 mm h^{-1}. The observed significant within-site differences proved difficult to explain in terms of individual controlling factors, also because of changing plot characteristics (e.g. vegetation and litter cover) and soil conditions (e.g. water

Table 8
Spearman rank correlation coefficients (ρ) of runoff and inter-rill erosion produced by the individual rainfall simulation experiments with the three ground cover classes and the two soil resistance parameters (n = 132). Only the coefficients that are significantly different from zero at α = 0.05 and 0.01 are shown and marked with one and two asterisks, respectively.

	Litter cover (%)	Vegetation cover (%)	Ash cover (%)	Torvane (kg cm^{-2})	Penetrometer (kg cm^{-2})
Total runoff (mm)	−0.44*	−0.19**	0.22**		
Total soil loss (g m^{-2})	−0.42*		0.22**		
Total organic matter loss (g m^{-2})	−0.45*		0.21**		
Specific soil loss (g m^{-2} mm^{-1} runoff)				−0.31*	
Specific organic matter loss (g m^{-2} mm^{-1} runoff)	−0.23*			−0.20**	

repellency) during the study period. Shakesby and Doerr (2006) likewise argued that the role of soil water repellency in recently burnt areas is difficult to untangle from that of other factors by means of field studies.

The between-site differences sustained Malvar et al.'s (2011) finding that pre-fire ground preparation operations lacked a clear impact on post-fire runoff and inter-rill erosion rates. An obvious explanation was that these operations had occurred sufficiently long ago for runoff and erosion rates to return to the background levels of long undisturbed forest stands. Shakesby et al. (1994) estimated that sediment losses declined rapidly after rip-ploughing, which Walsh et al. (1995) attributed to a rapid increase in soil erodibility through selective removal of the fine soil fraction by the initial erosion events. These sediment losses after rip-ploughing were mainly due to concentrated flow in down slope direction following the furrows. Therefore, the small plot size employed here could help explain the limited impact of ground preparation operations, especially in the case of the down slope ploughed site (DP05_A2).

4.4. Temporal variability with time-since-fire

The timing of the RSEs had a prominent effect on the runoff and inter-rill erosion rates. The joint analysis of the four sites burnt in

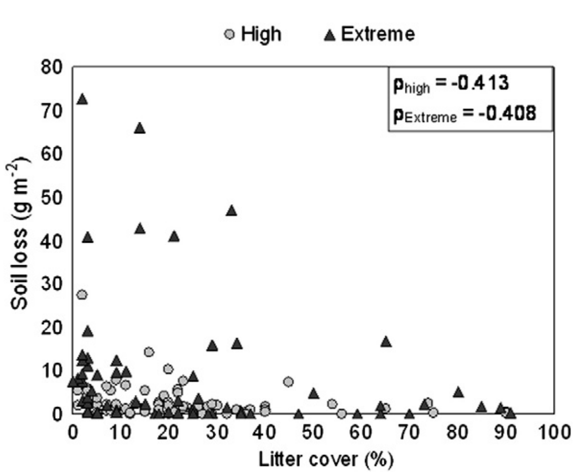

Fig. 8. Scatter plot of litter cover against total soil loss for the individual rainfall simulation experiments, grouped according to the two intensities. The Spearman rank correlation coefficient (ρ_{high}; $\rho_{extreme}$), is significantly different from zero, at α = 0.01, for both simulated intensities.

2005 agreed well with the analysis of two of them (UP05_A1/A2) in Malvar et al. (2011). The contrasting temporal patterns at the 2006-burnt sites could be related to the timing of the RSEs and, in particular, to the wetter antecedent rainfall conditions of the first two campaigns in October and November 2006. The comparatively minor temporal variation in runoff generation at the 2006-burnt sites could furthermore help explain the lack of overall as opposed to plot-specific differences. The shorter, 1- as opposed to 2-year study period at the 2006-burnt sites seemed of little influence; nonetheless, the last two campaigns at the 2005-burnt sites contributed markedly to the significant differences amongst their six campaigns.

In agreement with the two prior studies that also employed repeated RSEs to study post-fire runoff and erosion (Cerdà and Doerr, 2005; Sheridan et al., 2007), the temporal patterns in overland flow generation could not be easily attributed to changes in topsoil water repellency alone. This might be due to the fact that the soil water repellency measurements were destructive and, thus, were not carried out in the RSE plots themselves but in neighbouring plots. On the other hand, descriptors such as median ethanol class or its range might not fully capture the hydrological implications of soil water repellency, especially under heterogeneous repellency conditions.

The temporal patterns in inter-rill erosion rates with time-since-fire were less straightforward than the pronounced decreases reported by Sheridan et al. (2007) and especially Cerdà and Doerr (2005). Thus, the eucalypt plantations studied here did not reveal the marked transition from transport- to sediment-limited erosion typically reported by post-fire erosion studies, including under natural rainfall conditions (see Shakesby, 2011; Shakesby and Doerr, 2006). On the other hand, the present soil loss figures did agree well with the tendency for low erosion rates in the Mediterranean region due to its long land-use history (Shakesby, 2011). The elevated surface stone cover that emerged as the ash layer was removed from the study sites together with the mostly shallow soil depth fitted in with an intensive use of the study sites in the past.

Although post-fire forestry operations and in particular logging were commonly observed in the study areas, they only took place at one of the six study sites. After logging and wood extraction, three of the four plots of the UP06_S2 site revealed an increased runoff and inter-rill erosion. This logging effect could be attributed to a marked decrease in litter cover at all three plots. The litter cover also decreased at the fourth, “exceptional” plot but this was “compensated” by an exceptional increase in vegetation cover, attaining 70%. These results fitted in well with the findings of Fernández et al. (2007) that logging operations did not seriously affect soil erosion, except where they resulted in significant exposure of bare soil.

5. Conclusions

The principal conclusions of this study into post-fire runoff and inter-rill erosion in six recently burnt eucalypt plantations in north-central Portugal by means of repeated, high and extreme-intensity field rainfall simulation experiments (RSEs) were as follows:

(i) Erosion rates depended strongly on runoff volumes but seemed essentially sediment-limited. Namely, sediment losses were markedly lower than in prior RSE studies in the study region but especially outside Portugal, and did not reveal the commonly observed, sharp decrease with time-since-fire;
(ii) Mechanical ground preparation operations carried out several years before the latest wildfire did not have major impacts on post-fire runoff and erosion rates. There were no striking differences between the three practices, despite contour-ploughing and terracing being commonly regarded as soil conservation techniques as opposed to ploughing in down slope direction. Furthermore, the terraced and the two ploughed plantations

revealed intermediate sediment losses compared to the three unploughed plantations;

(iii) Unlike the pre-fire practices, post-fire logging and wood extraction seemed to increase sediment losses substantially. However, further work on the effect of logging is needed as the present evidence was based on a single study site;

(iv) There was an overall tendency for extreme-intensity RSEs (80–85 mm h^{-1}) to produce significantly more runoff and greater soil and organic matter losses than their paired high-intensity RSEs (45–50 mm h^{-1}). Nonetheless, the role of rainfall intensity was unexpected in that it differed markedly amongst the six study sites as well as between the two plot pairs at some sites. This and especially the lack of obvious explanations for the deviant results seriously hampered a consistent ranking of the six study sites in terms of post-fire erosion risk.

Acknowledgements

The present study was funded by the Foundation for Science and Technology (FCT) of Portugal, with co-funding by FEDER through the POCI2010 Programme, in the framework of the EROSFIRE project (POCI/AGR/60354/2004) and research grants of MMC (SFRH/BD/41320/2007) and JPCN (SFRH/BPD/39721/2007). Also, this manuscript greatly profited from the lengthy discussions with Artemi Cerdà on field rainfall simulation experiments and his simulator in particular, which were made possible by the Luso-Spanish Integrated Action E-76/09 funded by the Council of Rectors of the Portuguese Universities and the Spanish Ministry of Economy and Competitiveness. We further gratefully acknowledge the help of: Raquel Ferreira, Mart Houmann, Mark Lagewaard, Angela García-Monge, David Herrera, Ana Sofia Santos and Marifé Varela with field data collection and/or laboratory analysis of runoff and soil samples; Virgínia M.F.G. Pereira for the soil profile descriptions; Jorge Lucena, Carmen Magalhães, and Joaquim Sande Silva for part of the soil laboratory analyses. We finally wish to thank two anonymous referees for their useful comments and suggestion to improve this manuscript.

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Chapter 4: Overland flow and inter-rill erosion under natural rainfall in two recently burnt eucalypt plantations in north-central Portugal

Overland flow and inter-rill erosion under natural rainfall in two recently burnt eucalypt plantations in north-central Portugal

Maruxa C. Malvar*, Sergio A. Prats, Jan J. Keizer

Centro de Estudos do Ambiente e do Mar (CESAM), Departamento de Ambiente e Ordenamento, Universidade de Aveiro, 3810-193 Aveiro, Portugal.

* corresponding author: Maruxa Malvar Cortizo; Centro de Estudos do Ambiente e do Mar (CESAM), Departamento de Ambiente e Ordenamento, Universidade de Aveiro, 3810-193 Aveiro, Portugal; tel.: +351234370200; FAX: +351234370309; e-mail: maruxa@ua.pt

Abstract

Increases in runoff and erosion have been reported during the first post-fire year in eucalypt plantations of north-central Portugal, but little information is available about the effect of slightly longer time intervals as well as pre-fire management practices. Eight micro-plots (0.28 m^2) were installed at two adjacent eucalypt stands representing typical management activities in the region, i.e. unploughed vs. down-slope rip-ploughed several years before the 2005-fire studied here, and runoff and erosion measured weekly during two post-fire years. In order to assess some key factors controlling the hydrological and erosive response, an intensive monitoring (two-weekly) of selected soil properties was carried out.

Rainfall was 35% higher during the second than first year following the fire, but the runoff coefficient was around 20% for both sites and study years. By contrast, overall sediment losses differed significantly between the unploughed and the ploughed site during the first post-fire year (415 vs. 125 g m^{-2} $year^{-1}$), and even more during the second one (515 vs. 54 g m^{-2} $year^{-1}$). The organic matter fraction of the eroded sediment amounted to ca. 50 % throughout the study period. Time since fire played a role in runoff and erosion; however, post-fire runoff and erosion did not decrease gradually in the course of the study but revealed a marked seasonal component, with clear peaks surrounding the driest seasons.

Runoff generation could be explained best by rainfall amount or maximum rainfall intensity during fifteen minutes (I_{15}) and then by surface cover and soil water repellency. Maximum rainfall intensity substituted rainfall amount as main factor when a protective surface cover was attained or when soils were wettable. The sediment losses were explained best by I_{15} followed by surface cover.

Post-fire runoff and erosion at the study sites was also studied by repeated rainfall simulation experiences (RSE's). Comparison of the results obtained under natural and simulated rainfall suggested that the RSE's captured well the specific sediment loss rates, the organic matter contents of the eroded sediments, and erosion rates differences between sites. The important role of soil water repellency in post-fire runoff generation in eucalypt stands was also evident from both methodologies

Key words: wildfire, eucalypt, (un)ploughed, micro-plot, runoff, erosion, rainfall simulation,

1. Introduction

In Portugal, the introduction of flammable tree species (pine and eucalypt plantations), together with a decline in traditional practices (grazing, coppicing, etc) generated a fire prone forest formation, which begun to suffer an increase in wildfire frequency since the 1980s (Shakesby *et al*., 1996). Furthermore, the frequency of forest fires is expected to remain the same or increase in the future (Pereira *et al*., 2006). Especially since the severe fire seasons of 2003 and 2005 (during both of which over 300.000 ha burnt; AFN, 2011), forest fires are now an important public concern in Portugal (Ferreira *et al*., 2008).

Wildfires constitute a disturbance with a relatively severe but temporary impact (Cerdà and Doerr, 2005). Fires can reduce soil infiltration capacity and, consequently, increase runoff and erosion (Spigel and Robichaud, 2007; Cerdà and Robichaud, 2009; Scott *et al.,* 2009), thereby provoking on-site land degradation impacts such as soil fertility losses (Thomas *et al*., 1999; Verheijen *et al*., 2009), soil organic matter/carbon losses (Spigel and Robichaud, 2007; Prats et al., 2012) as well as downstream pollution with, for example, pyrolitic toxic compounds (Vila-Escalé *et al*., 2007; Campos *et al*. 2012).

Large increases in runoff and erosion following wildfires have also been reported for the two principal forest types in north-central Portugal, i.e. maritime pine and eucalypt plantations (e.g. Shakesby *et al*., 1994; Ferreira *et al*., 1997; Coelho *et al*., 2004). These prior studies commonly observed a pronounced temporal variability in post-fire runoff and erosion, associated to inter and intra-annual rainfall variability as well as post-fire vegetation recovery (Shakesby *et al*., 1993; 1994, 1996). An important role in the seasonal variations in erosion has frequently been attributed to soil water repellency (Ferreira *et al*., 2000; Coelho *et al*., 2004; Leighton-Boyce *et al*., 2007; Malvar *et al*., 2011; Prats *et al*., 2012). This is especially the case for the eucalypt plantations in this region, as both long unburnt and recently burnt stands are typically associated with very high to extreme hydrophobicity (e.g. Doerr *et al*. 1998, 2003, 2006; Keizer *et al*., 2005a, 2005b; 2008; Malvar *et al*., 2011; Prats *et al*., 2012). These factors limit the establishments of links between post-fire disturbances and enhanced runoff and erosions rates.

The most commonly-used techniques to quantify post-fire runoff and erosion are rainfall simulation experiments (RSE's) (e.g. Sevink *et al*., 1989; Imeson *et al*., 1992; Kutiel *et al*., 1995; Benavides-Solorio and MacDonald, 2001; Johansen *et al*., 2001; Cerdà and Doerr, 2005; Coelho *et al*., 2005; Ferreira *et al*., 2005a; Rulli *et al*., 2006; Leighton-Boyce *et al*., 2007; Sheridan *et al*., 2007) and runoff-erosion plots of various dimensions (e. g. Blong *et al*. 1982; Díaz -Fierros *et al*.1987; Soto *et al*. 1994; Shakesby *et al*. 1996; Soto and Díaz-Fierros, 1998; Ferreira *et al*., 2000; Dragovich and Morris, 2002). RSE's have the advantages of producing repeatable rainfall events and, and being more time and cost-effective but, at the same time, have the disadvantage of producing artificial rainfall events that, in general, have a constant intensity, a low kinetic energy and fall onto small surface areas (e.g. Rickson, 2001). The representativeness of RSE results for post-fire runoff and erosion under natural rainfall condition constitutes an important research gap, since few studies have made a comprehensive comparison of RSE- vs. plot-based runoff and erosion values. To address this knowledge gap, the present, plot-based study concerns the same two sites as where Malvar et al. (2011) carried out RSE's at six occasions during the first two years after a wildfire.

The main goal of this research was to assess the role of management practices in post-fire runoff and erosion in eucalyptus plantations in north-central Portugal. To this end, overland flow generation and the associated losses of soil and organic matter were compared for two contrasting eucalypt plantations, one of which had been ploughed before the wildfire whereas the other had not. This was done using micro-plots of the same dimensions as those used by Malvar et al. (2011) for repeated RSE's at the same two sites. The specific objectives of this study were to: (i) determine the between-site variability in runoff and erosion; (ii) assess the temporal patterns in runoff and erosion with time since fire; (iii) identify the key factors explaining the spatial and temporal runoff and erosion patterns; (iv) compare the runoff and erosion rates produced under natural rainfall conditions with those produced by artificial events of high and extreme intensity (45-50 vs. 80-85 mm h-1).

2. Materials and methods

2.1 Study sites

This study was conducted near the Açores locality of the Albergaria-a-Velha municipality, north-central Portugal, in an area that was burned by a wildfire during early July 2005. Two adjacent commercial eucalypt (*Eucalyptus globulus* Ait.) plantations were selected for their contrasting pre-fire land management practices, both which are commonly found in the study region. At the "unploughed" site, trees had been planted without mechanical ground operations, so that the soil profile was undisturbed. At the "rip-ploughed" site, a clear pattern of ridges and furrows (up to 20 cm high) running down the slope was present. Judging by the remaining tree stumps, both study sites had undergone at least two eucalypt regrowth cycles prior to the 2005-fire. Both sites has steep slopes but were relatively short, due to extensive network of paths in the area (Table 1). The 2005-fire had burnt the two sites with moderate severity, according to simple field indicators such as the consumption of tree canopies, the undergrowth and litter layer as well as the colour of the ashes (Shakesby and Doerr, 2006; Table 1). The soils at both sites were described by digging two soil profiles (at the base and halfway the slope) and collecting various samples. The soil samples collected at 0-5 cm depth were analysed in the laboratory with respect to bulk density (Porta *et al.,* 2003), soil texture (Guitian and Carballas, 1976) and organic matter content (Botelho da Costa, 2004). The soil profiles corresponded to *Umbric Leptosols* (WRB, 2006) that were developed from pre-Ordovician schists of the Hesperic Massif (Ferreira and de Brum, 1978; Pereira and FitzPatrick, 1995). The top 5 cm of the soils had a coarse texture, varying between sandy clay loam to clay loam, with an organic matter content of 10% (Table 1).

The climate at the study sites is Mediterranean and has an oceanic influence. It can be classified as humid meso-thermal with prolonged dry and warm summers (Csb, according to Köppen; DRA-Centro, 2001). The long-term mean annual temperature at the nearest climate station ("Estarreja", 17.5 km north-west of the study sites)was 13.9 ºC, with monthly mean temperatures ranging from 8.8 °C in December to 19.1 °C in July (reference: 1956-1977). The long-term mean annual rainfall at the nearest rainfall station (“Albergaria-a-Velha”, 4 km north of the study sites) was 1229 mm but annual rainfall varied markedly from 750 to 2022 mm (reference: 1941-1991).

2.2 Experimental design

Each site was instrumented with two pairs of square micro-plots (0.28 m^2) installed halfway in the lower and upper sections of the slope. Erosion episodes from a few rainfall events (up to 80 mm) occurred between the fire and the installation of the plots. Afterwards, during a period of 22 months, including 83 field trips, data was collected on runoff, soil erosion and several explanatory variables.

Rainfall was measured with a tipping-bucket rainfall gauge (Pronamic Professional Rain Gauge, Ringkøbing, Denmark). Surface runoff was accumulated and measured in tanks, weekly 1.5 l runoff samples were taken for laboratory determinations, which included sediments concentration, following the classical evaporation method (APHA, 1998) and organic matter fraction on the eroded sediments following the loss-on-ignition method (Botelho da Costa, 2004). Plot surface cover was described every two weeks by recording the presence–absence of five cover categories in each of the 5 cm × 5 cm cells of a grid (50 cm x 60 cm) laid out over the plot. The described cover categories were: stones (including rock outcrop and stones higher than 2 mm diameter), bare soil, litter (including all dead plant materials such as leaves, bark, stems, etc.), vegetation and ashes. Every two weeks, one transect of five (or three, from June 2006 onwards) equidistant sampling points along the slope length was selected to measure several soil properties. At each sampling point, the resistance of the soil surface to shear stress and penetration was measured three times using a pocket vane tester and a penetrometer. At the same spot, three soil water repellency (SWR) measurements were done in situ at the soil surface and between 2–3 and 7–8 cm depth. This was done using the “Molarity of Ethanol Droplet” (MED) test (Doerr (1998), Keizer *et al*. 2005a, 2005b, 2008). Three droplets of increasing ethanol concentration classes (decreasing surface tension) (0, 0%; 1, 1%; 2, 3%; 3, 5%; 4, 8.5%; 5, 13%; 6, 18%; 7, 24%; and 8, 36% or >36%) were applied to undisturbed parts of the soil until infiltration of at least two of three droplets of the same concentration had occurred within 5 s. Following the repellency measurements, at the same sampling points and depths, readings of volumetric soil moisture content were done (ML2 Theta Probe TM; Delta T-Devices Ltd, Cambridge, UK), (see Keizer *et al*. (2008) for further details). The random roughness of the plots was also determined, using a pin profile meter. This was done by placing the device at three fixed positions within each plot (at one, two and three quarters along the plot's length) (Table 1).

2.3 Data analysis

Rainfall amount, maximum rainfall intensity in 15 minutes (I_{15}), rainfall kinetic energy (KE), erosivity (R) (Wischmeier and Smith, 1978), and total event intensity were calculated on rainfall event basis. Events were separated by periods of at least 6 h with no precipitation. When multiple rainfall events occurred in a period between the weekly runoff and erosion measurements, total rainfall amount and erosivity, maximum I_{15}, maximum KE and maximum of total event intensity were the rainfall characteristics associated to the measured runoff and sediment. SWR measurements in ethanol class, at soil surface and 2-3 cm depth, were used to calculate the median ethanol concentration, the frequency of strong (SWR> 5 ethanol class; Freq5), very strong (SWR> 6 ethanol class) and extreme repellency (SWR> 7 ethanol class).

Data analysis was carried out using the SAS 9.2 software package (SAS Institute, Inc., 2008). The significance level for all the statistical tests was 0.05. Repeated measures analysis (ANOVA-2 way) was performed in order to determine the site and time influence on runoff and erosion measurements, with the plot as subject of repeated measured. The time factors tested were the annual and monthly values. When the overall effect was significant, a post-hoc LS-Means adjusted Tukey's test was used to assess in which periods the sites produced significantly different runoff and erosion values (Littel *et al*., 2006). In order to fit the normality assumption, the total runoff was log-transformed and square root transformation was used for the runoff coefficient, the erosion variables were fourth root transformed and the organic matter content was not transformed. The variance-covariance structure for the dependent variables was selected according to the smaller -2 restricted log likelihood (Littel *et al*., 2006).

Forward stepwise regression analysis was used to determine the influence on the weekly runoff and erosion measurements of the following 16 explanatory variables: (i) Related with rainfall: rainfall amount, rainfall Kinetic energy, erosivity, I_{15}, event intensity and antecedent rainfall; (ii) Related with soil water repellency: frequency of strong, very strong and extreme repellency; (iii) Related with soil: soil moisture, soil resistance to shear stress and penetration; (iv) Related with plot: position (top, bottom), slope angle, plot roughness and plot surface cover (ash, bare, litter, stone, vegetation). Collinearity diagnostics was used to determine the explanatory variables which were related, removing those with condition index higher than 10 (Belsley *et al.*, 1980). To better achieve the normality of the model residuals, periods with rainfall less than 10 mm and therefore runoff less than 4 mm were removed.

The differences between sites of the explanatory variables, including plot basis (surface cover) and transect basis measurements (soil moisture, soil water repellency and soil resistance), were tested through Mann-Whitney *U*-test (MWU-t) and Wilcoxon's signed-ranks test (WSR-T).

3. Results

3.1 Annual rainfall, runoff and erosion rates.

Table 2 summarizes the annual rainfall, runoff and erosion rates measured in the micro-plots. Rainfall volume was 35% higher during the second than from the first study year (1048 vs. 1608 mm). Compared to the long-term mean annual rainfall (1229 mm), the rainfall amount on the first post-fire year was 15% lower whereas on the second year it was 30% above. I_{15} was also higher during the second year, and consequently, the rainfall erosivity of the second study year was twice that of the first one (3115 vs. 1412 MJ mm ha^{-1} h^{-1}).

Following the increase in rainfall amount, the average runoff amount also increased from year 1 (228 mm) to year 2 (368 mm, 40% increase), but this was more pronounced in the case of the unploughed site (426 mm, 47% increase) when compared to the ploughed site (310 mm, 26% increase). The analysis of variance (Table 2) revealed that there was a significant difference in runoff between the two post-fire years ($F=8.84$; $p<0.05$), but not between the two sites ($F=5.40$; $p>0.05$). However, year-to-year differences were only significant in terms of runoff amount. In fact, the runoff coefficient was about 20% for both sites and post-fire years. Opposite from the runoff results, erosion variables did not follow variations in annual rainfall. Sediment losses were equal for post-fire year 1 and 2 (averaging 270 vs. 284 g m^{-2}), while specific sediment losses were significantly higher in year 1 than year 2 (averaging 1.18 vs. 0.68 g m^{-2} mm^{-1} runoff). Despite the similar runoff patterns between sites, there was a strong site effect on the erosion response (Table 2). The sediment losses as well as specific rates were significantly higher in the unploughed than in the ploughed site, probably due to lower sediment availability at the ploughed site. However, time (annual) effect over erosion was not consistent between sites and also between total and specific sediment rates. The sediment losses increased from the first year to the second in the unploughed site but decreased in the ploughed site. This also led to an increase in the differences in sediment losses between sites with time. Nevertheless, lower sediment availability on the second year was indicated by a significantly reduction in specific sediment rate for both sites. Finally, the organic matter fraction was roughly half of the eroded sediments, with an increasing trend with year since fire but no significant differences between sites.

The annual runoff and erosion values by plot pointed out that erosion was rather sediment than transported limited, as sediment transport did not simple increased with runoff amounts, especially on the second year (Figure 1). In the unploughed site, both runoff and sediment losses increased similarly for all the plots between year 1 and 2 (Figure 1a). In the ploughed site, runoff increased from year 1 to year 2 in all the plots but decreased in plot 8, whereas sediment losses decreased in all but plot 6. Despite these inconsistent plot patterns, the specific sediment losses invariably decreased between year 1 and 2 (Figure 1b).

The plot variability within-site in terms of runoff, but mainly in the erosion response was consistently higher in the first than in the second post-fire year, and in the ploughed compared to the unploughed site (coefficient of variation of sediment losses 87 and 19% respectively). Probably as consequence of the increasing in specific-plot characteristics variability by the ploughing (see Table 1).

3.2 Temporal patterns

3.2.1. Temporal patterns of surface cover, soil water repellency and soil moisture

The surface cover evolved following the washing up of the ashes, the subsequent exposure of a stone lag, and the development of a vegetation and litter. Ash cover decreased as the other categories increased (Figure 2). Besides these similarities, there were differences between sites. Litter fall from burned eucalypt trees and vegetation regrowth was lower in the unploughed compared to the ploughed site. Conversely, stone cover was higher in the unploughed site. Those differences were statistically significant globally (MW U-test) and also temporally specific (Wilcoxon's S–R test) (Table 3). For example one year after the fire, the mean litter plus vegetation cover in the unploughed site was 25% whereas in the ploughed site was 50%. At the same time, stone cover in the unploughed site was about 40% and 18% in the ploughed site. Additionally, bare soil was lower than 5% for both sites during all the study period. Furthermore, the within-site variability of plot surface cover also increased progressively with time since fire, as surface cover evolved.

In both sites, the overall soil water repellency of the near surface measurements was dominated throughout the 22 months post-fire study period by a very strong severity level (median ethanol class 7; depth 2-3 cm). Consequently, the median frequency of strong soil water repellency (SWR > 5 ethanol class) was around 65%. At the same time, the volumetric soil moisture medians were also similar (7% at 2-3 cm depth). Although overall soil moisture and water repellency levels were the same for both sites, spatial variability between sites occurred, but it was irregular in time and poorly related to overall values. In spite of the overall predominance of very strong repellency levels, non-repellent conditions also occurred, mainly after rainfall periods, when higher soil moisture was also recorded (Figure 3). During the first post-fire year, the ploughed site registered more frequent hydrophobic conditions than the unploughed site (percentile 25 was 6 vs. 3 ethanol class, respectively). However, during the second post-fire year, the ploughed site registered less hydrophobic conditions than the unploughed (percentile 25 was 0 vs. 4 ethanol class, respectively). Hence, statistically significant differences between the sites' soil water repellency variables were not found, besides some caution is required in the Wilcoxon's S–R test results analysis because the sites' sampling dates were not the same (Table 3).

3.2.2. Temporal patterns of rainfall, runoff and erosion rates

Over the 22 months there were registered 254 rainfall events monitored in 72 weekly periods. Those events produced runoff in 65 weeks and sediments in 54 weeks at the unploughed site, whereas at the ploughed site they produced 59 weeks with runoff and 48 with sediments.

Rainfall amount and intensity presented a marked seasonal component in both studied years. Even so, rainfall amount, intensity and their seasonal and monthly variations were higher in the second year (Figure 4a), especially during the autumn where the highest rainfall volumes (around 300 mm per month) were measured and the I_{15} increased from the common maximum value of about 20 mm h^{-1} until 40-70 mm h^{-1}.

Time since fire (month) was a significant factor for all the studied variables whereas site differences were significant for all variables but organic matter fraction (Table 4). However, the runoff variables were more affected by time, whereas the erosion variables showed a stronger site effect judging by the highest F values. Still, the significant interaction (site*month since fire) indicated that the site differences on runoff and erosion were not significant for all the months. The temporal trend in runoff and sediment production was not a simple decline with time since fire. Both runoff and erosion registered a high seasonal and monthly variation, with several peaks observed one and two years after the fire related with rainfall variations and SWR conditions (Figure 4 and Figure 5). Following the highest rainfall amounts, runoff amount was higher also during both autumn seasons. Similarly, runoff coefficient peaks were higher in the first autumn but not during the second autumn. On the other hand, in the first summer high runoff coefficient peaks occurred with low rainfall and runoff amount. These discrepancies between the peaks reached by runoff amount and coefficient coincided with extreme rainfall conditions (high and low), and therefore with either very strong soil water repellency or non repellent situations. During the wetter second autumn, the high rainfall amount (897 mm) generated a high total overland flow (averaging 130 mm) but the percentage converted to runoff (14%) was no higher than in other periods. In contrast, in the driest months of the first summer, rainfall (60 mm) and runoff amount (averaging 25 mm) were the lowest measured but the runoff coefficient (45%) was higher than in the other periods. The SWR effect was also evident during the first rainfall storms after dry periods, when soil moisture was about 5% (see Figure 3). The highest monthly runoff coefficient (50-60%) of October-05, September-06 and June-07 coincided with mean extreme soil water repellency level (8 ethanol class) and frequency of strong soil water repellency between 70-100%.

Additionally, significant differences in overland flow generation between sites coincided with differences between sites in soil water repellency levels. The analysis with LS-means differences, identified the runoff response in the unploughed site significantly higher mainly during the second winter and spring (from January 2007 throughout May 2007; Figure 4). At the same time, over that period, median repellency levels and the frequency of strong soil water repellency were higher in unploughed site even when the soil moisture was lower (see Figure 3).

Total as well as specific sediment losses were significantly higher at the unploughed compared to the ploughed site, except for a small period when the erosion was low and therefore the differences between sites were not significant (Table 4; LS-means, Figure 5). Both erosion variables were significantly affected by time since fire, but not in a unique way. On one hand, the time effect was greater for absolute values than for specific rates (Table 4). On the other hand, sediment rates peaks were a follow-up of runoff generation whereas in the case of specific sediment rate, they also coincided with runoff coefficient peaks in the dry seasons as in the first summer. Although annual specific sediment losses indicated a significantly reduction in specific rates from the first to the second year in both sites, the monthly values showed that peaks as high as in the first post-fire autumn happened in the second autumn (Figure 5).

3.3 Relationship of runoff and erosion with key explanatory variables:

The multiple regression model results revealed that the set of used independent variables accounted for 50% of variation in (log-transformed) runoff generation (Table 5). Rainfall amount was the main factor explaining 27% variation, the influence of SWR was reflected in the importance of the frequency of strong soil water repellency variable (Freq5; explaining 10% of runoff variation) and in the negative sign of the antecedent rainfall parameter estimate. The water retention capacity of litter and ash cover variables was represented by their negative parameter estimates and explained around 10% of runoff variation. The ploughed site regression analysis exhibited different covariates compared to the general and the unploughed site model, showing I_{15} as the main factor explaining 28% of runoff variation. Also in this site, the soil water repellency influence was slightly higher than in the unploughed site (12% vs. 7%), (Table 5). The differences in ground cover between sites were reflected in the site specific models; while the ash cover influence was higher in the unploughed site, the litter effect was only visible in the ploughed site.

The I_{15} followed for cover related variables accounted for 30-50% variation in (fourth root) sediment losses (Table 5). Ground cover differences between sites were represented by the different importance of I_{15} and the cover related variables in the sites specific model. The lower model performance at the ploughed compared to the unploughed site (R^2 0.45 vs. 0.57) may have caused by higher within-site variability on erosion rates, lower rates and a worse relationship between sediment losses and I_{15} at the ploughed site (Figure 6a). In both sites, plots summing more than 70% of litter and vegetation cover hardly had high sediment rates (Figure 6b). The relationship of sediment losses with runoff generation was represented by the effect of some runoff related variables as soil moisture and Freq5. The effect of hydrophobicity in the ploughed site was higher and represented by the influence of Freq5 (13%) on the sediment losses variation.

Since the Freq5 was a variable present in the runoff and sediment regression models, the data was divided in categories according to its frequency (SWR1=Freq5≤32; SWR2=32<Freq5<66; SWR3= Freq5≥66). The regression analysis was done for those categories individually to better evaluate the soil water repellency influence (Table 5). A shift in the first variable to explain runoff generation from I_{15} to rainfall amount was detected as the soil water repellency increased. So, in the lowest soil water repellency category, I_{15} was the main factor explaining 35% of runoff variation. For the most repellent conditions, rainfall amount explained 45% and 27% of runoff generation. At the same time, the influence of the cover variables with retention capacity (litter + ash) diminished with the increase in soil water repellency conditions.

4. Discussion

4.1. Overall runoff and erosion rates

Relatively few reports exist concerning post-fire runoff and inter-rill erosion in commercial eucalypt plantations. Comparison of this study results with other research in Portugal revealed that the first post-fire year runoff (22%) was similar to that of Prats *et al*. (2012) (30%), both of which were higher than the range registered by Shakesby *et al*. (1996) (4-16%). In terms of specific rates, the unploughed site rate (0.4 g $m^{-2}mm^{-1}$ rain) was similar to the one recorded by Prats *et al*. (2012) (0.33 g $m^{-2}mm^{-1}$ rain), both of which were comparable to the maximum values recorded by Shakesby *et al*. (1996) (0.07-0.34 g $m^{-2}mm^{-1}$ rain), while the ploughed site rate (0.12 g $m^{-2}mm^{-1}$ rain) was comparable to their minimum values. The lower rainfall amounts in Shakesby *et al*. (1996) (645 mm), compared to Prats *et al*. (2012) (1684 mm) and this study (1048 mm) are probable related with those differences between studies. Also the latter studies used bigger plots (16m^2) and generally, a reduction in runoff and erosion is expected as the contributing area increases (Le Bissonais *et al*., 1998; Bagarello and Ferro, 2004; Boix-Fayos *et al*., 2006). However, a different trend can be detected depending on the processes involved. The similarity of runoff and erosion data between the present study and those of Shakesby *et al*. (1996) but specially those of Prats *et al*. (2012) suggested that inter-rill erosion was the main process in all of the three studies. Blong *et al*. (1982) and Dragovich and Morris (2002) carried out plot studies (8 m^2) in recently burnt eucalypt forest in Australia. They found specific sediment losses of 0.33 to 1.08 g $m^{-2}mm^{-1}$ rain. Only the highest sediment losses at the unploughed site (0.4 g $m^{-2}mm^{-1}$ rain) can be compared to their minimum rates.

Runoff and erosion values at the unploughed site can be compared with other reported values for burnt eucalypt stands in the region, however when comparing with reported values outside Portugal the erosion figures only compare with the minimum values. The adjacent ploughed site presented comparable runoff amounts but lower sediment losses. Rip-ploughing (down-slope or contour) let the soil in a vulnerable condition and a few storms can easily cause severe soil losses (Verheijen *et al*., 2009). In fact, in a recently rip-ploughed eucalypt site, Shakesby *et al*. (1994) found specific sediment losses as high as 3.27 g m^{-2} mm^{-1} rain. Then, the erodibility should decrease gradually after the first events through selective removal of the fine soil fraction by initial erosive events, the formation of a protective stone lag, and the subsequent development of vegetation and litter cover (Shakesby *et al*., 1994; Walsh *et al*., 1995). The low sediment availability in the ploughed site of the present study, can be explained by the time elapsed since ploughing (as much as 20 years or 2 eucalypt production cycles). At the same time, the low post-fire disturbance erosion figures indicate sediment exhaustion, at least of the finer particles than can be transported by inter-rill erosion at micro-plot scale. In commercial eucalypt stands, ground preparation involving uprooting the old stumps occurred at least every 30-40 years (3-4 eucalypt cycles) (Shakesby *et al*., 1996) and, in recent times, it is often done after fires. Since ground preparation usually involves rip-ploughing and even terracing, sediment exhaustion at the ploughed site clearly shows the consequences and the threat for soil conservation of this type of management. On the other hand, Mediterranean erosion rates are generally lower than those in other areas; this is mainly attributed to the high soil stoniness, shallow soils and long intensive land use (Cerdan *et al*., 2010; Shakesby 2011). The lower erosion rates do not necessarily mean that erosion is a lesser threat for the soil resource, as the soil is already thin and therefore any additional loss may be considered detrimental (Cerdan *et al*., 2010). Additionally, the systematically high organic matter fraction on the eroded sediments (40-50%) founded in the area (Thomas *et al*., 1999; Malvar *et al*., 2011; Malvar *et al*., 2011; Prats *et al*., 2012) indicates a loss of soil organic matter which may affect soil fertility (Thomas *et al*., 1999) as well as caused off-site pollution (Spigel and Robichaud 2007; Vila-Escalé *et al*., 2007; Campos *et al*. 2010).

4.2. Key factors on hydrological and soil erosion response and its temporal variation

Rainfall amount was the main factor explaining runoff generation, followed with equal importance by the ash plus litter cover and the frequency of strong soil water repellency. The same factors were described by Prats *et al*., (2012) for untreated (eucalypt + pine) plots. A shift in the first descriptor from rainfall amount to 15-minutes rainfall intensity (I_{15}) was detected from the unploughed site to the ploughed site model. It was probably caused by the higher protective surface cover (litter + vegetation) in the ploughed site (25% more). The higher importance of I_{15} as surface cover increased over the plots was also detected between the eucalypt and the pine plots with higher litter cover of Prats *et al*. (2012). Equally, Vega *et al*. (2005), studying shrubs with a vegetation cover as high as 37% immediately after a prescribed fire, also found rainfall energy (accumulated kinetic energy) to be the main factor for runoff generation followed by litter depth.

The coverage of both litter and ashes (8% more in the ploughed than in the unploughed site) could explain about 10% reduction in runoff. Other authors have found that the interception and storage capacity of both litter and ash layer have reduced overland flow (Shakesby *et al*., 1996; Leighton–Boyce *et al*., 2007; Woods and Balfour 2008; Cerdà and Doerr, 2008; Bodí *et al*, 2011; Prats *et al*., 2012). Woods and Balfour 2008 attributed this retention to the highly porous nature of the ash layer, whereas Leighton–Boyce *et al*. (2007) suggested that the wettable patchy ash layer may have provided some moisture storage. Bodí *et al*. (2011) demonstrated that ash is not necessarily wettable, as widely assumed, but can be water repellent and therefore its effect over soil wettability will depend on the ash layer wettability. This study's measurements over the ash layer confirmed its wettability (the overall two post- fire years' median was "0" ethanol class and percentile 75 was "1" ethanol class).

The effect of the spatial and seasonal variation of soil water repellency on runoff generation founded by other authors in the same region (Ferreira *et al*., 2000; Keizer 2005a; Leighton-Boyce *et al*., 2007; Malvar *et al*., 2011; Prats *et al*., 2012) was detected in the general and site-specific runoff regression models. However, the spatial variability of the soil water repellency was irregular in time and poorly related to overall values. Keizer *et al*. (2008), at the same sites and during the first post-fire year, founded that the ploughed site exhibited greater repellency levels than the unploughed site. Further analyses founded that the opposite was true for the second post-fire year. At both sites, Keizer *et al*. (2008) confirmed a seasonal pattern of high repellency in dry periods and reduced or no repellency following prolonged rainfall. The intensive monitoring allowed distinctions in the key factors explaining runoff generation between those soil water repellency conditions. Under no repellency, I_{15} was the main factor controlling overland flow with a great importance (21%) of the interception (litter+ ash) layer. As repellency increased, the main factor changed from I_{15} to rainfall amount, and the interception layer decreased in importance (7%). It can be stated that, under repellent conditions, high rainfall volumes with medium I_{15} events were able to generate enough overland flow to transport sediments even with high protective cover. In unburnt eucalypt stands, Keizer et al., (2005a) suggests how the discrimination between (none to extreme) soil water repellency conditions could help to isolate the effect of repellency on overland flow generation. However, the soil water repellency effect was not straightforward, since exceptions of low runoff generation for high rainfall amounts under high soil water repellency conditions were also measured. So, the repellency measurement method is not accurate enough to fully capture the temporal-spatial dynamics. Keizer et al., (2008), detected significant increases and decreases in repellency severity over time intervals as short as 6–7 days. Further studies will have to verify if a higher temporal resolution of water repellency measurements can help to determine a closer relationship with runoff response. Ideally, this should be done in constant feedback with modelling approaches that considering temporal and spatial variation in soil water repellency, in order to enhance model performance and point out the necessary measurement resolution.

Sediment losses were controlled by I_{15} followed by litter cover. Previous studies have also reported the importance of rainfall intensity (Fernandez *et al*., 2004; Vega *et al*., 2005; Spigel and Robichaud 2007; Robichaud *et al*., 2008; Prats *et al*., 2012) and the contribution of cover-related variables (Shakesby *et al*., 1996; Robichaud *et al*., 2000; Wagenbrenner *et al*., 2006; Prats *et al*., 2012) in determining post-fire sediment losses. Erosion was also related with the variables that affect runoff, i.e., soil water repellency, soil moisture, and ash cover. Thus, the highest sediment losses did not occur only in the first months after fire (when the protective cover categories were the lowest), but also in the second post-fire year autumn when the I_{15} was higher or coinciding with runoff coefficient peaks following the dry seasons.

4.3. Natural vs. simulated rainfall

Malvar *et al*. (2011) carried out repeated rainfall simulation experiments (RSE’s) at the same unploughed and ploughed eucalypt stands. 46 RSE’s were performed, applying two rainfall intensities: high intensity with 45-50 mm h^{-1} (n= 12 in each site) and extreme intensity with 80-85 mm h^{-1} (n= 12 at the unploughed and n=10 at the ploughed site). The RSE’s were executed in six successive field campaigns during the first two years following wildfire, using the same plot type, size (0.28 m^2), number and slope position than the present natural rainfall study. Therefore, the present runoff and erosion results can be used to address the representativeness of the RSE-data of Malvar *et al*. (2011) for natural rainfall conditions. Inherent differences between the measurement techniques were the lower rainfall amount and kinetic energy in the

RSE's. Oppositely, the maximum intensity recorded in a natural event (24 mm h^{-1} with an I_{15}=33 mm h^{-1}) was much lower than the simulated rainfall intensity (45-85 mm h^{-1}). RSE's intensities were only comparable to the two maximum I_{15} recorded (I_{15}=44 mm h^{-1} and I_{15}=71 mm h^{-1}) at two single occasions.

Differences between the results were lower in terms of runoff response than sediment losses. In the unploughed site, the simulated rainfall was 70% lower than natural, generating 36% less runoff amount and 90% less sediment losses. In the ploughed site, 75% less rainfall originated 54% less runoff amount and 83% less sediment losses with simulated than with natural rainfall. Relative variables (runoff generation coefficient and specific sediment losses) were more appropriate to compare both methods. The average runoff coefficient generated by the RSE's (45%) was double than that under natural rainfall (22%). However, specific sediment rates remained comparable with the two techniques (Figure 7). In the unploughed site, specific sediment losses under natural rainfall (0.35 g m^{-2} mm^{-1} rain) were double than those with high intensity RSE's (0.16 m^{-2} mm^{-1} rain) but very similar to those from extreme intensity RSE's (0.31 g m^{-2} mm^{-1} rain). This means that the 12 extreme intensity RSE's executed in six campaigns during two post-fire years, were able to capture the same erosion rates than those of 4 natural rainfall micro-plots monitored during the same period (254 events monitored in 71 weekly periods). In the ploughed site, the natural rainfall micro-plots produced 0.06 g m^{-2} mm^{-1} rain whereas high (n=12) and extreme (n=10) intensity RSE's produced 0.08 g m^{-2} mm^{-1} rain. The absence of differences in specific sediment losses between both techniques was probably due to sediment exhaustion several years after it was ploughed. Independently of the technique or site, the organic matter fraction on the eroded sediments was around 40-50% with the implications above mentioned of such a high organic matter loss. In summary, the main similarities between both techniques were:

(i) The RSE's represented relatively well specific erosion rates, organic matter fraction losses and differences between sites. Both natural and artificial rainfall indicated that the ploughed site had comparable runoff amounts but less sediment losses than the unploughed site. However, the fact that only extreme intensity RSE's were able to capture the erosion figures in the unploughed site created uncertainty about the fitting of the RSE's methodology in sites with higher erosion rates.

(ii) The significant effect of time since fire on runoff and sediment losses had been captured by natural rainfall monitoring as well as repeated RSE's methodology. On one hand, both micro-plot scale techniques detected the role of topsoil water repellency in enhancing overland flow generation under dry antecedent weather conditions. On the other hand, runoff and sediment losses measurements as high as one month after the fire were also measured two years after the fire using both methodologies.

5. Conclusions

Runoff and sediment losses were measured in two burnt eucalypt sites, with different pre-fire management (unploughed and down-slope rip-ploughed), during two post-fire years using micro-plots (0.28 m^2), the main conclusions are the following:

The runoff response was consistently around 20% of the rainfall, independently of the site and post-fire year; this was comparable to other studies in the region. The erosive response of the unploughed site (4.15 Mg ha^{-1} $year^{-1}$) was comparable to other Mediterranean studies, but it was very low for the ploughed site (1.25 Mg ha^{-1} $year^{-1}$), probably due to the limited sediment supply. The time elapsed since ploughing can explain the lower sediment availability and sediment exhaustion. Ploughing increased within-site variability in sediment rates, probably by enhancing specific-plot variability. The measured sediment exhaustion at the ploughed site should consider ploughing as an additional risk for forest soils in this area, especially since ploughing and slope engineering (terracing), in both recently burnt and unburnt eucalypt stands, are increasingly more frequent in the region. Independently of the management, the organic matter fraction was around 40-50% of the eroded sediments. Despite the low measured erosion rates, the high overland flow generation highlighted the possible post-fire erosion risk. The importance of that risk should be considered due to the poor soils in this area, the historical and present intensive land use, as well as the importance of organic matter fraction on the eroded sediments.

Time since fire had a significant effect over runoff and sediment production. However, the observed temporal trend in runoff and sediment production was not a simple decline with time since fire, but had a marked seasonal component. High runoff and erosion peaks were measured two years after fire. This was mainly related to the role of soil water repellency in enhancing overland flow. Nevertheless, a moderate decline in specific sediment rates was observed.

Post-fire overland flow was controlled first by rainfall amount, followed with a similar contribution of surface cover and topsoil water repellency. However, site and temporal characteristics did influence that relationship. When either a protective surface cover (vegetation + litter) or some infiltration capacity (hydrophilic conditions) were present, there was detected a shift from rainfall amount to I_{15} as main factor controlling runoff generation. Independently of the site and/or temporal variation, sediment losses were controlled by the I_{15} followed by cover related variables. Variables that were proved to affect runoff (soil water repellency, soil moisture, ash layer) were also related to sediment losses.

The natural rainfall results confirmed that rainfall simulation experiences (RSE's) produced higher runoff coefficient but were able to capture the specific sediment losses and its organic matter content as well as differences between the ploughed and unploughed sites. The methodology of repeated RSE's also captured the role of soil water repellency in enhance runoff and subsequent sediment losses following the dry seasons, even two years after the fire. Soil erosion models will need to consider the role of soil water repellency in enhancing post-fire runoff.

Acknowledgements

The present study was carried out in the framework of the PhD research fellowship of MMC (SFRH/BD/41320/2007) with support of the EROSFIRE project (POCI/AGR/60354/2004) and research grant of SPA (SFRH/BD/33392/2008) and JPCN (SFRH/BPD/39721/2007) all funded by the Foundation for Science and Technology (FCT) of Portugal with co-funding by FEDER through the POCI2010 Programme. We wish to thank to: Raquel Ferreira, Marta Oñate, Pedro Cascão, Elena Palacios, Wouter Beekman, Joost Jansen, Joost Koenders & Ilse Leeftink, Ana Sofia Santos and Marifé Varela for sharing their ideas and help with field data collection and/or laboratory analysis of runoff and soil samples; Virgínia M.F.G. Pereira for the soil profile descriptions; Jorge Lucena, Carmen Magalhães, and Joaquim Sande Silva for part of the soil laboratory analyses.

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Table 1. General site soil and micro-plot characteristics, as well as fire severity indicators for the two study sites.

Site	Unploughed				Ploughed			
Coordinates	40º40'46.62''N 8º26'54.80''W				40º40'45.32''N 8º26'55.85''W			
Physiognomy								
Slope section length (m)	20-25				30-40			
Slope angle(º)	20				15			
Aspect	SE				NE			
Land management								
Rotation cycle	>2				>2			
Pre-fire ground preparation operations	Unploughed				Down-slope rip-ploughed			
Fire severity indicators								
Eucalypt crown damage	Partial				Partial			
Height of burned stems (m)	9				12			
Combustion of litter/herbs layer	Total				Total			
Combustion of shrub layer	Partial				Partial			
Ash color	Black				Black			
Soil characteristics								
Soil type	Umbric Leptosol				Umbric Leptosol			
Soil Depth (cm)	20-40				20-35			
Bulk Density (g cm^{-3}; 0-20 cm; n=10-14)	0.83				0.93			
Soil texture (0-5 cm; n= 4)	Sandy Clay Loam				Clay Loam			
OM (%)	11				10			
Clay (%); (<0.002 mm)	27				29			
Silt (%); (0.002-0.05 mm)	22				31			
Sand (%); (0.05-2 mm)	51				40			
Micro-plots characteristics								
Plot code	1	2	3	4	5	6	7	8
Slope section – micro-topography	Low-Flat ground	Low-Flat ground	Up-Flat ground	Up-Flat ground	Low-Ridge	Low-Furrow	Up-Furrow	Up-Ridge
Micro-plot angle (º)	24	25	19	20	15	22	17	16
Roughness (cm)	0.37	0.89	0.97	0.69	0.88	1.35	1.85	2.45

Table 2: Annual rainfall characteristics, runoff and erosion rates by site, and 2-way repeated measures ANOVA results (F-value) with plot-wise annual values by site (n=4), to determine site and time since fire (year) effect over the studied variables. The underlined F values are statistically significant at α ≤ 0.05.

Post-fire year		Year 1	Year 2
Period		26 Sep 2005 to 20 Sep 2006	20 Sep 2006 to 19 July2007
Rainfall (mm)		1048	1608
I_15_max (mm h^{-1})		44	71
Erosivity (MJ mm ha^{-1} h^{-1})		1412	3115
Dependent variable	Site	Year 1	Year 2
Runoff (mm)	Unploughed	227	426
	Ploughed	228	310
Runoff coefficient (%)	Unploughed	22	26
	Ploughed	22	19
Sediment rate (g m^{-2})	Unploughed	415	515
	Ploughed	125	54
Specific sed. losses (g m^{-2} mm^{-1} runoff)	Unploughed	1.82	1.21
	Ploughed	0.55	0.17
Organic matter (%)	Unploughed	52	60
	Ploughed	37	42

F Value

Source of variation	Runoff (mm)	Runoff coefficient (%)	Sed. rate (g m^{-2})	Specific Sed. losses (g m^{-2} mm^{-1} runoff)	O.M (%)
site	5.40	2.50	57.27	44.66	0.56
year	8.84	0.09	3.24	46.83	8.89
site*year	1.56	0.92	9.34	4.66	1.97

Table 3. Statistical comparison of the spatial variability of the explanatory variables between sites (unploughed vs. ploughed). Individual plot values were used for surface cover variables. Transect variables comparison involved median transect values by date. The statically significantly outcomes (α=0.05) of the MW U-test (Z) and Wilcoxon's S–R test (S) are the underlined values. SWR stands for soil water repellency.

Plot surface cover variables	**Z**	**p_value**	**S**	**p_value**
Ash (%)	1.5	0.143	1863	0.134
Bare (%)	1.7	0.095	-750	0.081
Litter (%)	-10.5	<0.001	-13826	<0.001
Stone (%)	12.0	<0.001	16756	<0.001
Vegetation (%)	-3.6	<0.001	-7622	<0.001
Transect Variables	**Z**	**p_value**	**S**	**p_value**
Median Soil Moisture (2-3 cm)	0.07	0.945	1.0	0.978
Median Soil Moisture (7-8 cm)	-2.31	0.021	117.5	0.001
Median SWR Ash layer	0.33	0.745	-3.5	0.768
Median SWR Soil Surface	-1.48	0.138	45.5	0.090
Median SWR (2-3 cm)	0.16	0.875	-17.5	0.493
Median SWR (7-8 cm)	0.70	0.485	-34.5	0.333
Frequency of extreme SWR (SWR> 7 ethanol class)	-0.13	0.897	-4.0	0.936
Frequency of very strong SWR (SWR> 6 ethanol class)	0.12	0.901	-6.5	0.896
Frequency of strong SWR (SWR> 5 ethanol class)	-0.72	0.474	38.0	0.397

Table 4. Results of the 2-way repeated measures ANOVA with plot-wise monthly values by site to determine the site and time since fire (month) effect over the runoff and erosion variables. The underlined F values are statistically significant at $\alpha \leq 0.05$.

Effect/Variable	Runoff (mm)	Runoff coefficient (%)	Sediment losses ($g\ m^{-2}$)	Specific Sed. Losses ($g\ m^{-2}\ mm^{-1}$ runoff)	Organic matter (%)
Site	8.64	7.01	55.6	42.89	1.78
Month since fire	33.23	13.93	29.11	8.24	4.49
Site*Month since fire	3.82	2.83	8.22	3.37	1.03

Table 5. Multiple regression models for weekly (log) runoff and (fourth root) sediment losses for all the plots combined (general model), separated by site and by soil water repellency category (SWR1, SWR2 and SWR3). Variables are: Rain=Rainfall (mm); I_15= maximum intensity in 15 minutes (mm h -1); Ant_Rain=antecedent rainfall (mm); Event_Int= maximum event intensity (mm h -1); Freq5= Frequency of strong soil water repellence (class ethanol>5); Soil Moist.=Volumetric soil moisture (%) at 2-3 depth; Angle=Plot slope angle (º).

	General model (n=340)			**Unploughed (n=172)**			**Ploughed (n=168)**		
	Variable	Estimate	R^2	Variable	Estimate	R^2	Variable	Estimate	R^2
Runoff	Intercept	0.221		Intercept	0.600		Intercept	0.248	
(mm)	Rain	0.005	0.27	Rain	0.010	0.32	I_15	0.011	0.28
	Freq5	0.006	0.11	ash	-0.007	0.10	Freq5	0.008	0.12
	ash	-0.006	0.06	Freq5	0.003	0.07	Rain	0.004	0.06
	litter	-0.007	0.04	Event_Int	0.020	0.01	Ash	-0.005	0.04
	I_15	0.006	0.01				Litter	-0.005	0.02
	Angle	0.014	0.01				Ant _Rain	-0.009	0.01
	Ant _Rain	-0.007	0.01						
Model R-Square			**0.50**			**0.50**			**0.53**
Sediment	Intercept	0.615		Intercept	1.513		Intercept	0.807	
losses	I_15	0.011	0.18	I_15	0.016	0.43	I_15	0.007	0.15
(g m^{-2})	litter	-0.014	0.16	ash	-0.006	0.06	Bare	0.021	0.14
	Angle	0.045	0.10	Soil Moist.	-0.012	0.04	Freq5	0.004	0.13
	Freq5	0.004	0.04	Rain	0.003	0.02	vegetation	0.002	0.02
	ash	-0.006	0.02	Freq5	0.003	0.02			
	Rain	0.002	0.02						
	vegetation	-0.002	0.01						
Model R-Square			**0.53**			**0.57**			**0.45**
	BY SWR CATEGORY								
	SWR=1 (n=72)			**SWR=2 (n=104)**			**SWR=3 (n=164)**		
	Variable	Estimate	R^2	Variable	Estimate	R^2	Variable	Estimate	R^2
Runoff	Intercept	0.181		Intercept	0.519		Intercept	0.980	
(mm)	I_15	0.020	0.35	Rain	0.009	0.45	Rain	0.004	0.27
	litter	-0.013	0.16	ash	-0.008	0.10	ash	-0.004	0.04
	ash	-0.005	0.05	Event_Int	0.065	0.03	litter	-0.005	0.03
	Angle	0.025	0.04	litter	-0.008	0.02			
Model R-Square			**0.59**			**0.61**			**0.34**
Sediment	Intercept	-17.910		Intercept	-2.422		Intercept	-36.807	
losses	I_15	0.937	0.61	Rain	0.195	0.24	I_15	0.605	0.26
(g m^{-2})	Angle	0.984	0.08	stone	0.178	0.07	Angle	1.367	0.13
	litter	-0.228	0.03	Ant _Rain	-0.637	0.04	stone	0.281	0.06
	Soil Moist.	-0.381	0.02				vegetation	0.138	0.02
Model R-Square			**0.74**			**0.36**			**0.48**

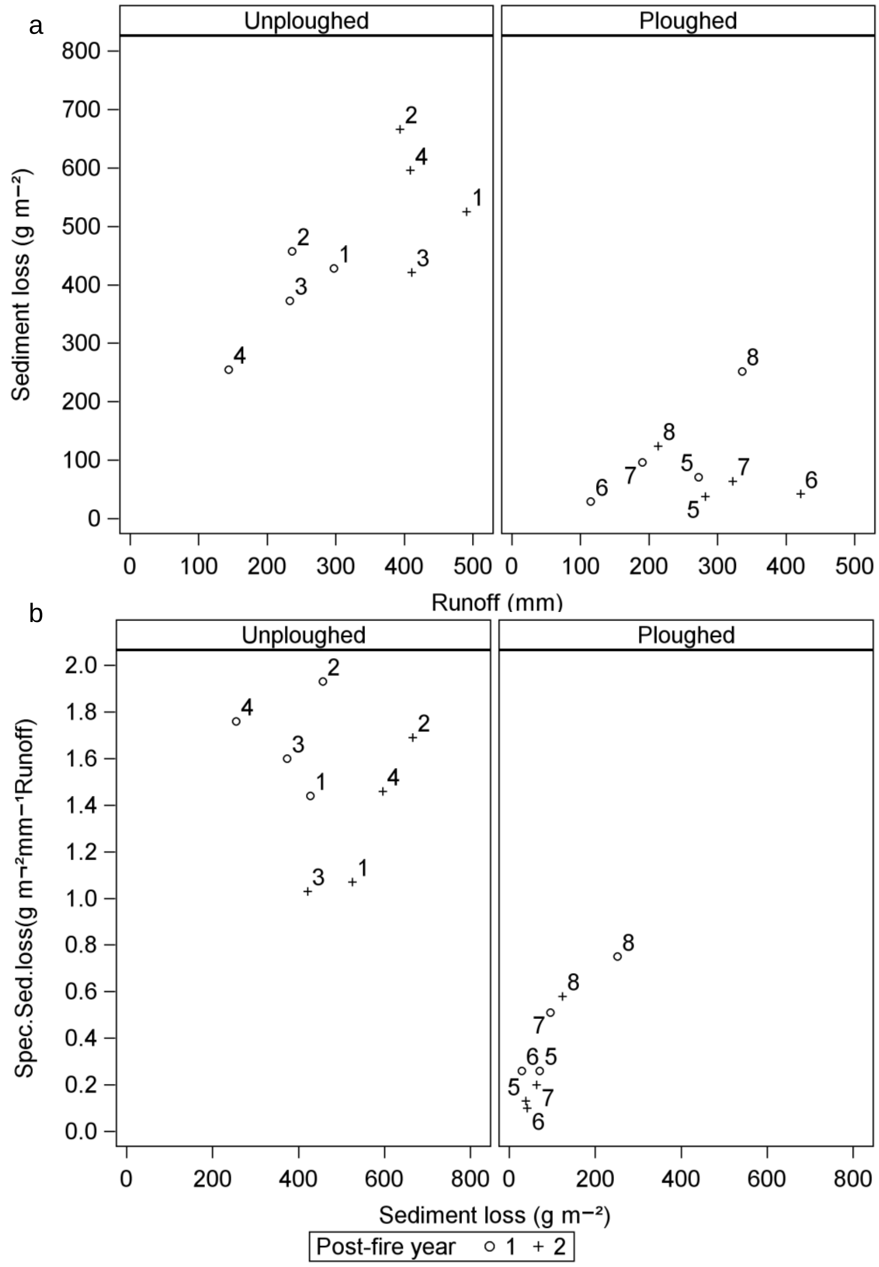

Figure 1. Overall relationship between annual runoff amounts and total sediment losses by plot (a) and sediment losses and specific sediment losses per mm runoff (b) at unploughed (left) and ploughed (right) site. Circle and cross symbols indicate total values for post-fire year 1 and 2, respectively. Data label indicate plot number as indicated in Table 1.

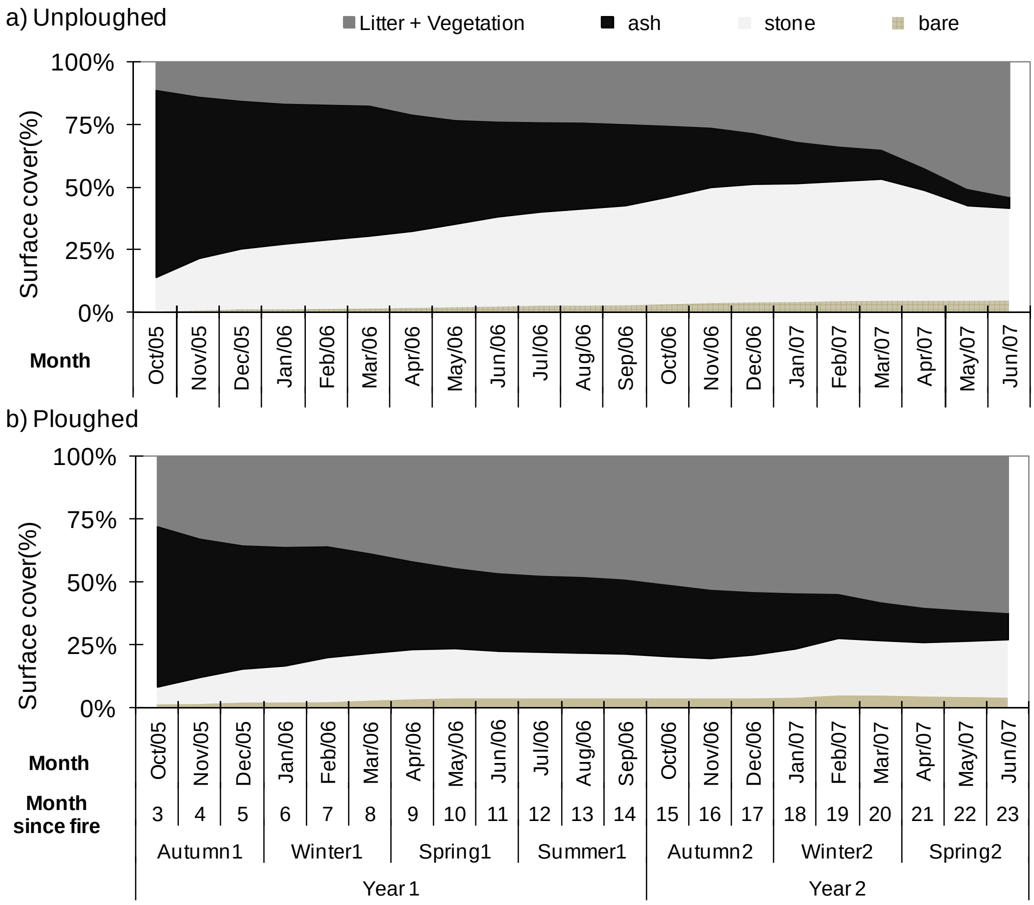

Figure 2. Mean surface cover by month after fire in the unploughed (a) and ploughed (b) sites.

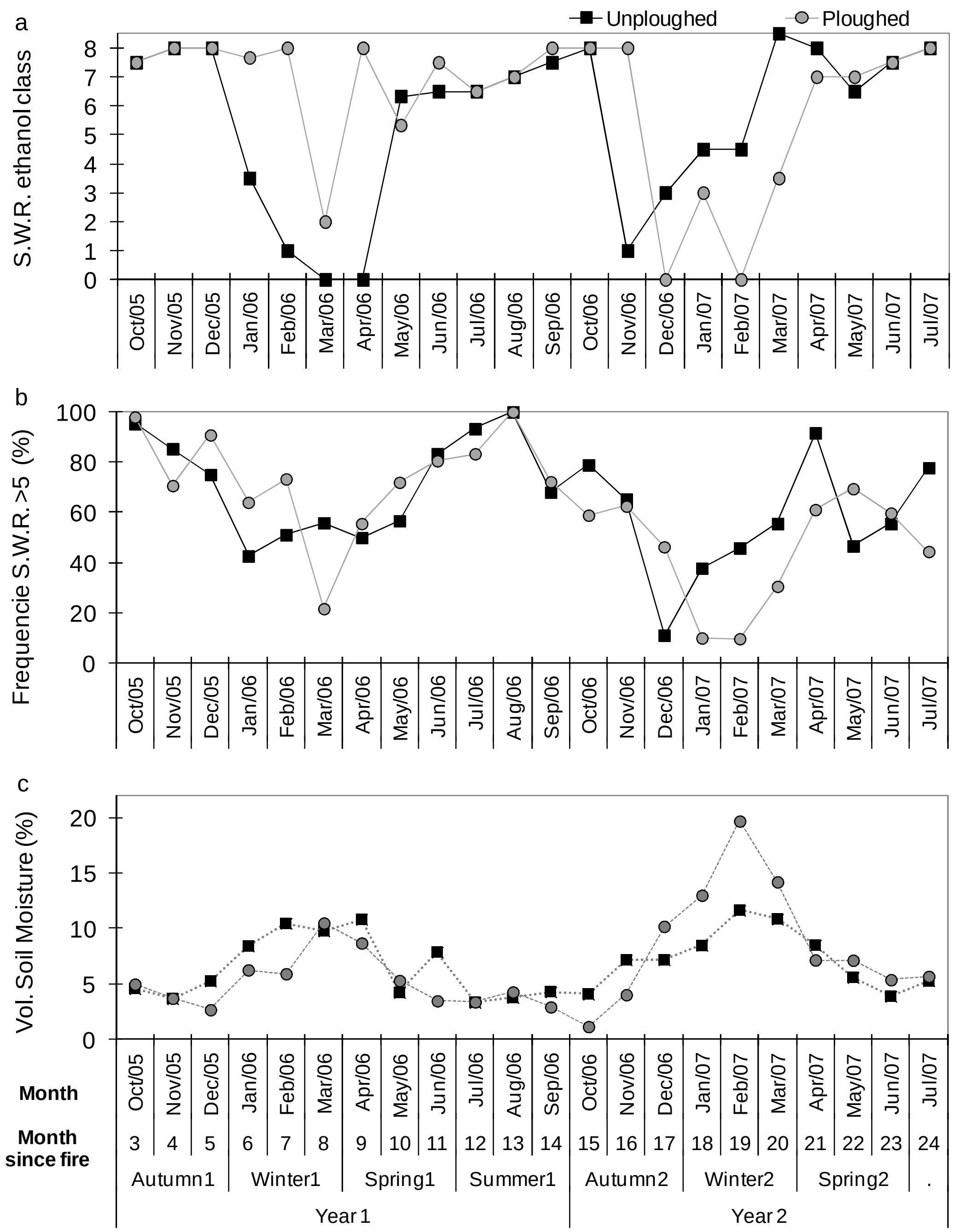

Figure 3. Monthly site means of soil water repellency (SWR) ethanol class at 2-3 cm depth (a), topsoil (soil surface + 2-3 cm depth) frequency of strong soil water repellency (SWR> 5 ethanol class) (b) and volumetric soil moisture at 2-3 cm (%) (c); dark and grey symbols represent the unploughed and ploughed sites, respectively.

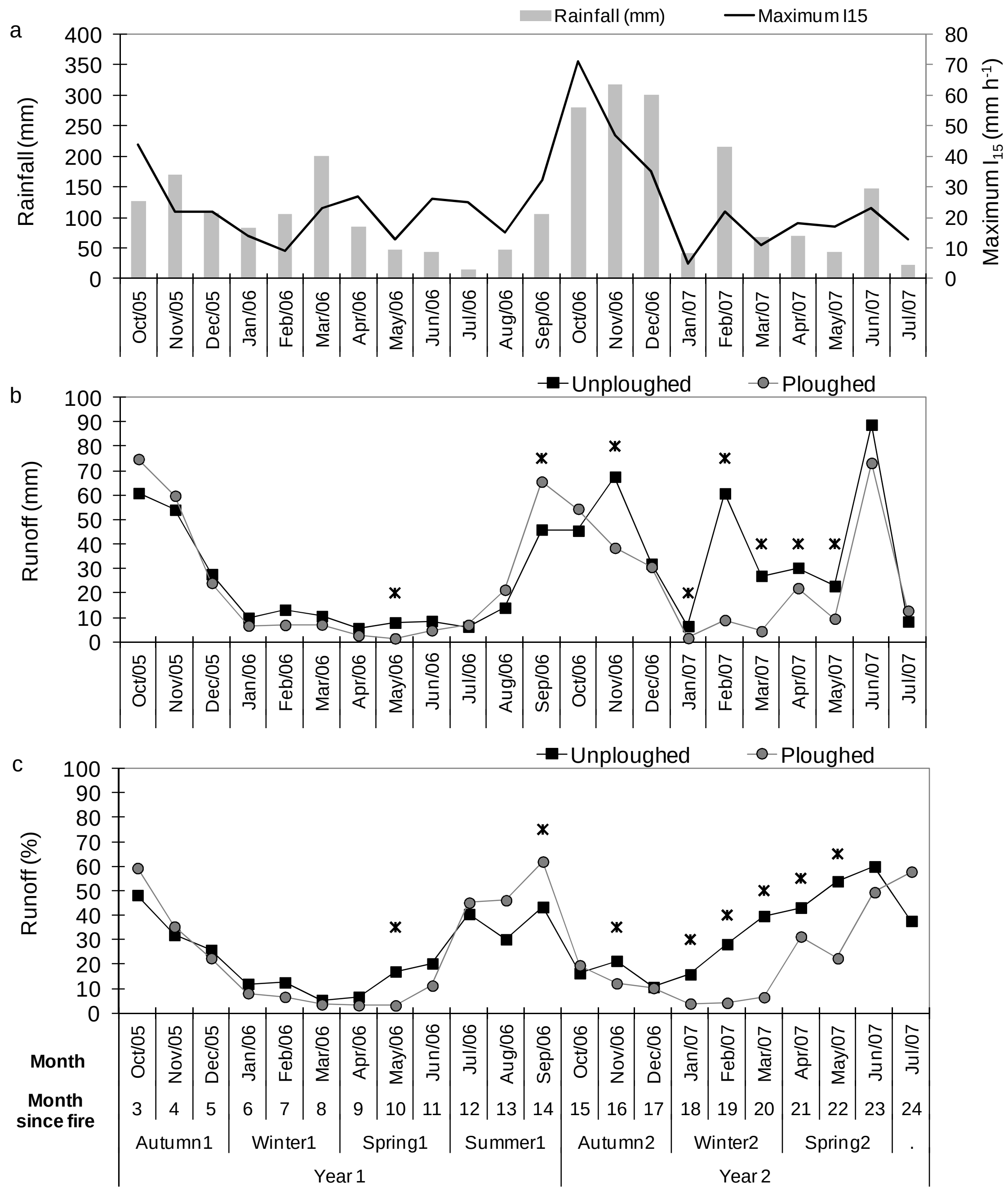

Figure 4. Monthly rainfall (mm) and maximum I_{15} (mm h^{-1}) (a), runoff amount (mm) (b) and runoff coefficient (c) in the unploughed (dark squares) and ploughed (grey circles) sites. Asterisks denote least mean squares significances at p<0.05 between monthly runoff generation in the unploughed and ploughed sites.

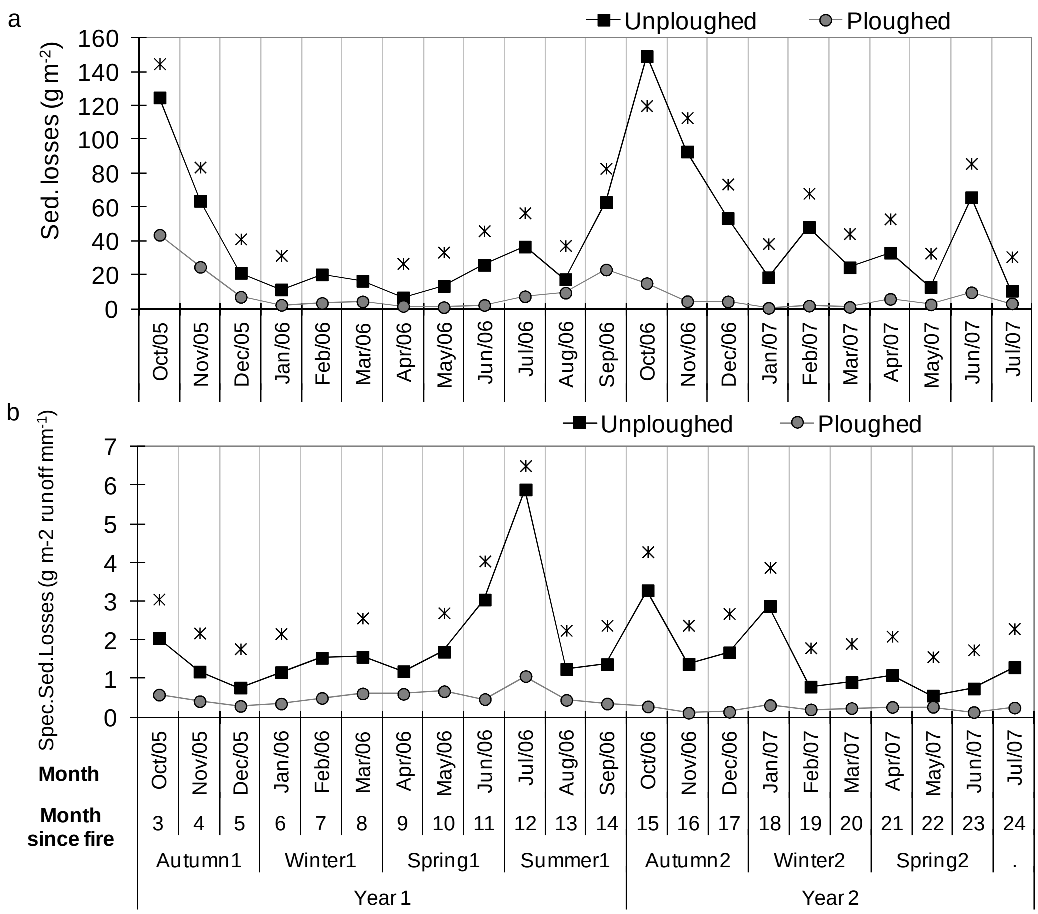

Figure 5. Monthly sediment losses (a) and specific sediment losses (b) in the unploughed (dark squares) and ploughed (grey circles) sites. Asterisks denote least mean squares significances at $p<0.05$ between monthly total and specific sediment losses in the unploughed and ploughed sites.

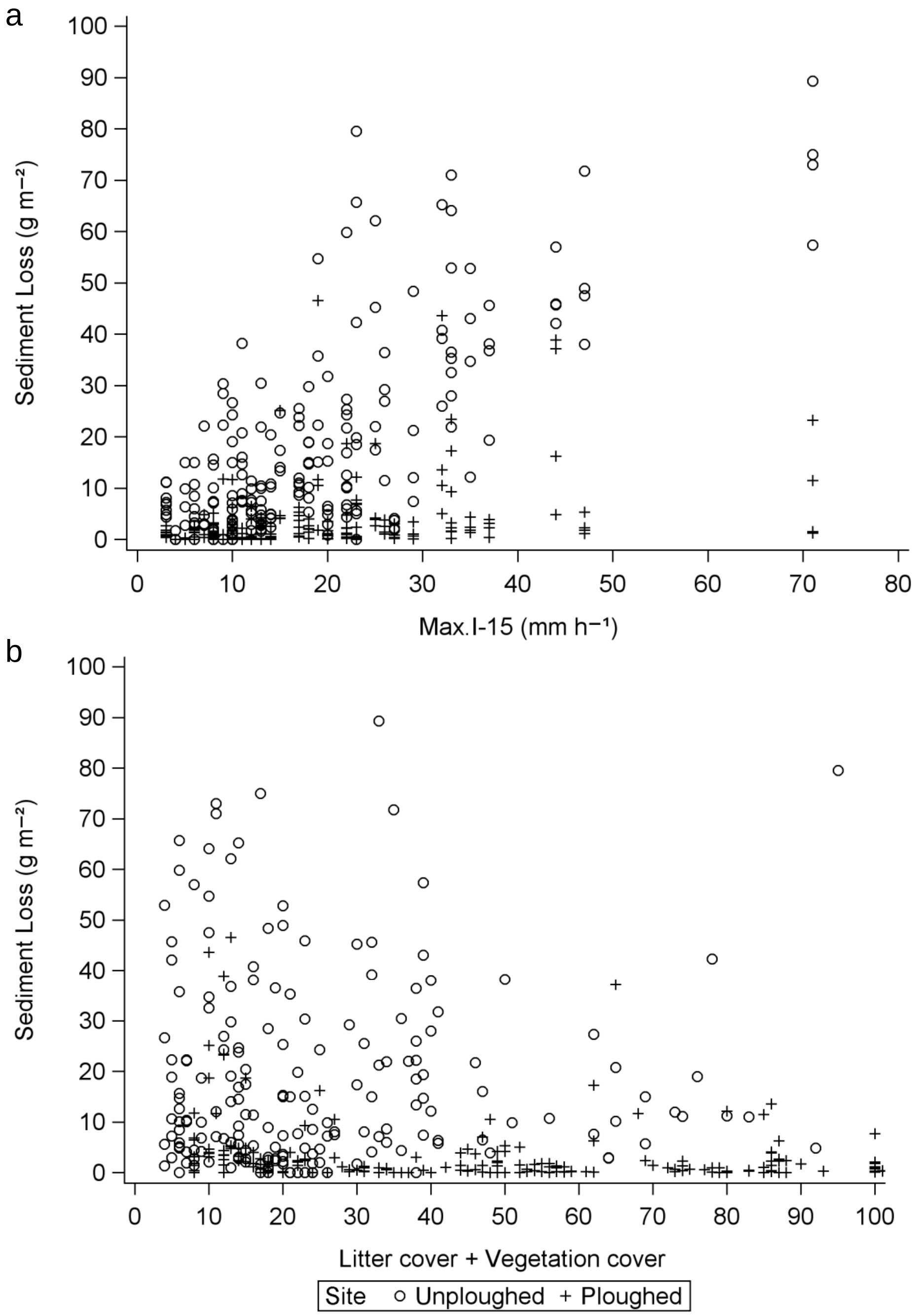

Figure 6. Relationship between sediment losses and (a) maximum I_{15} (mm h^{-1}), (b) protective surface cover (litter + vegetation), for the unploughed (circles) and ploughed (crosses) sites.

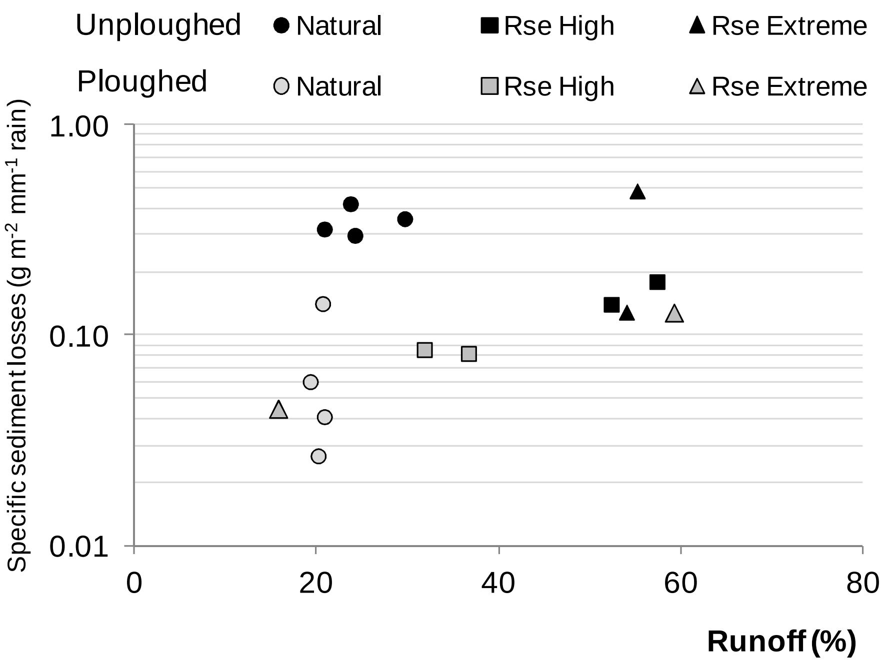

Figure 7. Overall runoff coefficient and specific sediment losses obtained with natural rainfall (two years study period) and repeated high (45-50 mm h^{-1}; n=12 by site) and extreme (80-85 mm h^{-1}; n=12 unploughed; n=10 ploughed) rainfall simulations experiences (RSE's) executed during two years at the unploughed (black symbols) and ploughed site (grey symbols). Note that the y-axis is shown in logarithmic scale.

Chapter 5: Effectiveness of hydro-mulching to reduce runoff and erosion in a recently burnt and logged Maritime Pine stand in north-central Portugal

LAND DEGRADATION & DEVELOPMENT
Land Degrad. Develop. (2013)
Published online in Wiley Online Library (wileyonlinelibrary.com) **DOI**: 10.1002/ldr.2236

EFFECTIVENESS OF HYDROMULCHING TO REDUCE RUNOFF AND EROSION IN A RECENTLY BURNT PINE PLANTATION IN CENTRAL PORTUGAL

Sérgio Alegre Prats[1]*, Maruxa Cortizo Malvar[1], Diana Catarina Simões Vieira[1], Lee MacDonald[2], Jan Jacob Keizer[1]

[1]*Centro de Estudos do Ambiente e do Mar (CESAM), Department of Environment and Planning, University of Aveiro, 3810-193 Aveiro, Portugal*
[2]*Department of Forest, Rangeland and Watershed Stewardship, Warner College of Natural Resources, Colorado State University, Fort Collins, CO 80523-1472, USA*

Received: 13 June 2013; Revised: 4 July 2013; Accepted: 4 July 2013

ABSTRACT

Forest fires can greatly increase runoff and surface erosion rates. Post-fire soil erosion control measures are intended to minimize this response and facilitate ecosystem recovery. In a few recent cases, hydromulch has been applied, and this consists of a mixture of organic fibers, water and seeds. The objectives of this research were to (i) analyze the effectiveness of hydromulch in reducing post-fire runoff and sediment production and (ii) determine the underlying processes and mechanisms that control post-fire runoff and erosion. After a wildfire occurred in August 2008, 14 plots ranging in size from 0·25 to 10 m^2 were installed on a 25 degree slope in a burnt pine plantation that had also been subjected to salvage logging. Half of the plots were randomly selected and treated with hydromulch. One of two slope strips adjacent to the plots was also hydromulched and used for monitoring some soil properties. Measurements made in each of the first 3 years following the wildfire included (i) the plot-scale runoff volumes and sediment yields; (ii) soil shear strength, soil moisture, and soil water repellency; and (iii) surface cover. The hydromulch reduced overland flow volume by 70% and soil erosion by 83%. The decrease in runoff was attributed to the increase in soil water retention capacity and the decrease in soil water repellency, whereas the reduction in soil erosion was initially attributed to the protective cover provided by the hydromulch and lately to an enhanced vegetative regrowth in the third year after burning. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS: wildfire; post-fire erosion; overland flow; soil water repellency; ash

INTRODUCTION

Soil erosion is a key process in the functioning of Mediterranean ecosystems (Cantón *et al*., 2001; Ceballos *et al*., 2003; Cerdà *et al*., 2010), and wildfires represent one of a number of disturbances in forests and shrublands that can greatly increase soil and fertility losses (Cerdà, 1998a, 1998b; Shakesby & Doerr, 2006; Shakesby, 2011). The consumption of the vegetation and litter layer by fire increases both overland flow—because of the reduction of rainfall interception and resistance to flow—and sediment losses by increasing the splash erosion by raindrops (Soto & Diaz-Fierros, 1997; Llorens & Domingo, 2006). Additionally, the fire-induced heating of the soil can reduce aggregate stability, decrease porosity, and increase soil water repellency (SWR), and these changes can decrease infiltration and increase soil erodibility (DeBano, 2000; Ferreira *et al*., 2008; Keizer *et al*., 2008; Malvar *et al*., 2011; Prats *et al*., 2012).

The association of wildfire with on-site soil erosion and downstream flooding and massive sediment deposition has become increasingly recognized (Kraebel, 1934) and, in the early part of the last century, led to the first systematic soil erosion control treatments following wildfires (Munns, 1919). The first post-fire rehabilitation efforts consisted of building engineering structures (check dams) in stream channels to trap the sediments and of seeding hillslopes to increase ground cover (Wohlgemuth *et al*., 2009). However, it was proved to be unrealistic to build check dams in the short periods between the occurrence of the wildfires and the occurrence of the erosion-producing rains; also, various studies started to question the effectiveness of seeding to reduce soil erosion during the 1980s (Gautier, 1983; Taskey *et al*., 1989).

During the 1990s and the 2000s, research on post-fire erosion mitigation concerned seeding (e.g., Pinaya *et al*., 2000; Fernández-Abascal *et al*., 2003; Beyers, 2004; Robichaud *et al*., 2006; Groen & Woods, 2008; Peppin *et al*., 2010), construction of erosion barriers by using logs (Wagenbrenner *et al*., 2006; Robichaud *et al*., 2008), and straw mulching (Bautista *et al*., 1996; Badía & Martí, 2000; Wagenbrenner *et al*., 2006). In a nutshell, these studies found seeding to be effective in some cases but not in others, log erosion barriers to be ineffective unless rain events are few and small, and mulching to be highly effective. The effectiveness of mulching was also well-established for agriculture lands (Harris & Yao, 1923; Meyer *et al*., 1970; Lyles *et al*., 1974; Meyer *et al*., 1999; Wilson *et al*., 2004; García-Orenes *et al*., 2009, 2010; Giménez-Morera *et al*., 2010; Jordán *et al*., 2010), cut slopes, and unpaved roads (Grismer & Hogan, 2005; Jordán & Zavala, 2008).

Post-fire straw mulching at rates of c.a. 2 $Mg\,ha^{-1}$ has been proved to reduce sediment yields by more than 80%

*Correspondence to: S. A. Prats, Centro de Estudos do Ambiente e do Mar (CESAM), Department of Environment and Planning, University of Aveiro, 3810-193 Aveiro, Portugal.
E-mail: sergio.alegre@ua.pt

(Bautista *et al*., 1996; Badía & Martí, 2000; Wagenbrenner *et al*., 2006; Groen & Woods, 2008; Fernández *et al*., 2011; Robichaud *et al*., 2013b). However, straw may be available in only limited quantities in certain regions, including Portugal (Prats *et al*., 2012), and may be redistributed by strong winds as a result of its low weight (Robichaud *et al*., 2000). Straw application can also introduce invasive weeds and inhibit native species recovery (Kruse *et al*., 2004). Despite the increased application costs, other mulches of higher specific weight have also been tested. Forest residues, at application rates of 8 Mg ha^{-1} in Prats *et al*. (2012) and 46 Mg ha^{-1} in Shakesby *et al*. (1996), or wood strands mulch, at rates of 4–12 Mg ha $^{-1}$ in Robichaud *et al*. (2013a), were found to be as effective as straw mulch, whereas wood chips mulch was found to be much less effective (Kim *et al*., 2008; Fernández *et al*., 2011).

Mulching is effective against erosion because it reduces runoff and erosion rates by two mechanisms. First, it increases interception storage capacity, which reduces the amount of rain available for producing runoff, it reduces runoff velocity, and it increases soil moisture (Bautista *et al*., 2009). Second, mulch protects the soil surface against the kinetic energy of rainfall drops and decreases the hydrodynamic power of flowing water (Smets *et al*., 2008).

A recent variant of mulching is that of hydromulching, which refers to the application of a water-based mixture of organic fibers, seeds and a green colorant. It is easily applied because it can be sprayed onto slopes by a jet hose (Naveh, 1975). It also tends to bind strongly to the soil surface by the action of the soil-binding agent, so it is particularly useful on steep slopes and strongly modified areas such as quarries, construction sites, and cut and fill slopes along roads (Emanual, 1976; Benik *et al*., 2003; Robichaud *et al*., 2010). Runoff and soil erosion will be reduced because the hydromulch increases interception storage and protects the soil surface. Additionally, the introduced seeds are intended to increase the vegetative cover, especially when the mulch starts decompose. In burnt areas, seeding requires careful selection of species that are adapted to the target environment, both to guarantee that the seeding produces an adequate cover and to avoid that the introduced species come to behave as invasive weed (Kruse *et al*., 2004). An important disadvantage of hydromulching is its elevated costs, which can range from $3,700.00 to $10,300.00 per ha for aerial application (Hubbert *et al*., 2012). By contrast, the costs for straw mulching are on the order of $600.00 and $1,200.00 per ha for application by helicopter and by hand-spreading, respectively (Napper, 2006). Despite this greater expense, hydromulching has been used especially in the USA after some fires when access was difficult, the slopes were too steep or subject to wind to use straw mulch and when there were particularly important 'values at risk', such as water reservoirs, cultural or natural heritage sites, or industrial plants.

The effectiveness of hydromulching in reducing post-fire runoff and erosion has not yet been fully established. Although Robichaud *et al*. (2013b) found no marked decrease in post-fire runoff, Hubbert *et al*. (2012), Rough (2007), and Robichaud *et al*. (2010, 2013a) did report substantial reductions in erosion rates (with 65–95%). However, these reductions were restricted to the first year after hydromulching, which the authors attributed to the rapid breakdown of the mulch layer. Wohlgemuth *et al*. (2011) also found hydromulching to markedly reduce overall erosion rates (by 60–80%) but not the sediment losses produced by high-intensity storms. Robichaud *et al*. (2010) suggested that hydromulching would be most effective on short slopes (10–20 m), where interrill erosion is the dominant process and the hydromulch mat is less likely to be detached by rill incision. However, Rough (2007) found aerial hydromulching to be highly effective on long hillslopes with elevated rill densities (0·1 rill m^{-2}).

Given the elevated potential of hydromulching for post-fire rehabilitation, there is a clear need to test its effectiveness in geographical regions outside the USA. Although hydromulch can include surfactants, the effectiveness of hydromulching has been poorly assessed for vegetation types associated with strong or extreme SWR, such as the eucalypt and pine plantations that dominate in north-central Portugal (Ferreira *et al*., 2008, Keizer *et al*., 2008; Prats *et al*., 2012). Also, the effectiveness of hydromulching after post-fire salvage logging is poorly known in spite of being perhaps the most common practice following wildfires in north-central Portugal. Salvage logging was typically being used to recover timber values and reduce the risk of insect infestation (McIver & Starr, 2000), but it can trigger runoff and soil erosion through soil alteration and forest floor disturbances (Rab, 1994; Castillo *et al*., 1997; Edeso *et al*., 1999; Fernández *et al*., 2004, 2007).

The overall aim of the present research was to study the effectiveness of hydromulching to reduce runoff and erosion over a three-year period in a recently burnt and logged pine plantation in north-central Portugal. The specific objectives were to (i) assess the effectiveness of hydromulching in reducing runoff volumes and sediment yields at the plot scale; (ii) analyze the changes in runoff and soil erosion over time and across plot size (0·25, 0·5, and 10 m^2 plots); and (iii) determine the effect of hydromulching on key soil properties, surface cover, and vegetative recovery, and the extent to which these mulching-induced changes can explain the observed differences in runoff and erosion between the hydromulched and untreated plots.

MATERIAL AND METHODS

Study Area and Site

This study was conducted near the village of Colmeal in the Góis municipality of north-central Portugal (N 40º08′42″, W 7º59′16″; 490 m asl). On 27 August 2008, a wildfire burnt 68 ha of forest lands. A west-facing 25 degree steep hillslope was selected to study post-fire vegetation recovery (Maia *et al*., 2012a, 2012b), and, at a later stage, also for this study. The hillslope had been planted with maritime pine (*Pinus pinaster* Ait.) some 25 years before the wildfire, at a density of 2,600 saplings per ha. The undergrowth was composed of a mixture of Mediterranean and Atlantic shrubs and was dominated by *Calluna vulgaris* I. and *Arbutus unedo* L. (Maia *et al*., 2012b). The study area has a Mediterranean climate with a mean annual temperature of 10–12·5°C (according to Köppen; APA, 2011). The annual precipitation as recorded by the nearest weather station (Cadafaz, N 40º08′02″, W 8º32′40″; 12 km W^{-1} from the study area; 25 years of data) was, on average, 1,130 mm but varied from 717 mm to 1,872 mm (SNIRH, 2012). The soils were shallow, 30- to 35-cm deep Humic Cambisols (WRB, 2007), overlying schist, as was observed from four soil pits dug during November 2008 (Table I). A soil sample was collected at 0–5 cm depth in each pit, and later analyzed, using standard laboratory methods, for bulk density (Porta *et al*., 2003), porosity, and grain-size distribution (Guitian & Carballas, 1976). Percent organic carbon was determined by a carbon analyzer (Flash EA 1112 series by Thermo Finnigan, USA) and multiplied by the van Bemmelen factor (1·724) in order to obtain the organic matter content on the soil (Jackson, 1958).

Experimental Design, Field Data Collection, and Laboratory Analyses

At the location selected for this experiment, the 2008 wildfire had completely consumed the pine crowns, so there was basically no needle cast after the fire (Table I). On 11 December 2008, 106 days after the fire, more than half of the soil surface corresponded to black ashes, a third to stones, and less than 10% to bare soil. The fire severity was classified as moderate according to various severity indices described in Maia *et al*. (2012b) at locations some 5–10 m distance from the present experiment. For example, the maximum temperature reached (Guerrero *et al*., 2007) by the soil at 0–3 cm depth, estimated with near-infrared spectroscopy, was, on average, 78°C; the twig diameter index (Maia *et al*., 2012a), which ranged between 0 (unburnt) and 1 (very intense wildfire) was, on average, 0·4 (Table I).

Table I. Indicators of fire severity, ground cover, and mean soil properties from 0- to 5-cm depth ($n = 4$)

Site characteristics	Average	±	SD
Overall fire severity		Moderate	
Tree canopy consumption		Total	
TDI	0·4	±	0·1
MTR (°C)	78	±	30
Ground cover in December 2008 (%)			
Litter	2	±	1·3
Black ashes	56·6	±	9·7
Bare soil	7·2	±	3·7
Stones (>2 mm)	34·2	±	8·3
Soil properties			
Soil depth (cm)	35·3	±	4·3
Slope (º)	24·5	±	3·4
Bulk density ($g\,cm^{-3}$)	0·8	±	0·1
Porosity ($cm^3\,cm^{-3}$)	0·5	±	0·1
Organic matter (%)	16·4	±	1·6
Soil texture			
Clay (%)	8·4	±	1·9
Silt (%)	35·8	±	9·0
Sand (%)	55·8	±	12·8
Stoniness (>2 mm) (%)	36	±	15·0
USDA soil texture class		Sandy loam	

TDI, twig diameter index; MTR, maximum temperature reached, following Maia *et al*. (2012a, 2012b); SD, standard deviation; USDA, United States Department of Agriculture.

Because the National Forestry Authority had decided to log the stand as soon as possible because of the risk of nematode infestation, the experimental set up of this study involved four phases. The first phase comprised the installation of a tipping-bucket rain gage (Pronamic professional rain gauge with an event logger) in combination with a storage gage for validation purposes. This was carried out on 15 September 2008, prior to any rainfall following the wildfire. After that, the rainfall was measured weekly from the storage gage, and the maximum weekly or monthly 30-min rainfall intensity ('I30', in mm h^{-1}) was calculated for each period from the tipping-bucket rain gage data series.

On 5 November 2008, the pretreatment period started with the installation of four plots bounded with metal sheets. Two were micro-plots of approximately 0·5 × 0·5 m, whereas the other two were small plots of approximately 0·5 m wide and 1·0 m long. The outlets of each plot were connected, using garden hose, to 30 L tanks, where the runoff was collected. The runoff volume in each tank was measured at 1- to 2-weekly intervals, depending on rainfall, from 5 November 2008 to 12 October 2010, except during March 2008 when the runoff measurements had to be interrupted because of the logging activities. This 23-month period was divided in a pretreatment and posttreatment period, as further specified in Table II. Whenever runoff exceeded 250 ml, a sample was collected for determination of sediment and organic matter contents by using standard laboratory methods (filtration at 14 µm, drying for 24 h at 105°C and loss-on-ignition for 4 h at 550°C; APHA, 1998).

The third phase began on 30 March 2009, after the logging had been completed, when two more micro-plots and two more small plots were installed at close distances from the previous micro-plots (<5 m) along with six sediment fences (Robichaud & Brown, 2002) that had been set up at some 10–20 m distance in the upslope direction. Following the design by Fernández *et al*. (2011), these sediment fence plots ('SF plots') of roughly 2-m wide and 5-m long were bounded by means of a geotextile fabric and delimited by metal sheets to avoid run-on into the plots. The geotextile fabric filtered the runoff, and only the sediments accumulated at the bottom of the SF plots were collected at monthly intervals from 31 March 2009 to 12 October 2010. Afterwards, the SF plots were emptied

Table II. Overall figures of rainfall, overland flow, soil losses, and effectiveness of hydromulching during the first 3 years after a wildfire in a maritime pine plantation

		Year 1		Year 2	Year 3
Period		Pre	Post	Post	Post
Start date		5 November 2008	31 March 2009	21 September 2009	12 October 2010
End date		11 February 2009	21 September 2009	12 October 2010	28 November 2011
Rainfall (mm)		609	282	1464	1527
Overland flow					
Number of plots (C/Hm)		*4/0*	*4/4*	*4/4*	—
Runoff (mm)	C	363	140	691	—
	Hm	—	61	152	—
Runoff coefficient (%)	C	60	50	47	—
	Hm	—	22	10	—
Erosion					
Number of plots (C/Hm)		*4/0*	*7/7*	*7/7*	*3/3*
Soil loss ($g\,m^{-2}$)	C	86	217	361	247
	Hm	—	36	63	109
Specific soil loss	C	0·14	0·77	0·25	0·16
($g\,m^{-2}\,mm\ rain^{-1}$)	Hm	—	0·13	0·04	0·07
Organic matter content (%)	C	48	50	52	—
	Hm	—	57	57	—
Effectiveness of	Runoff	—	−56	−78	—
hydromulching (% change)	Soil losses	—	−83	−83	−56
	OM %	—	15	10	—

C, control; Hm, hydromulching; OM, organic matter.

on a single occasion, on 28 November 2011, comprising the fourth phase of this study. The collected sediments were later analyzed for their moisture and organic matter contents by using standard laboratory methods (drying for 24 h at 105°C and loss-on-ignition for 4 h at 550°C; APHA, 1998).

On 31 March 2009, the hydromulch was applied to two of the four micro-plots, two of the four small plots, and three of the six SF plots, all of which were selected randomly. In addition, it was applied to one of two adjacent soil strips of 5-m wide and 10-m long, which had been delineated for monitoring of selected soil properties by using destructive techniques. The hydromulch was provided and applied by Serraic, Lda. by using a jet hose operated by a person on foot. It consisted of an aqueous mixture of wood fibers, seeds, a surfactant, nutrients, a natural bio-stimulant and a green colorant applied at a nominal ratio of 3.5 Mg ha^{-1}. The formulation is confidential, but the company guaranteed that the components are nontoxic for humans or the environment. The seed composition was also confidential, but detailed descriptions of the floristic composition in the SF plots suggested that it included grass (e.g., *Lolium perenne* L.) as well as shrub species [*Cytisus striatus* (Hill), *Ulex minor* Roth.].

Ground cover was measured at seven occasions between 31 March 2009 and 12 October 2010 and finally on 11 November 2011. The ground cover was recorded at each intersection point of a 5 × 5-cm grid in the case of the micro-plots and small plots, and of a 10 × 10-cm grid in the case of the SF plots, that is, at 100, 200, and 400 points, respectively. Each recording involved classifying the ground cover according to seven categories: stones bigger than 2 mm ('Stone'), bare soil ('Bare'), ashes ('Ash'), litter ('Litter'), hydromulch ('Hm'), native vegetation ('Natveg'), and vegetation introduced by hydromulch ('Introveg'). The data also were grouped into two lumped categories: total vegetation ('Tveg') and total protective ground cover ('Hlv'), with the latter being the sum of hydromulch, litter, and vegetation.

The soil strips were sampled at monthly intervals from 22 April 2009 to 11 August 2010 for a total of 17 occasions. Sampling involved destructive measurements of soil shear strength, using a torvane (vane tester, Eijkelkamp), and of SWR, using the molarity ethanol drop (Doerr, 1998). At the bottom of each 50 m^2-strip, 15 equally spaced measurements were made along a horizontal transect, and this transect was then shifted approximately 0·5 m upslope for the next sampling occasion. Before measuring shear strength or repellency, any hydromulch, stones, litter, or ashes were removed. The molarity ethanol drop test was slightly modified in accordance with our prior studies (e.g., Keizer *et al*., 2005a, 2005b, 2008). In this study, three drops of pure water were applied to the soil surface, and, if two of the three drops did not infiltrate within 5 s, three drops with successively higher ethanol concentrations were applied until two of the three drops infiltrated within 5 s. The nine ethanol concentrations used were 0, 1, 3, 5, 8·5, 13, 18, 24, and 36%. In data analysis, the overall median of the relative frequency of any ethanol concentrations higher than 0%, calculated over the total measurements in each strip, was called SWR frequency.

Volumetric soil moisture content was monitored at a depth of 0–5 cm at eight locations: four within the untreated SF plots and four within the hydromulched SF plots. This was carried out using eight EC-5 sensors linked to two Em5b data loggers (Decagon Devices, Inc.) and recording data at 10 min intervals. For each read-out period, initial soil moisture content ('Sm') was calculated as the soil moisture at the start of the largest rainfall event during that 1- to 2-weekly period by using the data of the automatic rainfall gage to identify this event.

Data Analysis

For the statistical analyses described in the succeeding text, runoff volumes and (specific) soil losses were fourth-root transformed so that the residuals did not fail the assumption of normality according to the Kolmogorov–Smirnov test at $\alpha \leq 0{\cdot}05$, whereas runoff coefficients were square-root transformed for the same reason. Furthermore, 16 read-outs with low rainfall amounts (less than 6 mm) had to be removed from the data set to prevent non-normality of the residuals.

The effects of hydromulching, plot size, and time-since-hydromulching on the dependent variables (runoff volume, runoff coefficient, soil losses, specific soil losses, and organic matter content of the eroded sediments) were assessed by means of a three-way repeated measures analysis of variance (ANOVA) (Ott & Longnecker, 2001). The variance–covariance structure of each dependent variable was selected according to the lowest values of the Akaike information criterion and the restricted maximum likelihood (REML) fit (Littell *et al.*, 2006). The heterogeneous first-order auto-regressive variance–covariance structure was selected for all dependent variables except runoff coefficient, for which a spatial power structure was selected. In addition, specific contrasts between the treated and control plots, for each individual read-out as well as between the three plot sizes, were tested by means of the least squares means and adjusted by the Tukey–Kramer method (Kramer, 1956). Repeated measures ANOVA was also used to test the treatment and time effects on the seven ground cover categories and the initial soil moisture content. In the case of soil resistance and SWR frequency, however, the treatment effect could only be tested using a nonparametric test, that is, the Mann–Whitney *U*-test ($\alpha \leq 0{\cdot}05$).

Stepwise multiple linear regressions using the REG procedure in SAS (Littell *et al.*, 1996) were used to determine how well the weekly runoff volumes ($n = 35$) and the monthly soil losses ($n = 17$) could be explained by a set of independent variables. These variables were selected sequentially in a forward selection procedure, in order of decreasing significance by using a minimum p value of 0·05. The 16 independent variables were plot size ('Plotsz'), rainfall amount ('Rain'), 30-min maximum rainfall intensity ('I30'), days since the last rainy day ('Drain'), the seven individual ('Stone', 'Bare', 'Ash', 'Litter', 'Hm', 'Natveg', and 'Introveg'), the two lumped categories ('Tveg' and 'Hlv'), soil shear strength ('Storv'), SWR frequency, and initial soil moisture content ('Sm'). Especially because the various cover categories can be expected to reveal strong correlations, collinearly tests were included in the stepwise procedure, removing independent variables with a condition index higher than 30 (Belsley *et al.* 1980) from the regression models.

RESULTS

Rainfall Amount and Intensity

Rainfall was considerably lower during the first year after the wildfire (1,014 mm) than during the two subsequent years (1,464 and 1,527 mm, respectively; Table II). Even though this study did not commence until 8 December 2008 and had to be interrupted, because of the salvage logging, during March 2009, the present analysis covered almost 90% of the rainfall during the first post-fire year (891 mm; Figure 1). From these 891 mm, 609 mm fell before the logging and the hydromulch application (designated here as 'pretreatment period'), and 282 were measured until the end of post-fire year 1. The highest rainfall amounts were measured during winter, in January 2009 and 2010 with 244 and 262 mm, respectively. The highest rainfall intensities, however, occurred during different times of the first

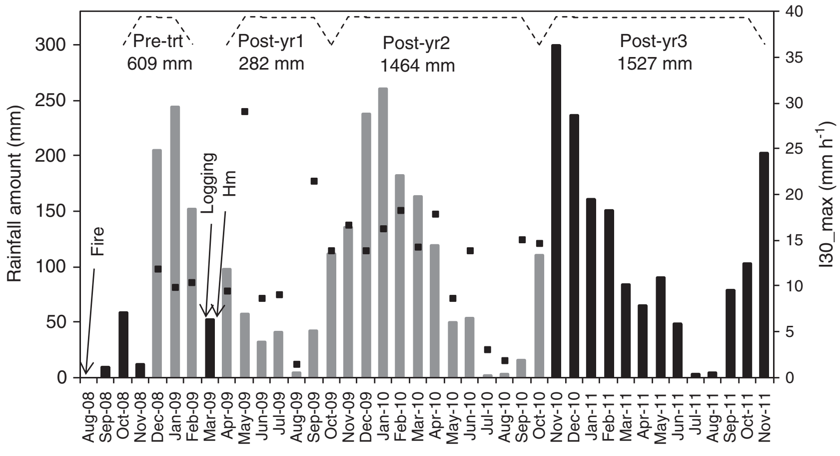

Figure 1. Monthly rainfall (mm) and maximum monthly 30-min rainfall intensity over the study period. Black columns represent total rainfall where no rainfall intensity data were collected. Arrows indicate the date of the fire, logging, and the hydromulch application (Hm), respectively.

post-fire year, during May 2009 and September 2009 with maximum I30 of 29 mm h^{-1} and 21 mm h^{-1}. During the second post-fire year, I30s of 15 mm h^{-1} occurred at least once a month from October 2009 to April 2010.

Ground Cover

At the start of this study, in December 2008, half of the soil surface was covered by ashes, and less than 10% was bare (Figure 2; Table I). By 26 March 2009, after the logging had been completed, ash cover had decreased to 28%, the bare soil cover had increased to 17%, and the stones had become the predominant cover category with, on average, 42%. The recovery of the vegetation was very slow on the control plots, as vegetative cover continued to be near zero 1 year after the fire (August 2009), but reached 30% after the second year (October 2010) and a mere 36% at the beginning of the fourth post-fire year (November 2011). Immediately after its application, on 31 March 2009, the hydromulch provided a cover of 80% on average, but this cover was significantly higher at the two micro-plots and two small plots (90% ± 4%) than at the three SF plots (64% ± 2) (ANOVA, $p < 0{\cdot}05$). This difference was no longer significant after five months (August 2009), even though the hydromulch cover continued higher at the four runoff plots (64% ± 12) than at the three SF plots (47% ± 7; ANOVA, $p = 0{\cdot}06$). There was a marked decrease (5·3% per month) in the average of the hydromulch cover during the first 5 months after its application. After 1 year from the application (1 April 2010), the hydromulch cover decreased to 27% on average (an annual decay rate of 4·6% per month). This decrease in hydromulch cover was, by and large, compensated by an increase in protective soil cover due to the native and introduced vegetation (including the litter it produced). The cover of the introduced vegetation was at its maximum (22%) in June 2010 and became practically zero by November 2011. The native vegetation recovered slowly on the hydromulched plots as well but by November 2011 did attain a clearly higher cover than at the control plots (52% vs. 36%). The total protective ground cover (lumped into the 'hlv' category) was around 75% through all the post-treatment period. When the stone cover is included, a protective layer consistently covered 90% of the surface.

Soil Properties

The monthly values of soil shear strength, frequency of SWR, as well as the soil moisture content over the post-treatment period are depicted in Figure 3. The three variables oscillated across the monitoring period according to the rainfall amounts. Soil shear strength and soil moisture varied in the wake of the rainfall variations. By contrast, SWR showed the lowest values during the rainiest months.

Overall, soil resistance to detachment was lower at the untreated than treated strip ($2{\cdot}4 \pm 0{\cdot}7$ kg cm^{-2} vs. $2{\cdot}8 \pm 0{\cdot}5$ kg cm^{-2}; *U*-test: $Z = -5{\cdot}04$; $p < 0{\cdot}01$). Shear strength was clearly lowest at the control strip during 12 out of 17 months as opposed to 2 months at the hydromulched strip, when shear strength was also greater than during the remaining months.

The hydromulched strip, overall, was less repellent than the control (15% vs. 35% SWR frequency; *U*-test: $Z = -6{\cdot}07$; $p < 0{\cdot}01$) and consequently had higher soil moisture (18·1% volume ± 9·7 vs. 14·3% ± 6·7; ANOVA: $F = 7$; $p < 0{\cdot}05$). In certain periods, however, the opposite was true, as is well-illustrated by Figure 3. In the case of soil moisture content, these periods were confined to the dry season of summer 2009; in the case of SWR, it also happened during summer 2010.

Overall Runoff and Soil Losses

Roughly half of the rainfall was converted into runoff on the control plots (Table II). This corresponded to 360 mm of runoff [runoff coefficient (rc) = 60%] during the pre-treatment period, 140 mm during the post-treatment

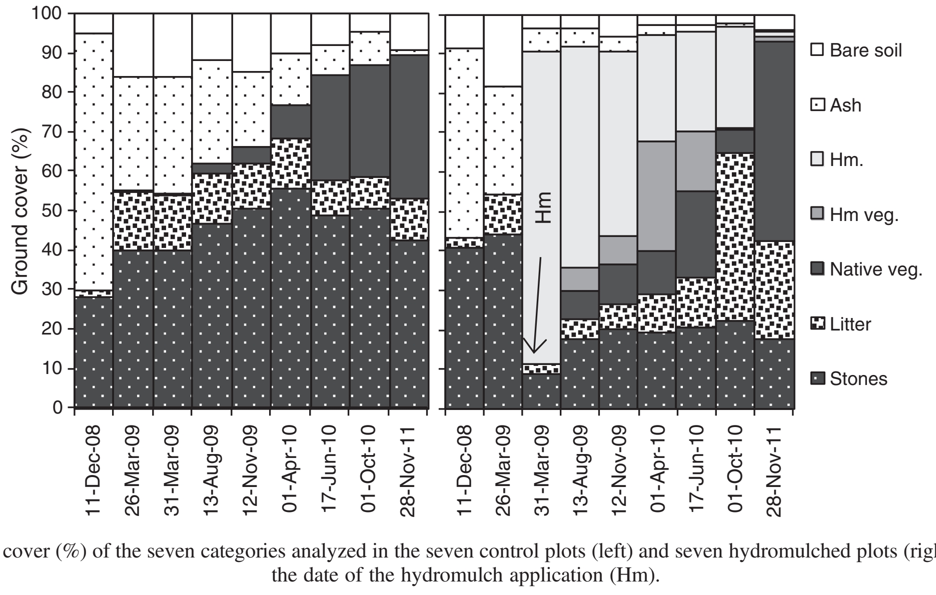

Figure 2. Mean ground cover (%) of the seven categories analyzed in the seven control plots (left) and seven hydromulched plots (right). The arrow indicates the date of the hydromulch application (Hm).

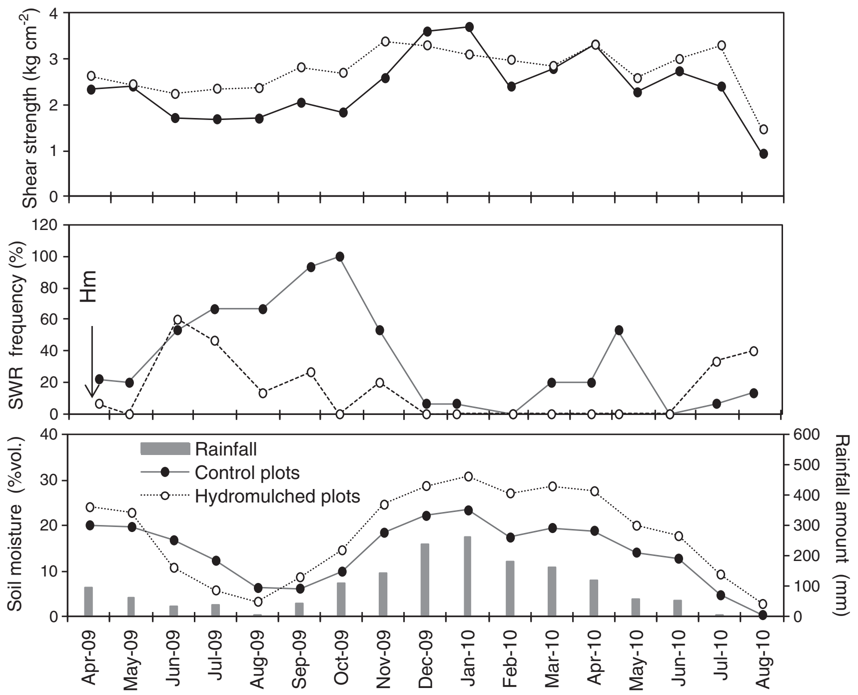

Figure 3. Monthly average values of soil shear strength (top), frequency of soil water repellency (middle) and initial soil moisture content (i.e., prior to rainfall events) and rainfall (bottom) for the control and hydromulched strips.

period of the first post-fire year (rc = 50%), and 691 mm during the second post-fire year (rc = 47%). These differences coincided with the variations in rainfall amount. However, the same was not true in the case of soil losses. The control plots produced, on average, 86 g m^{-2} during the pre-treatment period, 217 g m^{-2} during the post-treatment period of the first post-fire year, and 361 g m^{-2} during the second post-fire year. There was a fivefold increase in the specific soil losses between the pre-treatment and post-treatment periods (from 0·14 to 0·77 g m^{-2} mm rain^{-1}), and after that, the specific soil losses decreased progressively until reaching values similar to those prior to the logging during the third year (0·16 g m^{-2} mm rain^{-1}; Table II).

Hydromulching was highly effective in reducing overland flow, with, on average, 56% during the first post-fire year and even 78% during the subsequent year (Table II). Hydromulching effectiveness in decreasing soil losses exceeded the effectiveness at reducing overland flow to a marked extent, amounting to 83% during both years. During the third post-fire year, however, the effectiveness in mitigating erosion reduced to 56%. Hydromulching did, however, increase somewhat the relative amounts of organic matter in the eroded sediments to 57% as opposed to 50% and 52%.

The ANOVA analysis of Table III showed that the treatment effect strongly influenced all the variables, especially

Table III. Summary of the three-way repeated measures analysis of variance of the 1- to 2-weekly runoff amounts (fourth-root transformed), runoff coefficients (square-root transformed), as well as of the monthly soil losses, specific soil losses (fourth-root transformed) and organic matter contents of the eroded sediments during the posttreatment period (31 March 2009–12 October 2010)

Variable Unit n	Df num, den	Runoff amount mm 35	Runoff coeffient % 35	Df num, den	Soil losses g m^{-2} 17	Specific soil losses g m^{-2} mm^{-1} rain 17	Organic matter content % 17
Treatment	1,4	**80·2**	**176·3**	1,8	**71·7**	**63·7**	**9·3**
Size	1,4	1·0	0·0	2,8	3·3	2·6	2·7
Size*treatment	1,4	3·2	3·9	2,8	1·7	1·4	0·3
Time	34,136	**116·6**	**17·3**	16,124	**27·8**	**21·2**	**3·0**
Treatment*time	34,136	**8·4**	**3·2**	16,124	**5·0**	**4·5**	**1·9**
Size*time	34,136	**2·1**	0·7	30,124	**3·8**	**3·6**	**1·7**
Size*treatment*time	34,136	**2·1**	1·1	30,124	**3·1**	**3·0**	1·5

Df, degrees of freedom; num, numerator; den, denominator.
The F values in bold, or both in bold, and underlined were statistically significant at $\alpha = 0{\cdot}05$ and 0·01, respectively.

in the case of runoff coefficient (F value of 176) and less important in the case of the organic matter content ($F = 9$). The strong treatment effect, especially in the case of runoff coefficient as highlighted by the big F value (176), contrasted with the lack of effect of the plot size.

In Figure 4 it can be observed that the differences in runoff between plot sizes were very low (in the order of 12–20%, for micro-plots and small plots, respectively). The runoff on the control plots decreased with increasing plot size mainly because of the low runoff amount of one of the small plots (684 mm), whereas the same was true but in the opposite sense in the case of one small hydromulched plot (309 mm). These opposite tendencies resulted in a higher hydrological effectiveness of hydromulching for the micro-plots compared with the small plots (on average, 80% vs. 68%). Plot size also did not play a clear-cut role in soil losses, but the variance increased, especially in the case of the control SF plots (up to 70%). Consequently, the overall reduction in soil losses on the micro-plots and small plots was somewhat higher compared with the SF plots (90%, 89%, and 76%, respectively).

Temporal Patterns in Overland Flow and Soil Losses

The average monthly runoff amounts produced by the untreated plots revealed a marked seasonal pattern in which peak runoff values appeared to antecede the maximum monthly rainfall values during the winter season (Figure 5a). As a result, runoff coefficients were highest during the autumn months, varying between about 80% to 90% in December 2008, November 2009, and October 2010. High runoff coefficients were also observed during late spring and early summer, when rainfall amounts were comparatively small (<53 mm), attaining 62% in July 2009 and 81% in June 2010. The average monthly soil losses at the untreated plots revealed a less obvious temporal pattern (Figure 5b). The four peak losses of 50 $g\,m^{-2}\,month^{-1}$ or more occurred during autumn (December 2008, September and November 2009) and spring (May 2009). Apparently, the latter peak was associated with the elevated maximum rainfall intensity ($I30 = 29\,mm\,h^{-1}$), whereas the December 2008 and November 2009 ones were rather related to runoff peaks. The average specific soil losses suggested a contrast between the two months with the highest maximum rainfall intensities—that is, May and September 2009—and the remaining months. The specific losses during these two months amounted to 0·8 and 1·2 $g\,m^{-2}\,mm\,rain^{-1}$, respectively, as opposed to the baseline monthly average of 0·25 $g\,m^{-2}\,mm\,rain^{-1}$ for the rest of the study period.

The hydromulched plots produced, on average, consistently lower amounts of monthly runoff as well as monthly soil losses than the untreated plots (Figure 5a and 5b). In the case of runoff, these monthly differences were statistically significant from July 2009 onwards, with the exception of the summer 2009 and 2010 months with little to no rainfall. In the case of soil losses, however, the monthly differences were also statistically significant for the first 2 months following hydromulching and, thus, for basically all of the 19 months with noticeable rainfall. Even so, the three-way ANOVA results indicated that hydromulching did not have an unequivocal statistically significant effect on monthly soil losses, as the triple interaction term of treatment x time-since-mulching x plot size was statistically significant (Table III). The same applied to the corresponding specific soil losses as well as to the 1- to 2-weekly runoff volumes and *mutatis mutandis* (i.e., because of a significant treatment x time-since-mulching interaction) to the runoff coefficients and the organic matter content of the eroded sediments.

Hydromulching failed to produce significant reductions in overland flow generation (average 1- to 2-weekly values) across the whole range of maximum rainfall intensities (Figure 6). There was, however, a tendency for the hydrological effectiveness of hydromulching to decrease with maximum rainfall intensity, reflecting first and foremost the comparatively low effectiveness (<50%) for the two more intense measurement periods that happened in May and September 2009. Also, the effectiveness of hydromulching to reduce average monthly soil losses was comparatively low for these two highest maximum rainfall intensities, albeit it still amounted to some 80% and corresponded to a statistically significant difference between the hydromulched and untreated plots. In overall terms, however, the reduction in soil losses lacked an obvious relationship with rainfall intensity.

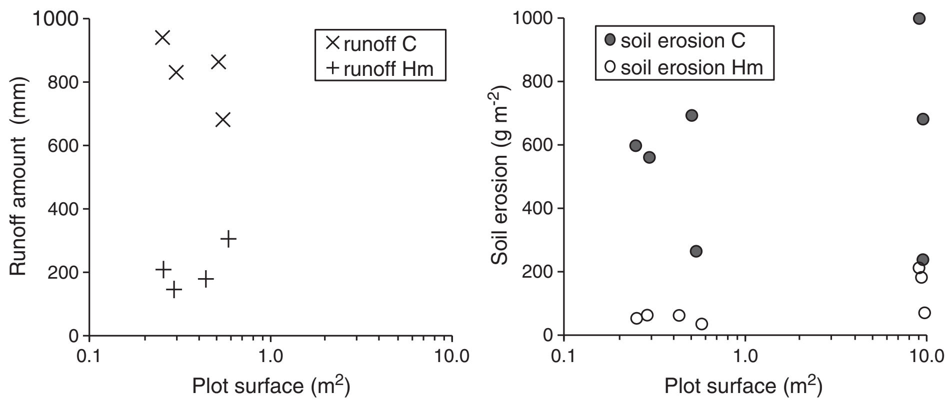

Figure 4. Total overland flow (mm) and total soil losses ($g\,m^{-2}$) of the individual untreated and hydromulched plots over the first and second year of the posttreatment period (31 March 2009 to 12 October 2010).

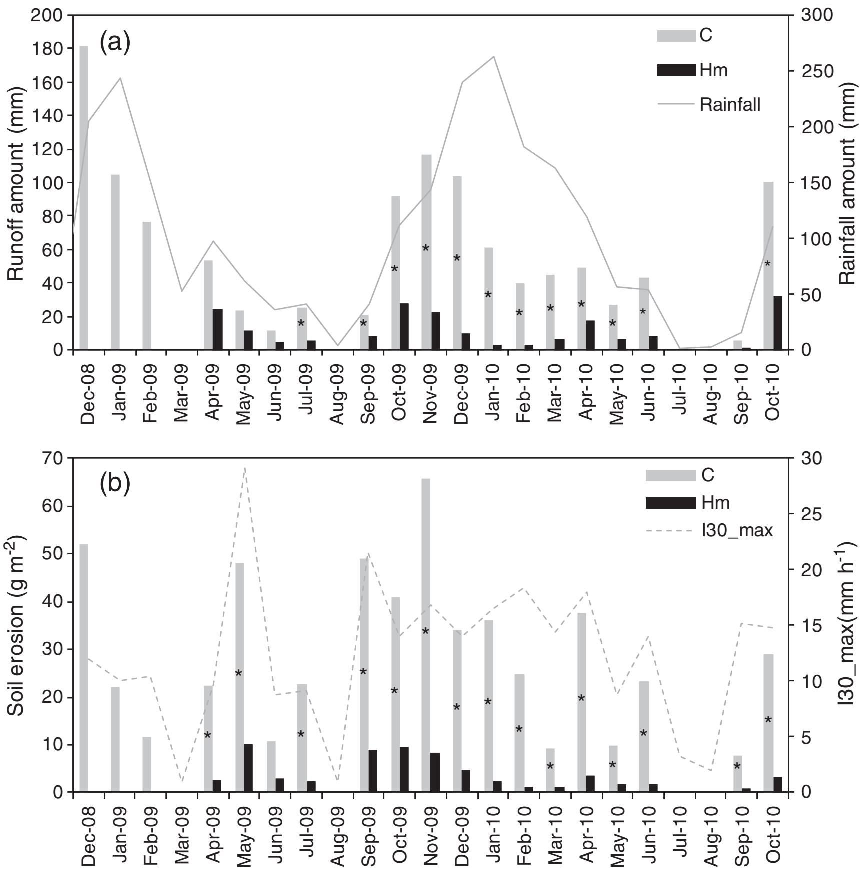

Figure 5. Average monthly values of rainfall (mm) and overland flow (mm) (5a) and of 30-min maximum rainfall intensity (I30; mm h^{-1}) and soil losses (g m^{-2}) (5b) for the untreated and hydromulched plots from the fourth through the twenty-sixth month after the wildfire. Asterisks denote significant least squares mean differences between hydromulched and control plots ($p < 0{\cdot}05$).

Key Factors Explaining Runoff and Soil Losses

Stepwise multiple linear regression with all eight hydromulched and untreated runoff plots together ('global model') revealed that the total protective ground cover ('hlv') stood out as the principal factor in overland flow generation, explaining more than twice as much of the variation in fourth-root transformed runoff amount than the second factor, I30 (31% vs. 13%; Table IV). The hydrological response of the untreated plots alone, however, could clearly be explained best by rainfall amount (41% of variance), whereas that of the hydromulched plots alone was mainly controlled by maximum rainfall intensity, albeit to a lesser degree (19% of variance). Initial soil moisture content was the second most important (and significant) explanatory variable of the runoff produced by the untreated but not the hydromulched plots. The negative sign of its coefficient suggested that the role of initial soil moisture was indirect, with SWR increasingly enhancing overland flow generation as soils dry out. Figure 7 illustrated well that the hydrological response of the untreated plots was stronger under drier than wetter soil conditions. A similar tendency was suggested for the hydromulched plots but just for rainfall amounts below 60 mm, as higher rainfall amounts were associated with wetter soils at the hydromulched than untreated strips.

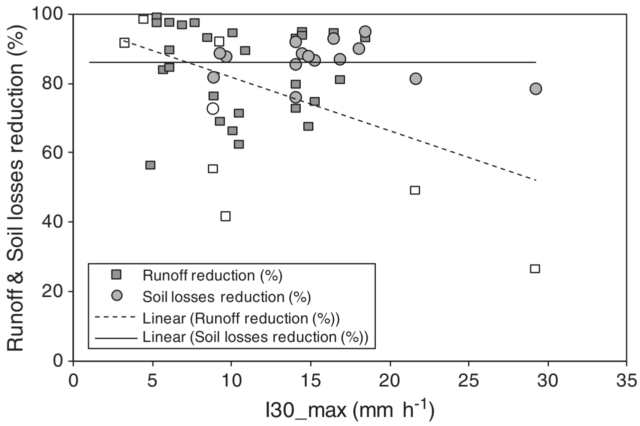

Figure 6. Weekly runoff (squares) and monthly soil losses (circles) reductions at the hydromulched plots compared with untreated plots in relation to 30-min maximum rainfall intensity for the posttreatment period (31 March 2009 to 12 October 2010). Gray-filled/white-filled symbols correspond to significant/not significant least squares mean differences between control and hydromulched plots (at $\alpha = 0{\cdot}05$). Dotted and continuous lines correspond to linear regression equations fitted to runoff and soil loss reductions, respectively.

The predominant role of total protective ground cover ('hlv') was even more pronounced in the case of the global model for soil losses than that for runoff volumes, explaining over half of the variation (55%; Table IV). The most conspicuous contrast between the erosion and runoff

Table IV. Multiple regression models for 1- to 2-weekly runoff amounts ($n = 35$) and monthly soil losses ($n = 17$) for all plots together ('Global') and for the untreated ('Control') and hydromulched plots separately

Selected variable		Global models			Control models			Hydromulching models		
		Parameter estimate	Variable name	Partial r^2	Parameter estimate	Variable name	Partial r^2	Parameter estimate	Variable name	Partial r^2
Runoff amount (mm; 4th root transformed)	Intercept	1·86			1·97			0·40		
	1st variable	−0·01	Hlv	0·31	0·01	Rain	0·41	0·05	I30	0·19
	2nd variable	0·02	I30	0·13	−0·03	Sm	0·11	0·01	Hm	0·05
	3rd variable	−0·02	Sm	0·06	−0·01	Tveg	0·03			
	4th variable	0·01	Rain	0·03						
	Cumulative r^2			0·53			0·54			0·24
Soil losses ($g\,m^{-2}$; 4th root transformed)	Intercept	1·65			1·58			0·76		
	1st variable	−0·01	Hlv	0·55	0·03	Bare	0·26	0·08	Bare	0·35
	2nd variable	0·03	Bare	0·07	0·03	I30	0·11	0·02	I30	0·08
	3rd variable	0·03	I30	0·05	−0·01	Hlv	0·06			
	Cumulative r^2			0·68			0·43			0·43

The independent variables selected (statistically significant at $\alpha = 0{\cdot}05$) were: Rain, rainfall amount; I30, 30-min rainfall intensity, total protective ground cover; Hlv, the sum of hydromulch, litter, and vegetation cover; Hm, hydromulch cover; Tveg, total vegetation cover; Bare, bare soil cover; Sm, initial soil moisture.

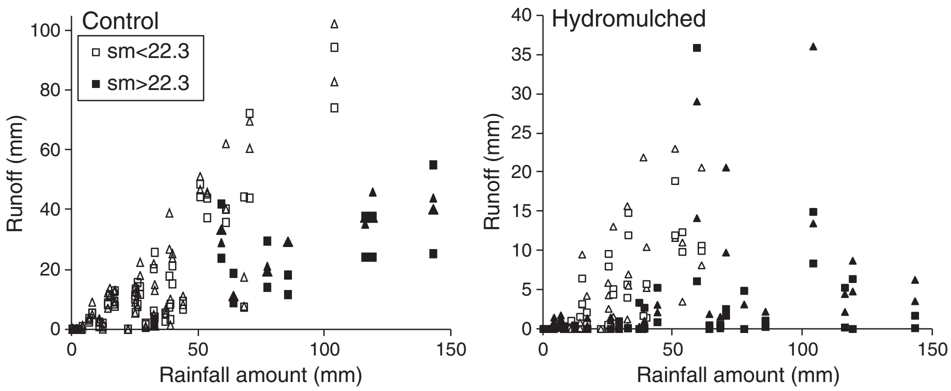

Figure 7. Runoff versus rainfall amounts for the untreated (left) and hydromulched (right) micro-plots (triangles) and small plots (squares) under contrasting initial soil moisture conditions, of less versus greater than 22·3% (open and filled symbols, respectively). Note the different scales of the two Y axes.

results, however, was evidenced by the treatment-specific models. Bare soil cover clearly outranked rainfall amount/intensity as the prime factor explaining soil losses, not only at the untreated plots (26% vs. 11% of variance) but also at the hydromulched plots (35% vs. 8% of variance).

DISCUSSION

Post-Fire Hydrological and Erosion Response in Pine Sites of Central Portugal

Post-fire runoff coefficients as high as observed here were also reported by previous studies in north-central Portugal, such as Ferreira *et al*. (2008) and Malvar *et al*. (2011) by using rainfall simulation experiments. Both prior studies related their strong hydrological response to extreme SWR. In the present study, however, the role of SWR would be limited to the first year after the wildfire, when repellency was moderate, and mostly hydrophilic after November 2009. This reduced importance of SWR was also suggested by the multivariate linear regression model that was fitted to the runoff data from the control plots. The global regression model attested that it was rather ground cover that played a key role in overland flow generation. Pierson *et al*. (2009) likewise argued that ground cover exerted a greater influence on post-fire hydrological response than SWR. Various studies in Portugal (Shakesby *et al*., 1996; Ferreira *et al*., 2008; Prats *et al*., 2012) have furthermore attributed low post-fire runoff coefficients in pine stands to needle cast from scorched tree crowns (Shakesby *et al*., 1996; Cerdà & Doerr, 2008; Ferreira *et al*., 2008; Prats *et al*., 2012).

The soil losses from the control plots during the first post-fire year (302 g m^{-2}) were higher than the range of 80–220 g m^{-2} year^{-1} reported by other studies in burnt pine plantations (Shakesby *et al*., 1996; Fernández *et al*., 2007; Ferreira *et al*., 2008; Prats *et al*., 2012). This could be due to the salvage logging activities that took place during late winter/early spring 2009, as was also suggested by the markedly higher specific soil losses immediately after logging than during the pretreatment period. Logging-enhanced erosion rates were also reported by Inbar *et al*. (1997) and suggested by Malvar *et al*. (2013) but not by Fernández *et al*. (2007). The latter authors attributed their findings to the low severity of the fire, the low rainfall erosivity, and the reduced perturbations of the soil by the machinery employed. To minimize the erosion effects of post-fire logging, it is widely recommended to delay the logging activities until litter fall from scorched tree canopies has provided a ‘natural’ mulching (Rab, 1994; Castillo *et al*., 1997; Edeso *et al*., 1999; Fernández *et al*., 2004, 2007; Cerdà & Doerr, 2008).

The soil losses during the first post-fire year fitted in well with the low values that were reported by Shakesby (2011) for moderate severity on field plots in the Mediterranean region (321 g m^{-2} year^{-1}), which was attributed to an intensive land-use history. By contrast, in regions of lower forest interventions such as North America, post-fire erosion rates can be one order of magnitude higher, amounting to 2,500 g m^{-2} year^{-1} (Spigel & Robichaud, 2007). The discrepancy between these two geographical regions seems to be much smaller for organic matter losses, with values of 200 and 150 g m^{-2} year^{-1}. High losses of organic matter are of particular relevance as they can easily compromise soil fertility and, thus, on-site land-use sustainability and downstream surface water quality through pollution with toxic pyrogenic organic compounds (Vila-Escalé *et al*., 2007; Campos *et al*., 2012).

A protective ground cover was also the most important factor explaining the monthly soil losses observed in this study and the differences therein between the treated and untreated plots. This agreed well with the bulk of post-fire soil erosion studies (e.g., Benavides-Solorio & MacDonald, 2001; Pannkuk & Roubichaud, 2003; Benavides-Solorio & MacDonald, 2005; Fernández *et al*., 2008; Larsen *et al*., 2009). At the same time, bare soil cover played a key role in the differences in soil losses among the hydromulched plots, as well as among the control plots. Pietraszek (2006) equally attested to the relevance of bare soil cover for soil losses from untreated areas. It could explain 50% of the variability in soil erosion produced by ten sites that had burnt from less than one up to 10 years earlier.

Effectiveness of Hydromulching in Reducing Runoff and Soil Losses

The hydromulch was a complex mixture which contained water, wood fibers, seeds, surfactants, seed-growing biostimulants, nutrients and a green colorant. It is intended that each component affected some of the pieces of the post-fire runoff erosion process.

Runoff was highly reduced at the treated plots, between 56% and 73%, which is higher than in other post-fire mulching experiments, both with straw (Bautista *et al*., 1996; Groen & Woods, 2008) and forest residues (Shakesby *et al*., 1996; Prats *et al*., 2012). Probably, this high effectiveness could be related to the effect of the wood fibers, because it increases the surface water storage capacity, but also due to the effect of the surfactants, a wetting agent that reduces SWR and increases soil infiltration (Leighton-Boyce *et al*., 2007; Madsen *et al*., 2012).

Soil losses were highly reduced in the hydromulch plots during the 3 years after the wildfire. Ground cover was pointed out as the main factor controlling soil losses, but the hydromulch mat showed a rapid decay during the first year after the application. This was identified as one of the disadvantages of hydromulchings (MacDonald & Robichaud, 2007). In the present study, the decayment rates of the hydromulch ranged between 4% and 6% per month, very similar to other research with hydromulch (Hubbert *et al*., 2012; Robichaud *et al*., 2013a). In contrast to those sites, our hydromulch was highly conducive to germination and growth of plants from seeds. Thus, the introduced seeds compensated for the loss of hydromulch with progressively more plant and litter cover, which resulted in more than 70% protective ground cover since the hydromulch application until the third post-fire year (Figure 2).

Besides the composition, the application technique can influence the hydromulch effectiveness. In this study, the area was already logged and the plots were small, which a priori will facilitate the spread of the hydromulch from a jet hose operated on foot. However, the hydromulch cover was significantly lower on the SF plots despite being sufficient to reduce soil erosion. Rough (2007) and Robichaud *et al*. (2010) reported that the hydromulch sprayed from vehicles was intercepted by the standing trees, and they recommended special caution when applying the mixture in areas with a high density of dead trees and from long distances. Aerial hydromulch can be a better and less expensive option, but Hubbert *et al*. (2012) checked that the intended application rates of 50% and 100% hydromulch cover resulted in only 20–26% and 56%.

Unsuccessful hydromulch experiences were first attributed to extreme rainfall events (Wohlgemuth *et al*., 2011) or to the long length of the plots (Napper, 2006). Robichaud *et al*. (2010) pointed out that hydromulch effectiveness depended on slope length, only being effective at slopes shorter than 10–20 m, when interrill erosion was the dominant process instead of rill erosion. The former authors hypothesized that in their long slope sections, the smooth and dense hydromulch mat had little resistance against the sheer force of concentrated flow. But on the other hand, the research of Rough (2007) showed that aerial hydromulching was highly effective and was carried out at the hillslope scale (2,500 m^{-2}, on average), where rills were frequent (0·1 rills m^{-2}) and after extreme rainfall events (I30 = 40 mm h^{-1}). Many other hydromulch formulations are available and are being evaluated for their capacity to reduce soil losses. As concluded by Robichaud *et al*. (2013a), the differences in hydromulch components, application techniques, and application rates can greatly impact hydromulch effectiveness. However, Napper (2006) referred that one of the major problems is the difficulty in knowing the specific chemical composition that was applied in a given situation because most of the hydromulch formulations are kept confidential.

Hydromulching Effects in Soil Properties

Soil properties in agriculture had been typically improved by mulching (Smets *et al*., 2008) by materials such as manure, stones, straw, forest residue, and wood shreds (Harris & Yao, 1923; Mulumba & Lal, 2008; Foltz & Copeland, 2009). Regarding post-fire soil shear strength, the results are not conclusive. Bautista *et al*. (1996) and Fernández *et al*. (2011) found no differences between control and straw mulch plots. Fernández *et al*. (2007) found lower figures in logged compared to unlogged plots. They related these lower values to the absence of roots, once that the logged plots showed a much lower vegetation cover. Agreeing with them, the statistically higher soil shear strength measured on the hydromulch strip could be related to a higher vegetation cover compared to the control strip. Regarding soil water properties, our results are consistent with other mulch experiments (Smets *et al*., 2008; Bautista *et al*., 2009; Prats *et al*., 2012) in which higher soil moistures were found on the mulched areas. The hydromulching layer acted as a water adsorbent dense mat, which effectively increased the soil water retention capacity. It prevented sunlight from reaching the soil surface and thereby decreased soil temperatures. Still, the surfactants included on the hydromulch could have a role in increasing soil infiltration and improve the seed germination (Madsen *et al*., 2012). Besides the positive impacts over plant recovery and soil microbial activity (Bautista *et al*., 2009), a major insight suggested by Prats *et al*. (2012) supported the fact that mulching affected the SWR regime of the burnt forest, promoting the hydrophilic soil conditions. However, this was not true during the dry seasons. Probably, the higher plant cover of the hydromulch (13% vs. 3% during the first post-fire summer) could increase the transpiration and thus lowering soil moisture and increasing SWR. Brainard *et al*. (2012) reported a higher water demand of plants during water stress periods in agriculture, and Soto & Diaz-Fierros (1997) found lower soil moisture on the vegetated areas as compared with bare and burnt plots during the first post-fire summer.

CONCLUSIONS

The main conclusions of this study in the effectiveness of hydromulching to reduce runoff and erosion in a recently burnt and logged pine plantation were as follows: (i) hydromulching, providing coverage of 80%, produced marked changes in SWR and soil moisture, especially in the soil cover. Despite a decrease of up to 30% after 1 year from the application, the treatment induced a highly protective ground cover because of an increase of both vegetative and litter cover; (ii) hydromulching was highly effective during the first 19 months after its application, reducing total runoff volumes by 70% and total soil losses by 83%, and continued effectively during the third year following the wildfire, reducing erosion by 56%; (iii) hydromulching was less effective in reducing runoff (around 30%) but not in reducing soil losses (80%) for the more intense storms (I30 higher to $20\,\mathrm{mm\,h^{-1}}$); (iv) the protective soil cover provided by hydromulch, in combination with litter and vegetation, explained runoff and soil losses better than any other variable, however, rainfall intensity and soil moisture explained a considerable portion of the variation in runoff generation; (v) the application of hydromulch was lower than expected on the larger plots (only a 64% hydromulch cover as compared with 90% in the smaller plots), despite both applications having significantly reduced soil losses. Further research will be needed to determine the effective ground cover in order to match hydromulch decayment rate and vegetative cover increase over time, especially to minimize application costs; and (vi) soil losses were similar across the range of plot sizes studied here ($0{\cdot}25$–$10\,\mathrm{m}^{2}$). This, plus the small size of the plots, indicates that interrill erosion was the dominant erosion process. Further research is needed to determine how the effectiveness of hydromulching may vary with increasing slope length when rill erosion is more likely to occur.

ACKNOWLEDGEMENTS

We would like to thank especially the companies Serraic—Create and Innovate, Lda., Atlalusi Europe and USSA corporate, for freely providing and applying the hydromulch, the fire brigade of Arganil municipality for providing the water needed for producing the hydromulch, and the Forestry Office of Arganil and the Portuguese National Forestry Authority for giving authorization to carry out the experiment. The authors also gratefully acknowledge Paula Maia for her the active help with the floristic descriptions, Isabel Fernandes, Rosa Sjerps, and Alexandra Albuquerquer for their help with the fieldwork and laboratory analyses, and, more in general, to all of those who somehow contributed to the EROSFIRE-II project. This research was supported financially through the PhD grants attributed to SPA, (SFRH/BD/33392/2008), MMC (SFRH/BD/41320/2007), and DCSV (SFRH/BD/65907/2009), by the Portuguese Foundation for Science and Technology (FCT), in the framework of the IV program, as well as by the EROSFIRE-II project (PTDC/AGR-CFL/70968/2006), funded by the Portuguese Foundation for Science and Technology, with co-funding by FEDER through the POCI2010 Programme. We also wish to thank the two anonymous reviewers for their valuable help in improving this manuscript.

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Chapter 6: Temporal variation in topsoil water repellency in two recently burnt eucalypt stands in north-central Portugal

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www.elsevier.com/locate/catena

Temporal variation in topsoil water repellency in two recently burnt eucalypt stands in north-central Portugal

J.J. Keizer [a,*], S.H. Doerr [b,1], M.C. Malvar [a,2], S.A. Prats [a,2], R.S.V. Ferreira [a,2], M.G. Oñate [a,2], C.O.A. Coelho [a,2], A.J.D. Ferreira [c,3]

[a] Centro de Estudos do Ambiente e do Mar (CESAM), Departamento de Ambiente e Ordenamento, Universidade de Aveiro, 3810-193 Aveiro, Portugal
[b] School of the Environment and Society, Swansea University, Singleton Park, Swansea SA2 8PP, UK
[c] Departamento de Ciências Exactas e Ambientais, Escola Superior Agrária de Coimbra, Bencanta, P-3040-316 Coimbra, Portugal

Received 1 June 2007; received in revised form 14 December 2007; accepted 31 January 2008

Abstract

The aim of this study is to improve our knowledge of the temporal and spatial variations of soil water repellency following wildfire, in particular for the eucalypt stands that now dominate the landscape of north-central Portugal.

Topsoil water repellency was monitored on 21 occasions over a 10-month period, starting in September 2005, six weeks after a moderately severe wildfire. This was done, on mostly alternating dates, in two neighbouring commercial eucalypt plantations, one with an undisturbed and one with a ploughed soil profile, in the foothills of the Gralheira Massif in north-central Portugal. Water repellency severity was measured *in situ* at soil depths of 2–3 and 7–8 cm using the 'Molarity of an Ethanol Droplet' (MED) test, and accompanied by soil moisture measurements using a ThetaProbe™ or, at a few occasions, sample analysis in the laboratory for gravimetric content.

The results show a broadly seasonal pattern of overall very high water repellency in dry periods and reduced or no repellency following prolonged rainfall. This was more pronounced at the undisturbed compared to the ploughed site, as the latter exhibited strong to extreme water repellency at almost all sampling dates. Significant changes in repellency severity, including major increases, occurred within periods as short as 6–7 days, suggesting that the sampling intervals used here may have not captured the full dynamics of topsoil repellency. Repellency severity was consistently lower at greater soil depth, in particular when considering the whole study period. Soil moisture was found to relate to the temporal variations in repellency. As found in previous studies, however, soil moisture alone was not sufficient to predict the temporal variations in water repellency.

Keywords: Soil water repellency; Soil hydrophobicity; Wildfire; Eucalypt; Soil moisture

1. Introduction

The present study was carried out in the framework of a larger project (EROSFIRE; Keizer et al., 2006, 2007), which aimed at modelling soil erosion at the slope scale in recently burnt eucalypt stands in north-central Portugal. Fire-induced soil water repellency has been identified in the 1960s as a key factor in enhanced soil erosion in southern California chaparral following wildfires (see DeBano, 2000). Fire-induced or -enhanced soil water repellency is widely regarded as an important factor in enhanced runoff response and accelerated soil erosion on recently burnt hillslopes (see e.g. DeBano, 2000; Shakesby and Doerr, 2006). Its relative importance in post-fire catchment responses, compared to other factors such as litter and vegetation destruction, however, has remained uncertain (Shakesby and Doerr, 2006), and its inclusion in soil erosion modelling is still in its infancy (Miller et al., 2003; Larsen and MacDonald, 2005; Robichaud et al. 2007).

* Correspoding author. Tel.: +351 234429290.
E-mail addresses: jjkeizer@ua.pt (J.J. Keizer), s.doerr@swansea.ac.uk (S.H. Doerr), maruxa@ua.pt (M.C. Malvar), sergio.prats@ua.pt (S.A. Prats), raquel.ferreira@ua.pt (R.S.V. Ferreira), onate_marta@hotmail.com (M.G. Oñate), coelho@ua.pt (C.O.A. Coelho), aferreira@esac.pt (A.J.D. Ferreira).
[1] Fax: +44 1792295955.
[2] Fax: +351 234429290.
[3] Fax: +351 239802979.

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doi:10.1016/j.catena.2008.01.004

It is generally accepted that soil water repellency and its hydrological and erosional impacts tend to be transient, with repellency often varying between wet and dry seasons and, where affected by fire, with time since burning (e.g. Doerr et al., 2000; Shakesby et al., 2000). Determining the patterns of temporal variation in water repellency, however, has been the focus of relatively few studies. One of the better studied environments in this context is eucalypt forests. For example, in Australia Crockford et al. (1991) have provided some insight into the soil water repellency fluctuations between wet and dry periods, and Doerr et al. (2006a) have determined inter-annual changes following burning. In north-central Portugal, Keizer et al. (2005b,c) and Leighton-Boyce et al. (2005) have monitored repellency at regular intervals over extended periods. In the latter study, repellency levels and soil water content were measured concurrently on the basis that water content is one of

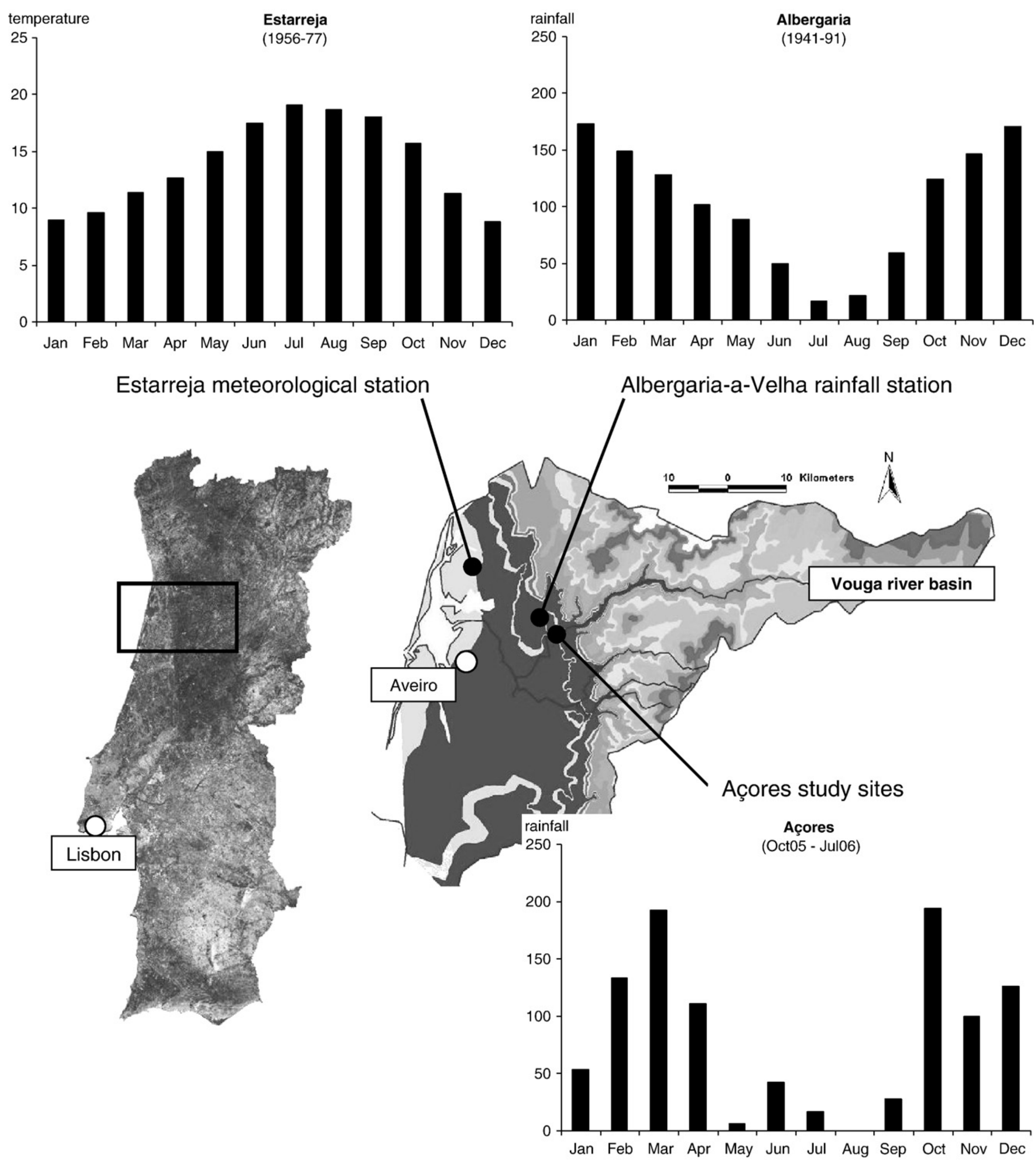

Fig. 1. Location of the study area and of the nearest meteorological and rainfall station (Estarreja and Albergaria-a-Velha, respectively), with their average monthly temperature (°C) and rainfall (mm) values. Also shown are the monthly rainfall amounts (mm) recorded at the study sites during the study period.

the key variables relating to short-term (days to weeks) temporal fluctuations in water repellency (Doerr and Thomas, 2000; Dekker et al., 2001).

In the context of fire-affected environments, eucalypt stands appear to constitute a somewhat unusual case in that very high water repellency levels have commonly been reported also for (long-)unburned stands under summer dry conditions in Australia (Doerr et al. 2006a), South Africa (Scott, 2000) and Portugal (Doerr et al., 1998). In the latter study, long unburned stands showed similar repellency levels to recently burned stands. Thus, for wildfire-affected sites of this type, a major difficulty lies in attributing the observed post-fire water repellency patterns to a fire-related and/or a fire-independent (i.e. pre-fire) component. A further complication in these eucalypt stands is that monitoring temporal repellency patterns is often limited by the typically rapid post-fire intervention (harvesting, ploughing). Irrespective of any fire-effects on water repellency in these eucalypt forests, it is clear that the greatest impact of water repellency on soil hydrological and erosional response is in the post-fire period until some protective ground cover is re-established (Shakesby et al., 2000).

The main aim of the present work was therefore to determine the variations in soil water repellency in eucalypt stands in north-central Portugal at two different depths following a wildfire from shortly after burning to the onset of dry conditions in the following summer, ten months later. Special consideration is given to common, but contrasting forest planting practices in the region by including a ploughed and an unploughed site. Soil moisture content and antecedent rainfall are explored as potential factors in explaining the observed variations in repellency.

2. Materials and methods

2.1. Study area and sampling sites

The work was carried out in two adjacent commercial tree plantations in the foothills of the Gralheira Massif in north-central Portugal (Fig. 1). The two study sites are located at approximately 40° 42′ North, 8° 29′ West at an elevation of 60–70 m a.s.l., and are within the Açores locality of the Albergaria-a-Velha municipality. The sites' slope length, angle and aspect are presented in Table 1.

The study sites were burnt by a wildfire that occurred in early July 2005 and affected an area of about 16 km^2. The complete consumption of the litter and herb cover, in conjunction with the only partial consumption of the shrub layer, suggests that the fire had been of moderate severity (Shakesby and Doerr, 2006; see Table 1 for more details). At the time of the fire, the two sites were – like most of the burnt area – covered with eucalypt trees (*Eucalyptus globulus* Ait.) and, judging by the remaining tree stumps, had experienced at least two prior harvesting and regrowth cycles. Eucalypt plantations have been introduced widely in Portugal since the mid 1950s, stimulated by the demand from cellulose and paper industries (Daveau, 1998; Radich and Alves, 2000), and now dominate the hills and mountains of central Portugal. The two sites were selected for their different land management practices typical for this region.

Table 1
General characteristics of the unploughed (Açores1) and ploughed (Açores2) study sites

Variable	Açores1	Açores2
Physiognomy		
Slope section length (m)	20–25	30–40
Slope angle (degrees)	20	15
Aspect	SE	NE
Fire severity indicators		
Crown damage	Partial	Partial
Height of tree scorching (m)	≤9	≤12
Combustion of litter/herbs layer	Total	Total
Combustion shrub layer	Partial	Partial
Ash colour	Black	Black

At Açores1, trees had been planted without heavy mechanical ground operations, resulting in a relatively undisturbed soil profile. At Açores2, a clear pattern of ridges and furrows (up to 20 cm high) running down the slope is present. Rip-ploughing in preparation for planting is a common practice in this region and, judging by the stand age, would have taken place around 5 years prior to the fire.

The study area is situated at the transition of the region's two major physiographic units, the Littoral Platform dominated by Ceno-Mesozoic deposits and the Hesperic Massif dominated by pre-Ordovician schists and greywackes and Hercynian granites (Ferreira, 1978; Pereira and FitzPatrick, 1995). The soils of the area are mapped – at a scale of 1:1.000.000 – as a complex of Humic Cambisols and, to a lesser extent, Dystric Litosols (Cardoso et al., 1971, 1973). At both study sites, two soil profiles were excavated in the middle and at the bottom of the study slopes. The sites' soils correspond to Umbric or Dystric Leptosols (FAO, 1988), depending on the depth of the A horizon. They are developed over schists and have sandy loam textures and high organic matter contents (8.8–10.4%) (Lucena, 2006).

The climate of the study area can be characterised as humid meso-thermal, with a prolonged dry and warm summer (Köppen Csb) (DRA-Centro, 1998). Mean annual temperature at the nearest meteorological station, located at circa 17.5 km from the study sites (Estarreja: 40° 47′ N., 8° 35′ W., 26 m a.s.l.; 1956–1977) is 13.9 °C, with monthly means ranging from 8.8 °C in December to 19.1 °C in July (DRA-Centro, 1998). The nearest rainfall station, located at circa 4 km distance from the study sites (Albergaria-a-Velha: 40° 42′ North, 8° 29′ West, 131 m a.s.l.; 1941–1991) has an average annual rainfall of 1229 mm and yearly values varying between 750 and 2022 mm (DRA-Centro, 1998). The rainfall data used for the study period were obtained with a tipping-bucket rainfall gauge (Pronamic Professional Rain Gauge) linked to an ONSET Hobo Event Logger that was installed at the foot of the Açores1 study site on September 24 2005. The data prior to this date were obtained with the same instrumentation at a site at less than 1 km distance. The locations of the study sites and of the climate and rainfall station are given in Fig. 1. Monthly rainfall over the study period, which shows the pronounced seasonal variation, is also depicted in Fig. 1. Rainfall from November 2005 to

January 2006 at the study sites was roughly half of the long-term average of the nearby Albergaria-a-Velha station (i.e. 280 *vs*. 520 mm).

2.2. Field sampling and data analysis

Over a period of 10 months, starting September 20 2005 and ending July 24 2006, a total of 1125 field soil water repellency measurements and 861 accompanying soil moisture readings/samples were taken, divided more or less equally between the two study sites. The lower number of soil moisture values arose from initial soil moisture sensor malfunctioning and the occasional presence of stones, which impeded the insertion of the sensor into the soil. At both sites, sampling was carried out at 21 occasions separated by intervals of typically two weeks, and occasionally one, three or four weeks. For logistic reasons, the two sites could not be sampled on the same dates but had to be sampled on alternating dates, except on six occasions more towards the end of this study.

On both sites, sampling was carried out within an area roughly 30 m wide. This area corresponds to one of the three slope parts in which the study sites were divided to carry out the various tasks of the EROSFIRE project (Keizer et al., 2006, 2007). The central slope part was reserved for the installation of eight erosion plots, whilst the two lateral parts were selected randomly for either rainfall simulation experiments or the present work. On each sampling occasion, a transect was laid out across the full length of the slope section (see Table 1), starting at one corner of the area and shifting its location at subsequent sampling dates by fixed distances of roughly 1 m across the width of the slope. Along each transect, five sampling points were selected, except at the last four sampling occasions in June and July 2006, when only three points were sampled. Thus, the transects were divided in five (and later three) sections of the same length, each of which with the sampling point in the middle.

At each transect point, a grid of 50 cm wide by 60 cm long and divided in cells of 5 by 5 cm was laid out and soil water repellency was measured at three fixed points within this grid: the middle cell and the third cell left and right of it. Where rock outcrops or tree stumps coincided with these points, measurements were made as close as possible to these points. At each grid cell, soil water repellency was determined *in situ* at depths of 2–3 and 7–8 cm in order to provide direct comparability with soil moisture values obtained for these depths (see below). Water repellency severity was measured using the ‘Molarity of an Ethanol Droplet’ (MED) test (e.g. King, 1981; Doerr, 1998). This involved applying three droplets of increasing ethanol concentration to fresh parts of the soil surface until infiltration of at least two of three droplets of the same concentration occurred within 5 s. Test results are given as median ethanol concentrations (vol.%) and associated median concentration classes. These are given in Table 2, together with corresponding molarity of ethanol and surface tension (γ) values, which are included as a look-up table for comparison of the present results with those of studies presenting molarity or surface tension values. Repellency measurements were normally followed by *in situ* volumetric soil moisture determinations using an ML2 ThetaProbe™ connected to a HH2 ThetaMeter (Delta T-Devices Ltd.), except where the presence of stones did not allow insertion of the probe. The probe was inserted horizontally into the soil at 0–5 cm and 5–10 cm depth, using the hole dug for the purpose of the repellency measurements. 5 cm is the minimum soil depth required to acquire moisture data given the spacing of the probe's prongs. For the first three (Açores1) or four (Açores2) sampling occasions, due to technical problems with the probe, three samples were taken for determining soil moisture content gravimetrically by drying at 105 °C for 24 h and converting this to volumetric estimates based on Saxton et al. (1986) for saturated soil moisture content and Costa (1999) for specific density.

Table 2
Volumetric ethanol percentage concentrations used in the ‘Molarity of an Ethanol Droplet’ (MED) tests, and corresponding ethanol classes, MED and surface tension values as well as water repellency severity rating (based on King, 1981; Doerr, 1998)

Ethanol concentration (vol.%)	Ethanol class	Molarity (MED)	Surface tension (mN m^{-1})	Repellency severity rating
0	0	0	72.1	None
1	1	0.17	66.9	None
3	2	0.51	60.9	None
5	3	0.85	56.6	Slight
8.5	4	1.45	51.2	Moderate
13	5	2.22	46.3	Strong
18	6	3.07	42.3	Very strong
24	7	4.09	38.6	Very strong
≥36	8	6.14	33.1	Extreme

Statistical analyses were carried out using STATISTICA for Windows Release 5.5, by StatSoft Inc., except for the “runs test above and below the median” which was computed manually following Sokal and Rohlf (1981) and Rohlf and Sokal (1981). Since the ethanol concentrations utilised in the MED test do not correspond to an ordinal scale with a constant measurement unit, rank-based descriptive statistics and non-parametric statistical tests using the ethanol classes were used. Comparison-wise type I errors α were computed for the multiple, unplanned comparisons between water repellency measurements of subsequent sampling dates (Table 4), and of median ethanol classes and median soil moisture contents with antecedent rainfall amounts (Table 7). This was done following the Dunn–Šidák method (Sokal and Rohlf, 1981).

The independence of the soil water repellency and soil moisture values obtained for a certain sampling depth and date was tested using the “runs test above and below the median” (see Sokal and Rohlf, 1981). The three measurements at the three to five transect points were arrayed in their natural order of increasing numbering of transect and grid point numbers. Whenever a series of values differed significantly from a random sequence, only the median values of three to five transect points were retained for further analysis and, thus, considered to constitute the individual measurements. A lack of independence was detected more frequently in the case of the moisture measurements than the repellency measurements, i.e. in 17 and 11 instances out of 84, respectively. The latter can be identified in Table 4 on the basis of the number of measurements (i.e. N=3 or 5).

3. Results and discussion

3.1. Temporal variations in water repellency

Overall water repellency levels of the near-surface samples are dominated throughout the 10-month measurement period by very strong to extreme severity (ethanol classes 6 to 8; Fig. 2). High levels of soil water repellency under *Eucalyptus* spp. stands have previously been reported: (i) in the region for fire-affected soils of similar texture (Shakesby et al, 1993; Coelho et al., 2005) and for unburned eucalypt stands on coastal dune sand (Keizer et al., 2005a, c); (ii) from their native Australia (e.g. Burch et al., 1989; Crockford et al., 1991); and (iii) other areas such as northern and southern Africa (e.g. Scott, 1993; Coelho et al., 2005) and north-western Spain (e.g. Varela et al., 2005; Rodríguez-Alleres et al., 2007b).

At both sampling depths, overall repellency levels are higher for the ploughed (Açores2) than the unploughed (Açores1) site (ethanol classes 8 and 7 *vs*. 6 and 5). According to Shakesby et al. (1993), deep-ploughing can render previously hydrophobic soils hydrophilic. The higher repellency levels at the ploughed site suggest that the effect of ploughing in lowering water repellency does not last for more than the 4 to 5 years that have passed since the ploughing of this site. Broadly in line with the present results, Doerr et al. (1996) found similar repellency values for air-dried surface samples from an undisturbed eucalypt site and from one that had been ploughed six years before. In a later study, Doerr et al. (1998) found that the effect of ploughing could be as short-lived as two years, in particular locally around young eucalypt trees. In a more detailed study in the same region, Leighton-Boyce et al. (2005) suggested that a period as short as six months could be sufficient for the widespread development of water repellency from the soil surface up to a depth of 20 cm.

Notwithstanding the overall predominance of very strong to extreme median repellency levels, non-repellent median conditions occur on six (Açores1) and three (Açores2) occasions (Fig. 2), corroborating the transient nature of topsoil water repellency reported from burnt and unburned eucalypt stands (e.g. Crockford et al., 1991; Doerr and Thomas, 2000; Coelho et al., 2005; Keizer et al., 2005a). The most straightforward temporal pattern of water repellency (median ethanol class values) is evident for the upper sampling depth of the unploughed (Açores1) site. Its median repellency levels are very strong to extreme before January 2006 and after April 2006, and non-repellent from February to April 2006. This pattern agrees reasonably well with the broadly seasonal cycle of low repellency frequency during wet winter conditions and greatest repellency frequency in late summer that Leighton-Boyce et al.

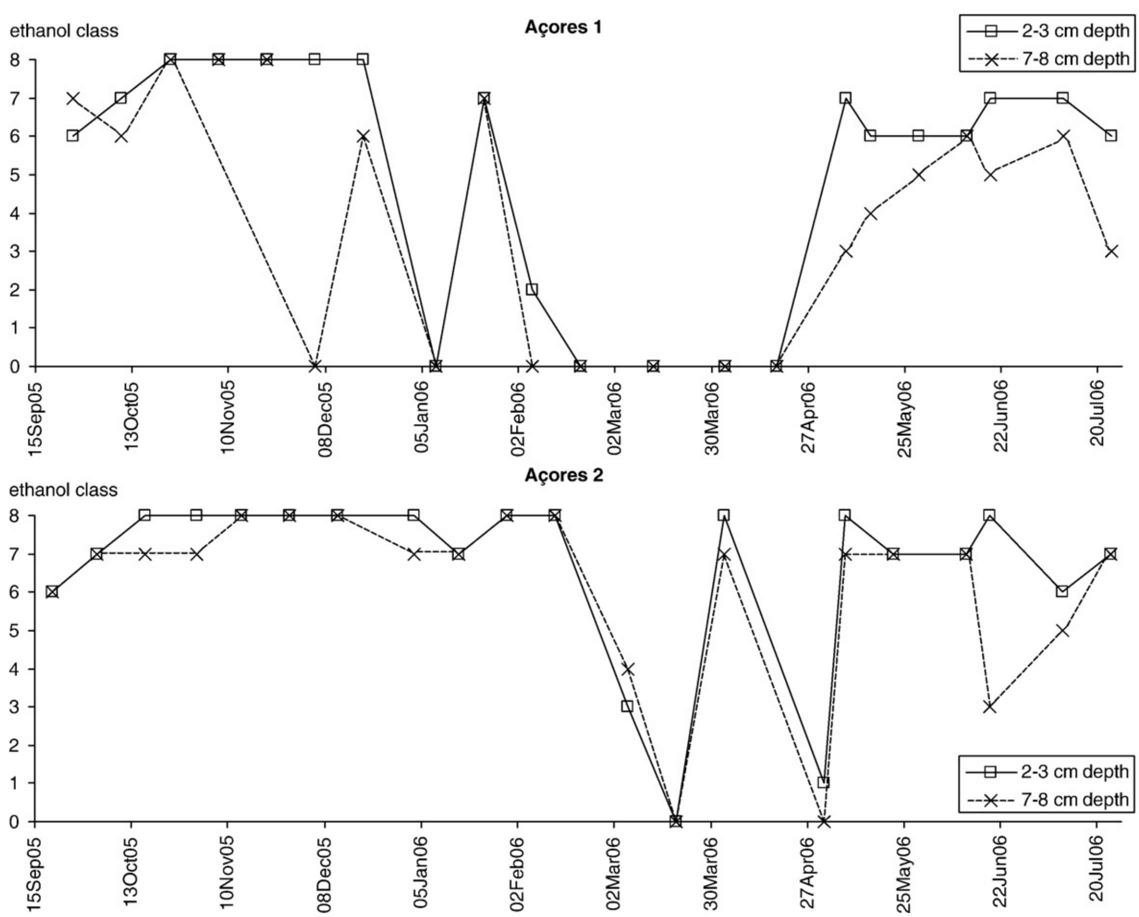

Fig. 2. Temporal variation in median ethanol classes at 2–3 and 7–8 cm below the soil surface on the two study sites.

Table 3
"Runs test above and below the median" for the median and inter-quartile ethanol classes at 2–3 and 7–8 cm depth on 21 sampling dates between September 2005 and July 2006

Site	Açores1 (unploughed)		Açores2 (ploughed)	
Soil depth (cm)	2–3	7–8	2–3	7–8
Median ethanol classes				
n_above-median	10	9	0	5
n_equal-to-median	5	2	11	10
n_below-median	6	10	10	6
nr runs	<u>4</u>	7	–	<u>2</u>
Inter-quartile ethanol classes				
n_above-median	5	9	10	11
n_equal-to-median	8	2	2	0
n_below-median	8	10	9	10
nr runs	4	9	7	10

Underlined numbers of runs are significant at $\alpha = 0.05$.

(2005) reported for burnt and unburned eucalypt stands, despite the below average rainfall received during the study period (see Section 2). Similar rainfall-related seasonal patterns in soil water repellency have also been suggested for other vegetation types (see review by Doerr et al., 2000). The ploughed (Açores2) site presents a somewhat contrasting situation, with non-repellent median conditions being restricted to only two sampling dates (March 20 and May 2 2006). A similar brief intermission of mostly wettable soil has also been reported for an unburned eucalypt stand but its brevity was considered somewhat atypical and due to unusually low rainfall (Keizer et al., 2005c).

The present results, supported by findings in Keizer et al. (2005c) in which similar sampling intervals were used, reveal that major changes in repellency levels can occur within a period of a few weeks. Changes of five or more ethanol classes are common, occurring between three and five times at each of the two sampling depths at both sites and occurring mostly simultaneously at the two depths of each site. These simultaneous major changes occur on three subsequent occasions, i.e. between December 19 2005 and February 6 2006 in the case of unploughed (Açores1) site, and between March 20 and May 8 2006 in the case of the ploughed (Açores2) site. The statistical significance of these and other changes is addressed in Section 3.2. Relatively rapid increases in water repellency under eucalypts have previously been reported by Keizer et al. (2005b: 3–4 weeks) and Leighton-Boyce et al. (2005: 22 days) and Crockford et al. (1991: 6–9 days). In the latter study, however, initial repellency levels had not been quantified. The fact that changes from non-repellent to extreme repellent conditions occur over such short time intervals implies that an adequate description of the temporal dynamics of water repellency under field conditions requires frequent sampling, especially during soil wetting and drying phases. This would be best achieved by a non-destructive measurement technique, which, ideally, would also be applicable during rainfall events as also advocated by Leighton-Boyce et al. (2005). Such a technique is currently not available and frequent field visits using destructive sampling techniques thus remain the best available option. With respect to the results of the current study, the dramatic changes between subsequent sampling dates imply that caution is required in comparing the data from the two sites as their sampling dates were not identical.

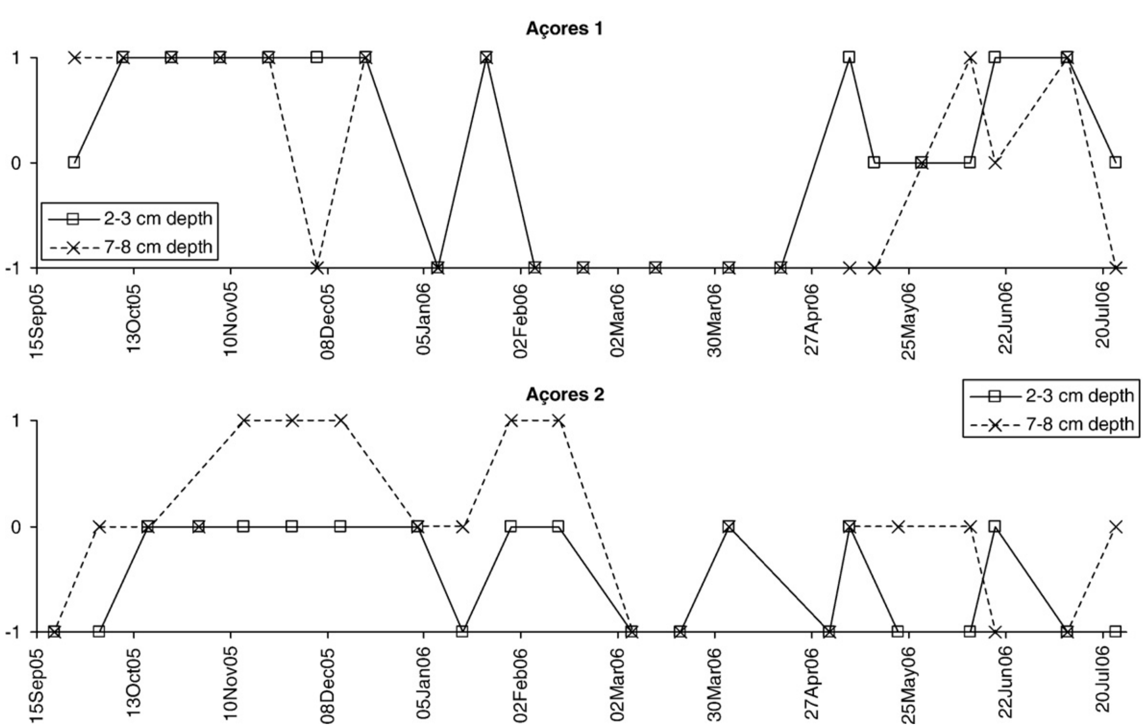

Fig. 3. Visualisation of the "runs test above and below the median" for median ethanol classes at 2–3 and 7–8 cm depth on the two study sites. 1 = above the median; 0 = equal to the median; −1 = below the median.

Table 4
Mann-Whitney U-Test (Us) between ethanol classes, at 2–3 and 7–8 cm depth, of subsequent sampling dates

Açores1 (unploughed)					Açores2 (ploughed)				
Date first period (i)	2–3 cm depth		7–8 cm depth		Date first period (i)	2–3 cm depth		7–8 cm depth	
	U	$N(i)$	U	$N(i)$		U	$N(i)$	U	$N(i)$
26-Sep-05	12.0	15	97.5	15	20-Sep-05	62.0	15	18.0	15
10-Oct-05	26.0	5	62.0	15	03-Oct-05	39.0	15	12.0	5
24-Oct-05	84.0	15	100.0	15	17-Oct-05	84.0	15	12.0	5
07-Nov-05	98.0	15	106.5	15	01-Nov-05	87.0	15	34.0	5
21-Nov-05	87.5	15	21.5	15	14-Nov-05	90.0	15	67.5	15
05-Dec-05	99.0	14	28.5	5	28-Nov-05	105.0	15	82.5	15
19-Dec-05	2.0	15	37.5	15	12-Dec-05	84.0	15	75.0	15
09-Jan-06	12.5	15	37.5	15	03-Jan-06	102.0	15	32.0	15
23-Jan-06	12.0	5	55.5	15	16-Jan-06	84.0	15	20.0	5
06-Feb-06	26.0	5	93.0	15	30-Jan-06	105.0	15	105.0	15
20-Feb-06	110.0	15	99.0	15	13-Feb-06	25.5	15	25.0	15
13-Mar-06	90.0	15	111.0	15	06-Mar-06	21.0	5	33.0	5
03-Apr-06	110.0	15	90.0	15	20-Mar-06	42.5	15	52.0	15
18-Apr-06	9.0	15	15.0	15	03-Apr-06	42.0	9	37.5	9
08-May-06	13.0	9	20.0	9	02-May-06	12.0	15	13.5	15
15-May-06	67.0	15	25.0	5	08-May-06	30.0	9	57.0	9
29-May-06	57.5	15	62.0	15	22-May-06	58.0	15	47.0	15
12-Jun-06	35.5	9	25.0	9	12-Jun-06	26.5	9	24.0	9
19-Jun-06	37.5	9	34.0	9	19-Jun-06	20.0	9	36.0	9
10-Jul-06	22.5	9	27.5	9	10-Jul-06	24.0	9	24.0	9

H_0: MED classes on date i=MED classes date $i+1$, with Us significant at $\alpha'=0.025$ (following the Dunn–Šidák method for 2 comparisons at $\alpha=0.05$) being underlined. $N(i)=N$ of date i.

Two of the four temporal patterns in Fig. 2 correspond to time series that differ significantly from random sequences (Table 3). They are that of the upper sampling depth of the unploughed (Açores1) site and that of the lower sampling depth of the ploughed (Açores2) site. Fig. 3 clearly shows that the two non-random patterns are rather distinct. That of the unploughed site reveals two periods with "equal and above median" values (before January 2006 and after April 2006), whereas that of the ploughed site reveals just a single period with "equal and above median" values (before March 2006). In other words, the test results seem to imply that water repellency breaks down earlier and, thus, more readily to "below-median" levels at the unploughed than ploughed site (January *vs.* March 2006). Repellency also restores earlier and, thus, more readily to prior "above-median" levels at the unploughed than ploughed site (May *vs.* after July 2006). This earlier recovery, however, does not coincide with noticeably higher median repellency values at the ploughed than unploughed site from May 2006 onwards. The earlier fall in median repellency levels at the unploughed site constitutes the most conspicuous difference with the ploughed site. This difference could be related to greater water losses at the ploughed site through: (i) enhanced overland flow, channelled downslope through the furrows, as found by Ferreira et al. (2000); and/or (ii) accelerated preferential infiltration, through cracks resulting from the destruction of the soil profile, as suggested by e.g. Scott (2000).

Although the temporal pattern of the upper sampling depth at Açores2 (Fig. 2) appears quite similar to that of the site's lower depth, it is not significantly different from a random series (Table 3). This is due to the fact that none of the individual values is "above the overall median value (Fig. 3), thereby hampering the respective runs test. The number of individual values that is equal to the overall median value (and, thus, does not contribute to the runs) is also high in three of the other runs tests in Table 3. This, together with the large number of ties in other statistical tests (Tables 4 and 5), suggests the need for a

Table 5
Wilcoxon's Signed-Ranks Tests (Zs) between ethanol class measurements at 2–3 and 7–8 cm depth on 21 sampling dates

Açores1 (unploughed)			Açores2 (ploughed)		
Date	Non-ties (N)	Z	Date	Non-ties (N)	Z
26-Sep-05	7 (15)	1.51	20-Sep-05	7 (15)	0.00
10-Oct-05	3 (5)	0.00	03-Oct-05	1 (5)	–
24-Oct-05	7 (15)	0.00	17-Oct-05	2 (5)	0.70
07-Nov-05	5 (15)	1.78	01-Nov-05	2 (5)	0.70
21-Nov-05	7 (15)	2.26	14-Nov-05	5 (15)	1.78
05-Dec-05	3 (5)	1.15	28-Nov-05	0 (15)	–
19-Dec-05	10 (15)	2.21	12-Dec-05	4 (15)	0.50
09-Jan-06	4 (15)	1.50	03-Jan-06	8 (15)	1.76
23-Jan-06	2 (5)	-0.70	16-Jan-06	3 (5)	1.15
06-Feb-06	4 (5)	1.50	30-Jan-06	3 (15)	0.00
20-Feb-06	4 (15)	1.50	13-Feb-06	1 (15)	–
13-Mar-06	4 (15)	1.50	06-Mar-06	3 (5)	0.00
03-Apr-06	1 (15)	–	20-Mar-06	7 (15)	0.00
18-Apr-06	4 (15)	1.50	03-Apr-06	2 (9)	0.70
08-May-06	6 (9)	2.04	02-May-06	7 (15)	1.51
15-May-06	4 (5)	0.50	08-May-06	6 (9)	2.04
29-May-06	11 (15)	0.60	22-May-06	10 (15)	1.58
12-Jun-06	6 (9)	1.22	12-Jun-06	3 (9)	0.00
19-Jun-06	7 (9)	1.51	19-Jun-06	6 (9)	2.04
10-Jul-06	5 (9)	0.89	10-Jul-06	8 (9)	1.06
24-Jul-06	6 (9)	2.04	24-Jul-06	5 (9)	0.00

H_0: MED classes at 2–3 cm=MED classes at 7–8, with Zs significant at $\alpha=0.05$ being shown underlined.

more extended repellency measurement scale for studies in eucalypt stands. Indeed a higher concentration (50%) has already been introduced in the recent study by Leighton-Boyce et al. (2005). This, however, has to be balanced against the increased demand in terms of the additional effort and sampling space required.

3.2. Temporal patterns of spatial variability

The spatial variation in repellency at the different sampling dates, expressed here by the inter-quartile ranges of the individual ethanol class values, is shown in Fig. 4 for both study sites and both sampling depths. In all four cases, spatial variability varies substantially throughout the sampling period, with inter-quartile ranges covering the entire or almost entire span of ethanol class values from zero to eight.

The temporal patterns in inter-quartile ranges (Fig. 4) are more complex than those in median levels (Fig. 2). The upper sampling depth of the unploughed site (Açores1) is an exception, with spatial variability being low (≤ 1) before mid January 2006 (except on December 5 2005) and, again, after April 2006. According to the "runs test above and below the median", however, none of the four temporal patterns differs significantly from a random series (Table 3). The relationship between spatial variability and median levels of repellency is also not straightforward. The Spearman rank correlation coefficients (rho = −0.09, 0.25, −0.40 and −0.20 for the upper and lower sampling depths of Açores1 and Açores2, respectively) do not differ significantly from zero (at $\alpha = 0.05$) for any of the two sites and depths. Furthermore, extreme median severity levels can be equally associated with high or low spatial variability, and so can non-repellent median levels. This is particularly well illustrated by the lower sampling depth of the ploughed site and the upper sampling depth of the unploughed site. In the latter case, for example, on November 21 and December 5 2005 median ethanol classes are 8 and inter-quartile ranges are 0.5 and 5, whereas on March 13 and April 3 2006 median ethanol classes are 0 and inter-quartile ranges are 7 and 0.5.

The results obtained here confirm earlier observations in burnt and unburned eucalypt stands that repellency can be spatially homogeneous (e.g. Doerr et al. 1998, 2006a; Keizer et al., 2005c). Even though (largely) uniform conditions – extremely repellent but also wettable – are not exceptional in the current study, transitional states between these two extremes prevail. An adequate descriptor of the various states-of-repellency would ideally combine overall repellency level and degree of spatial variability, in view of their distinct temporal patterns and poor correlation. Even though such a combined index would not take into account the spatial organisation of repellent patches *per se*, it would also be useful for analysing

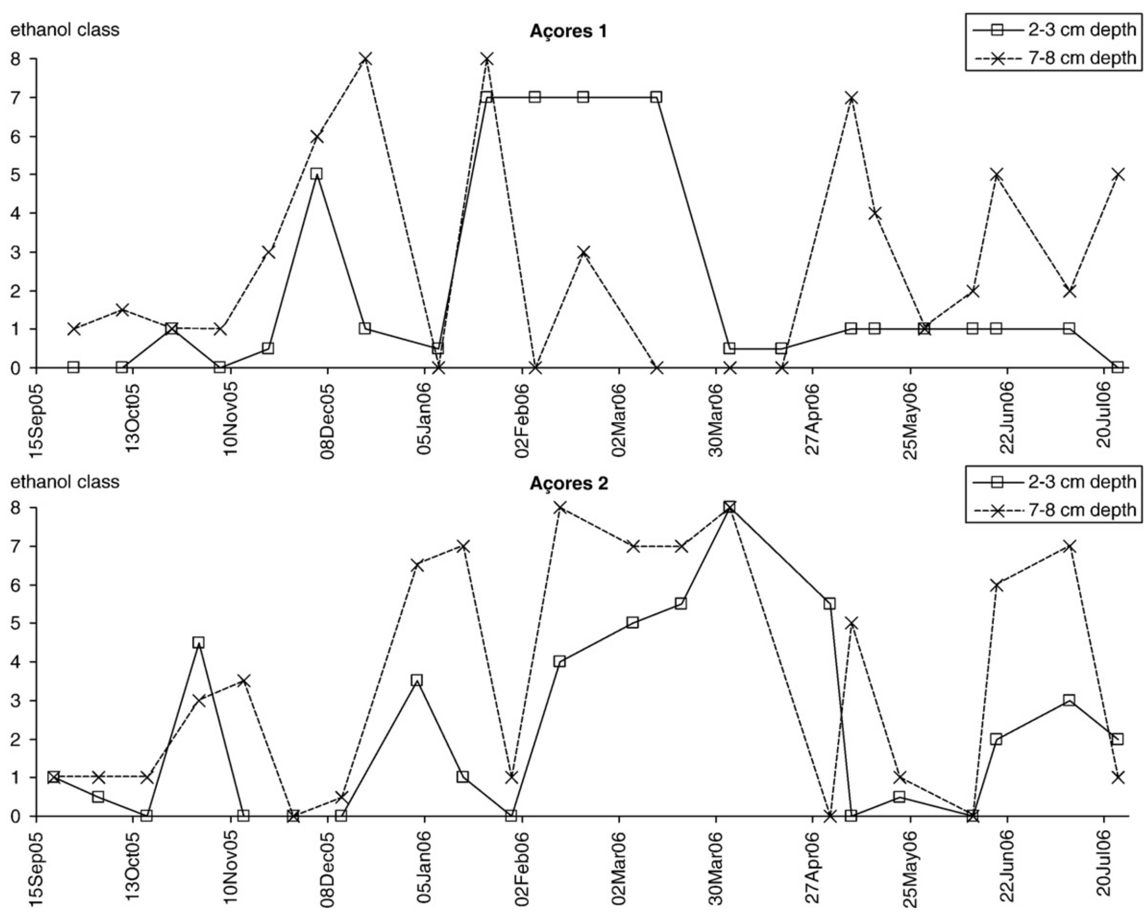

Fig. 4. Temporal variation in inter-quartile ethanol class ranges at 2–3 and 7–8 cm depth on the two study sites.

repellency's spatial contiguity and the associated effects in terms of repellency enhancing overland flow and erosion risk, as postulated by Shakesby et al. (2000).

The spatial variability explains why only half of the above-mentioned major changes in median ethanol classes correspond to statistically significant differences (Table 4). This proportion is higher for the ploughed (Açores1) than unploughed (Açores2) site, i.e. six out of nine as opposed to two out of seven. Five of these six differences at the unploughed site coincide with the above-mentioned three simultaneous major changes at the two sampling depths, i.e. the drops between December 19 2005 and January 9 2006 and between January 23 and February 6 2006 as well as the intermittent rise. The two significant and major differences at the ploughed site also occur simultaneously at the two depths but they concern the rise between May 2 and May 8 2006 and not the antecedent reductions.

The seasonal fall in water repellency in winter is rather distinct at the two sites. Not only does it occur later at the ploughed than unploughed site but it is also less well-defined statistically. That the winter reduction at the ploughed site is masked statistically by a more pronounced spatial variability tallies with non-uniform infiltration and, as mentioned before, profile disturbance by ploughing. On the other hand, the lower sampling depth of the unploughed site equally reveals an initial major fall that is not statistically significant, probably associated with to the high inter-quartile range on December 5 2005 in particular.

In contrast to the winter reduction in repellency, the spring re-establishment to prolonged repellent conditions is remarkably similar for the two sites as well as the two sampling depths. It occurs at roughly the same period (i.e. between April 18 and May 8 2006) and involves statistically significant changes in all four cases, even in that of the lower sampling depth of the unploughed (Açores1) site where the difference amounts to just three ethanol classes. The spring re-establishment at the ploughed (Açores2) site is worth further reference for involving a period as short as six days (May 2 to 8 2006). This agrees well with the 6–9 days suggested, as referred earlier, by Crockford et al. (1991). A similarly short period of seven days is involved in the statistically significant change at the upper sampling depth of the unploughed (Açores1) site between May 8 and 15 2006 but this concerns a decrease and just a minor one of only one ethanol class. These three instances of rapid significant changes further substantiate the earlier observation that even a comparatively intensive monitoring scheme as applied in this study may not capture the complete temporal dynamics of water repellency.

From the 13 statistically significant differences listed in Table 4, four correspond to particularly minor changes in median repellency levels of just one ethanol class. All four are restricted to the upper sampling depths and involve low spatial variability at both of the sampling dates under comparison. Also, the differences occur roughly simultaneously at the two sites and, in each period, have the same sign. Whereas the decrease at the unploughed site between May 8 and 15 2006 was already mentioned in the previous paragraph, that at the ploughed site occurs between May 8 and 22 2006 and, thus, equally after the spring re-establishment to prolonged repellent conditions. The other two changes occur in the initial phase of this study, between September 26 and October 10 2005 at the unploughed site, and between October 3 and 17 2005 at the ploughed (Açores2) site. They could indicate a gradual recovery of subsurface repellency following its (partial) destruction by the wildfire or, alternatively, a gradual increase in pre-fire repellency following downward translocation of hydrophobic substances from the burned/heated overlying litter and topsoil (see e.g. DeBano, 2000). The former hypothesis is perhaps less likely for the lower than upper sampling depth, also because of the moderate severity of the wildfire. In eucalypt stands, the removal of topsoil repellency during burning has been reported to a depth of 3 cm by Scott (1993) and of 5 cm by Doerr et al. (2006a), with a well-documented role of fire severity in the latter case. While Scott (1993) did not find conclusive evidence for intensification of repellency at greater soil depths, such evidence was found in the study by Doerr et al. (2006a) and in studies examining other vegetation types (e.g. Huffman et al., 2001; Mataix-Solera and Doerr, 2004; Hubbert and Oriol, 2005).

3.3. Water repellency variation with soil depth

At both study sites, the temporal patterns in median ethanol classes at the two sampling depths are strongly correlated. The Spearman rank correlation coefficient is 0.71 and significantly different from zero at $\alpha=0.01$ for both sites. However, as evident in Fig. 2, the median ethanol classes at the upper sampling depth tend to be systematically higher from those at the lower depth. According to the Wilcoxon's Signed-Ranks Test (and notwithstanding the considerable numbers of ties (9 and 12)), this tendency is statistically significant (at $\alpha=0.05$) for both study sites ($Z=2.59$ and 2.00 for Açores1 and Açores2, respectively).

The Wilcoxon's Signed-Ranks Test was also used to compare the two sampling depths on the individual sampling dates (Table 5). In agreement with the results mentioned in the previous paragraph, all six instances of statistically significant differences involve higher ethanol classes at the upper than lower sampling depth. They include three of the four differences in median repellency values that amount to three or more ethanol classes, i.e. on May 8 and July 24 2006 at the Açores1 and on June 19 2006 at the Açores2. The fourth of these larger differences (Açores1, December 5 2005) is by the far largest comprising eight ethanol classes, but it is exceptional in involving pronounced spatial variability at both sampling depths. The remaining three depth-related and statistically significant differences (Açores1, November 21 and December 19 2005; Açores2, May 8 2006) concern differences in median ethanol classes ranging from two down to zero. All three cases, however, typically involve an upper sampling depth with extreme and homogeneous water repellency conditions.

It is not clear if the observed tendency for less severe repellency at greater depth can be attributed to the wildfire, in particular through a decreased influx of hydrophobic substances with depth or a decreasing degree of heat-induced structural alteration of organic compounds already present (Doerr et al., 2006a). In (long-)unburned soils under eucalypts, decreasing occurrence and/or severity of repellency with increasing depth has been reported in a range of studies, for example, in South Africa (Scott, 2000), Australia (Doerr et al., 2006a) or Spain (Rodríguez-Alleres et al., 2007a), whereas little or no differences between depths were found in Portugal by Leighton-Boyce et al. (2005: 10 *vs*. 20 cm depth) and Keizer et al. (2005a,b: 2–3 *vs*. 7–8 cm depth). Evidence from burnt soils under eucalypts is even scarcer, but equally inconsistent. In studies in Portugal, Doerr et al. (1996) reported a lack of consistent patterns and Leighton-Boyce et al. (2005) observed no substantial differences between 10 and 20 cm depth. In burnt sites in Australia, however, Doerr et al. (2006a) reported a substantially higher frequency of wettable samples at 0–2 than 2–5 cm depth.

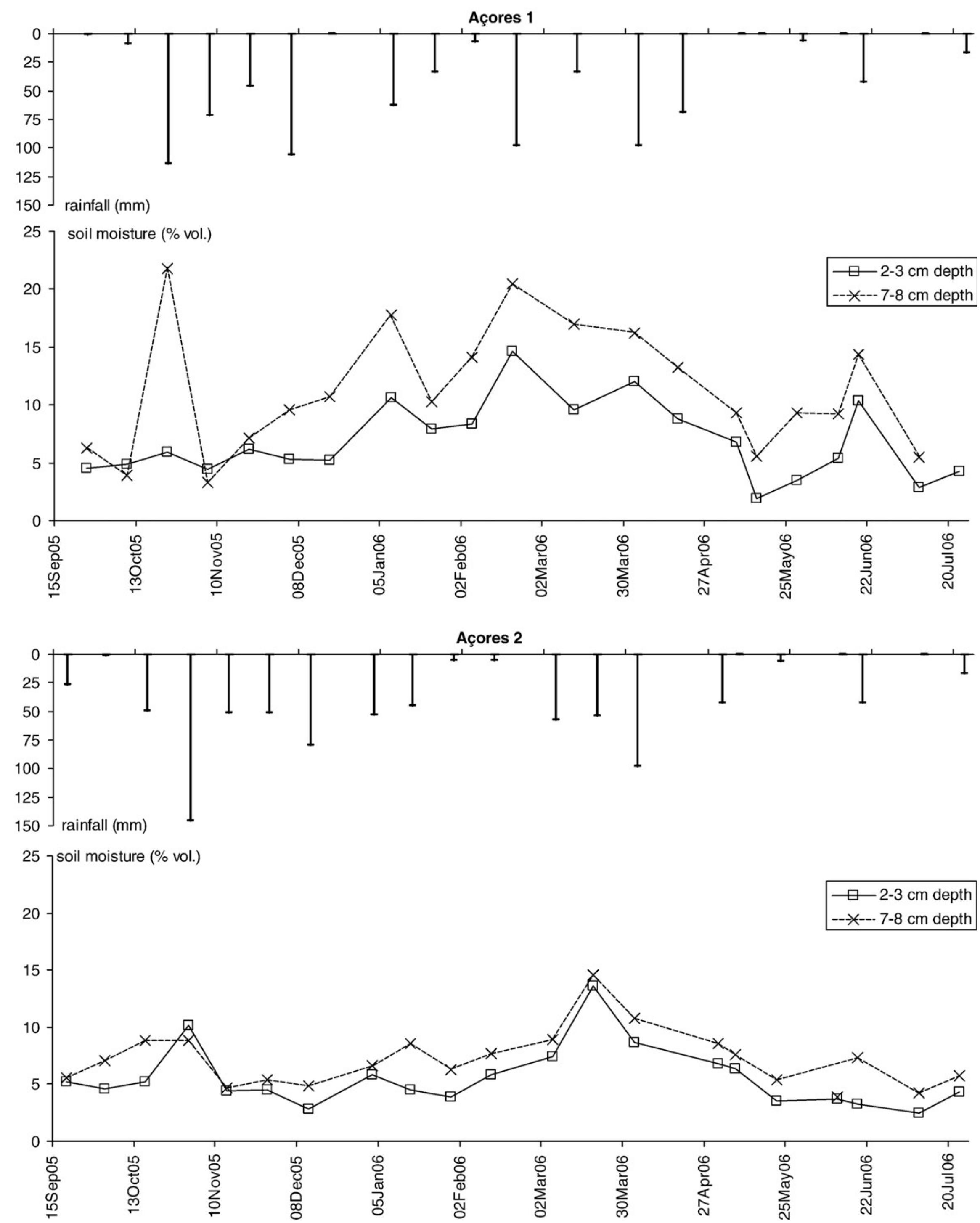

Fig. 5. Temporal variation in median volumetric soil moisture contents at 2–3 and 7–8 cm below the soil surface on the two study sites, and corresponding total rainfall amounts over the 14-day period prior to sampling.

Table 6
Spearman's rank correlation coefficients (rho) between median ethanol classes and median volumetric soil moisture contents at 2–3 and 7–8 cm depth on 21 sampling dates, as well as between individual measurements of ethanol class and accompanying volumetric soil moisture content

Site	Açores1 (unploughed)		Açores2 (ploughed)	
Soil depth (cm)	2–3	7–8	2–3	7–8
Median values	<u>−0.46</u>	<u>−0.52</u>	0.11	−0.39
n	21	21	21	21
Individual measurements	<u>−0.41</u>	<u>−0.56</u>	<u>−0.36</u>	<u>−0.50</u>
N	141	167	180	157

Underlined rho values are significant at $\alpha=0.05$.

3.4. Relationship of soil water repellency with soil moisture and antecedent rainfall

Fig. 5 depicts the median volumetric soil moisture values of the individual sampling dates for both sites and sampling depths. In agreement with the commonly reported inverse relationship between soil water repellency and soil moisture (see review by Doerr et al., 2000), overall soil moisture levels at both sampling depths are higher at the overall less repellent unploughed than ploughed site (5.9 *vs.* 5.2% and 9.6 *vs.* 7.1 vol.%). Accordingly, they are lower at the upper than lower soil depth at both sites (5.9 *vs.* 9.6 and 5.2 *vs.* 7.1 vol.%). As for water repellency, median moisture values at the two sampling depths are, throughout the study period, strongly correlated (Spearman's rho=0.80 for Açores1 and 0.81 for Açores2; $ps<0.01$) as well as systematically different (Wilcoxon's Signed-Ranks Test $Z=3.49$ for Açores1 and 3.93 for Açores2; $ps<0.01$).

At the level of the individual measurements, the above-mentioned inverse relationship of water repellency with moisture content is statistically significant for both study sites and both sampling depths (Table 6). At both sites, the correlation is noticeably stronger for the lower than upper sampling depth but, at each depth, it differs little between the two sites. The median values of the sampling dates, however, reveal a significant monotonic correlation for the two sampling depths at Açores1, but not at Açores2 (Table 6). Especially for the upper Açores2 depth, the coefficients are rather distinct for the two data sets. The particularly weak correlation for the median values seems to correspond to some sampling artefact (involving a strong skew towards high median ethanol classes in a small sample) rather than to indicate some location-specific repellency–moisture relationship. Such a specific relationship is neither suggested by the Spearman's rank correlation coefficient for all 84 median values (rho=−0.51; $p<0.01$), nor is it evident from Fig. 6.

For eucalypt soils, a broad inverse relationship between water repellency and moisture content, as found here, is perhaps more commonly accepted than substantiated. Whereas some datasets are consistent with such relationship (Walsh et al., 1994; Coelho et al., 2005; Keizer et al., 2005a), others are not (Crockford et al., 1991; Ferreira et al., 2005; Rodríguez-Alleres et al., 2007a). The most detailed previous studies in Portugal (Doerr and Thomas, 2000; Leighton-Boyce et al., 2005) and elsewhere (Dekker et al. 2001; Doerr et al, 2006b) reported a general association of wettable soil conditions with moist soil status and high repellency with dry soil, but also suggest soil moisture alone is insufficient to explain temporal fluctuations in water repellency. The current study supports these findings and demonstrates that this applies equally to unburned and recently burnt eucalypt stands. A transition zone, rather than a distinct threshold demarcating wettable and repellent conditions (Dekker et al., 2001; Leighton-Boyce et al., 2005), can also be detected in the data obtained here (Fig. 6), especially at Açores1. For this site, the transition zone encompasses a narrower soil moisture range (9–11 vol.%) than in the case of Leighton-Boyce et al.'s mature eucalypt site (14–27 vol.%).

Fig. 5 also shows the cumulative rainfall amounts over the 14-day periods preceding the sampling dates. This 14-day period was chosen over shorter periods for presenting, on overall, the best correlation with median soil moisture values (Table 7). It is worth noting, however, that none of the Spearman's rank correlation coefficients in Table 7 is significantly different from zero when the multiple-comparison correction following the Dunn–Šidák method is taken into consideration. Overall, it is clear that median ethanol class values correspond better to median soil moisture contents than to antecedent rainfall. This is to be expected since, in addition to water repellency,

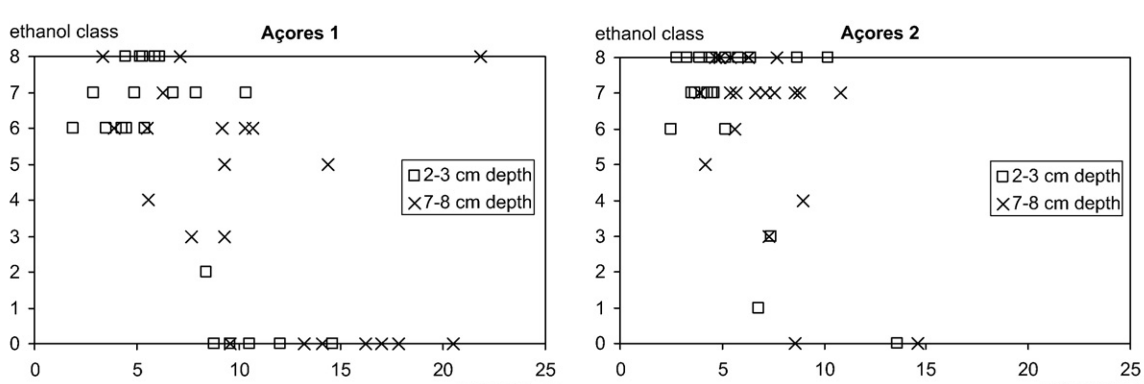

Fig. 6. Relationship between median soil moisture contents (in vol.%) and median ethanol classes at 2–3 and 7–8 cm depth on the two study sites.

Table 7
Spearman's rank correlation coefficients (rho) of median ethanol classes (swr) and median volumetric soil moisture contents (sm) at 2–3 and 7–8 cm depth with antecedent rainfall amounts (in mm) recorded at the study sites over varying periods prior to the 21 sampling occasions

Site	Açores1 (unploughed)				Açores2 (ploughed)			
Soil depth (cm)	2–3		7–8		2–3		7–8	
Rainfall	swr	sm	swr	sm	swr	sm	swr	sm
3 h	−0.30	0.37	−0.26	0.33	−0.21	0.07	−0.05	0.01
6 h	−0.30	0.37	−0.26	0.33	−0.21	0.07	−0.05	0.01
12 h	−0.30	0.37	−0.26	0.33	−0.06	0.02	0.10	0.06
24 h	−0.30	0.37	−0.26	0.33	−0.03	0.13	0.08	0.19
2 days	0.03	0.11	−0.23	0.02	−0.05	0.25	0.08	0.27
4 days	0.03	0.11	−0.23	0.02	0.12	0.35	−0.04	0.45
7 days	0.18	0.17	0.01	0.15	0.21	0.33	−0.12	0.51
14 days	0.03	0.49	−0.15	0.40	0.17	0.47	−0.01	0.47

Underlined rho values are significant at $\alpha=0.05$ but not at $\alpha'=0.006$, following the Dunn–Šidák method for 8 comparisons at $\alpha=0.05$.

spatial variability in rainfall, interception, evapotranspiration and preferential flow will determine how much rainfall is available to ultimately penetrate the soil matrix.

It is therefore not surprising that the existing findings on the relationship of water repellency with antecedent rainfall for eucalypt stands show even less consistency than those for the repellency–soil moisture relationship. Thus, Keizer et al. (2005b) found a monotonic correlation for repellency at 2–3 cm below the soil surface, which is comparable (i.e. statistically significant at $\alpha=0.05$) to that reported here with soil moisture content, whereas Leighton-Boyce et al. (2005) reported an only very generalised relationship with antecedent rainfall totals. In the present case, the poor relationship is well illustrated by Açores1, where four subsequent 2-week periods of 50–100 mm and a total of 300 mm rainfall do not result in a significant decrease in repellency, but 65 mm of rain precede the distinct reduction in repellency in early January. Clearly other factors such as rainfall intensity, temperature, microbial activity and other seasonally variable factors may play a role in determining temporal changes in water repellency.

4. Conclusions

The main conclusions arising from this study concerning the temporal variation in water repellency as measured for *in situ* topsoil of two recently burnt eucalypt stands on steep hillslopes in north-central Portugal are as follows.

- Overall severity levels of soil water repellency reveal broadly seasonal variations, however, specific temporal patterns in spatial variability are more irregular and poorly related to overall levels. Therefore, overall levels alone are not sufficient to assess the likely impact of repellency on soil hydrological behaviour.
- Statistically significant increases and decreases in repellency severity were detected over time intervals as short as 6–7 days, suggesting that a higher sampling frequency than that used here is required to fully capture the temporal dynamics of soil water repellency in this environment.
- The ploughed and unploughed sites show perceptible differences in their overall levels of repellency and its temporal variations. Although ploughing has been shown to destroy repellency by mixing repellent and wettable soil, the site ploughed 4–5 years ago shows overall similar or greater levels of repellency than the unploughed site examined here.
- It is not clear whether burning had any effect on water repellency levels at the two soil depths examined in this study. The decrease of water repellency with depth is similar to those reported from unburnt forests examined elsewhere.
- Soil moisture content is a better predictor for water repellency levels than antecedent rainfall, however, its value for predicting repellency occurrence is limited.

Acknowledgements

The present study was carried out in the framework of the EROSFIRE project (POCI/AGR/60354/2004) and with support of the PHOENIX project (POCI/AGR/58896/2004), both financed by the Portuguese Foundation for Science and Technology (FCT) with co-funding by FEDER through the POCI2010 Programme. Also the funding by the FCT through a post-graduate fellowship attributed to JJK (SFRH/BPD/14608/2003) is gratefully acknowledged, and so is the travel funding by the Council of Rectors of Portuguese Universities (CRUP) under the Luso-Britisch Integrated Action B-28/06. SHD acknowledges funding from the NERC (Advanced Fellowship NER/J/S/2002/00662).

Special thanks go to Virgínia M.F.G. Pereira for the soil profile descriptions, to Mart Houmann, Mark Lagewaard, Angela García-Monge and David Herrera for their help with the field data collection, and to Jorge Lucena, Carmen Magalhães, and Joaquim Sande Silva for their help with the laboratory soil analyses.

The two anonymous reviewers are gratefully acknowledged for their help in improving this manuscript.

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7 Overall discussion and general conclusions

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7.1 Overall runoff and erosion rates

This research provides an understanding into post-fire runoff and soil erosion, at the micro- and small- plot scales, related with different pre- and post- fire land management operations under natural and artificial rainfall. The research was carried out in six eucalyptus plantations and in one pine plantation.

The maximum and minimum plot values of runoff and specific sediment losses, during two years following the wildfire highlighted the effects of: (i) land use (pine vs. eucalypt); (ii) pre-fire ploughing and (iii) application of the hydromulch treatment (Chapter7, Figure 5). The land use had an effect on runoff production (runoff coefficient of 22% on the two eucalypt sites vs. 56% on the pine site) but it was not a key factor in post-fire erosion risk (415 g m^{-2} for the unploughed eucalypt vs. 549 g m^{-2} for the pine site). At the eucalypt sites, the ploughing did not influence overland flow generation, whereas there were marked differences on the erosion response (415 g m^{-2} for the unploughed compared to 125 g m^{-2} on the pre-fire down-slope ploughed). Additionally, at the pine site, the hydromulch significantly reduced both variables, whereas plot size (0.25, 0.5, 10 m^2) did not have significant differences in the hydrological or soil erosion response. Invariably, the pine treated plots generated the lowest runoff amounts but only similar specific sediment losses compared to the down-slope ploughed eucalypt site.

Lower hydrological and soil erosion response in pine compared to eucalypt stands had been reported earlier in North-Central Portugal (Prats et al., 2012; Shakesby et al., 1996). It was attributed to lower soil water repellency levels and to the presence of a pine needle "carpet". Actually, overall soil water repellency levels at the untreated pine site were much lower than at the eucalypt sites (median "0" ethanol class vs. median "7" ethanol class, respectively; Figure 6) but those lower repellency levels did not produce lower runoff generation. In addition, the logging at the pine site caused the removal of the protective litter cover (mean litter cover 5% just after logging). The few studies that have monitored the first post-fire year runoff and sediment losses, on unlogged pine sites in Portugal (Table 2; Prats et al., 2012; Ferreira et al., 2008 and Shakesby et al., 1996), found lower runoff coefficient (6-16% versus 56%) and sediment losses (38-220 vs. 302 g m^{-2}) than the Colmeal pine site. In fact, these studies differed mainly in soil cover (they reported more than 50% of needle carpet), which could reflect a difference in the monitored time since fire, in fire intensity or in the disturbance caused by logging. Probably due to logging, the pine site had higher runoff coefficient and sediment losses than previous Portuguese studies but lower rates compared to other studies outside the Mediterranean region (Shakesby, 2011). In agreement with the soil cover importance in reducing runoff and sediment losses, the hydromulching effectiveness was attributed to the increase of soil cover. The present study results coincided with other experiments with post-fire mulch (Prats et al., 2012; Bautista et al., 1996; Shakesby et al., 1996).

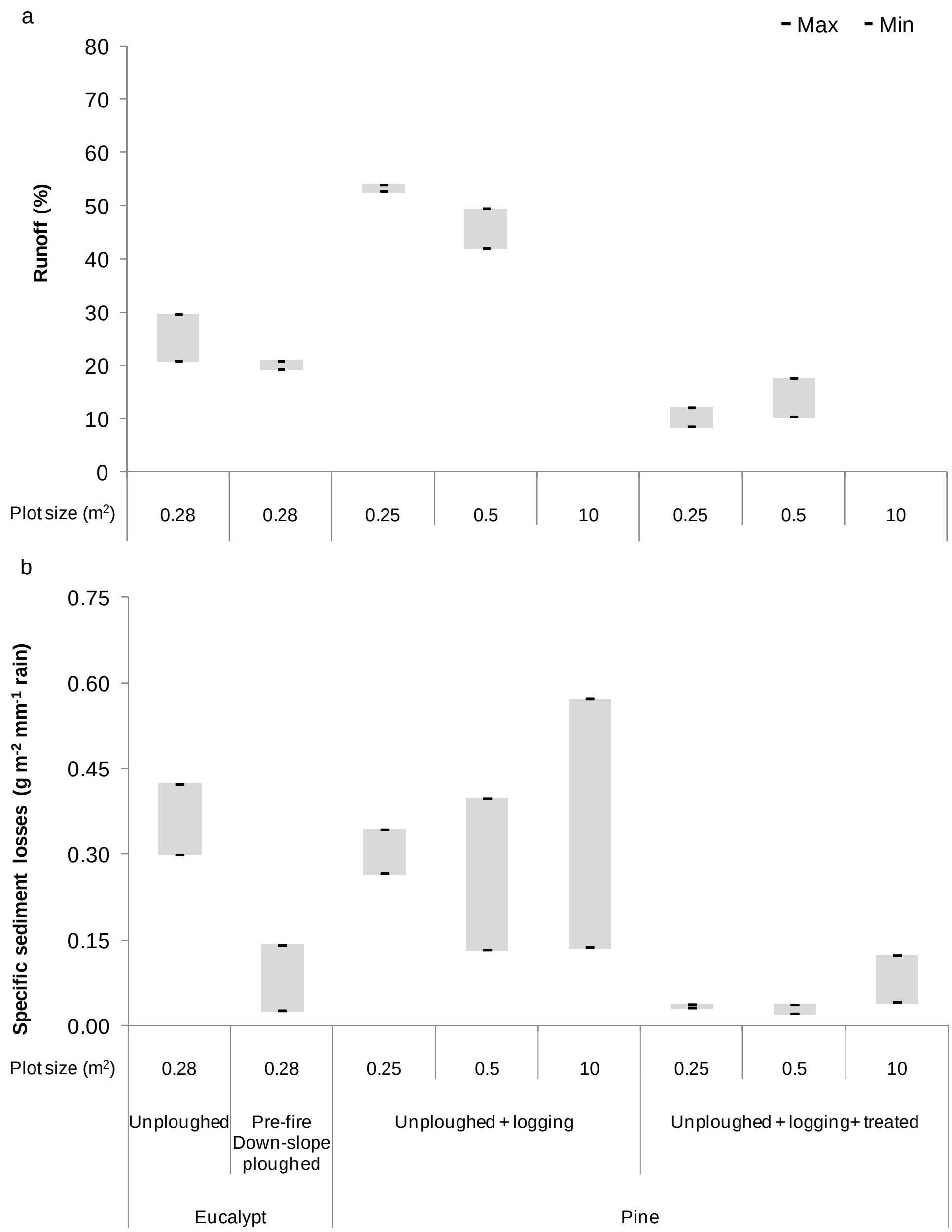

Figure 5. Overall maximum and minimum runoff (a) and specific sediment losses (b) plot values for two post-fire years in the eucalypt and pine sites (2656 and 2355 mm rainfall, respectively).

The post-fire logging activities (manual chain saw + mechanised wood extraction) at both pine and eucalypt sites, had a marked impact in increasing sediment losses (Figure 5 and Figure 7). In fact, increases in the specific sediment losses by plot of 5 to 10-fold were described at both logged sites. Fernández et al. (2007) also found that logging operations affect soil erosion mainly through changes in the significant exposure of bare soil.

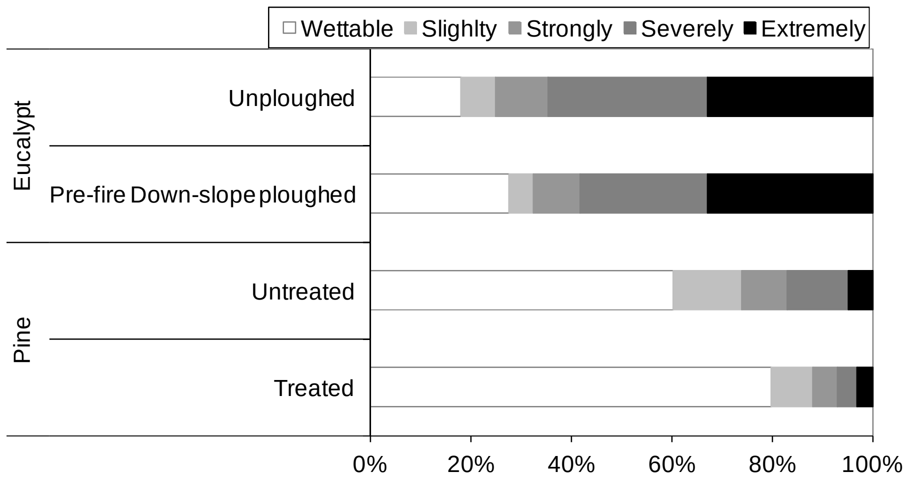

Figure 6. Frequency of topsoil (soil surface + 2-3 cm) water repellency levels at eucalypt (two post-fire years) and pine sites (one post-fire year).

At the eucalypt sites, the contrasting pre-fire soil preparation techniques were not a key factor on post-fire hydrological response (Figure 7a). However, the pre-fire ploughed areas consistently showed the lowest specific sediment losses figures (below 0.20 g m^{-2} mm $rain^{-1}$); either with natural rainfall, high or extreme intensity simulated rainfall (Figure 7b). These facts suggested that erosion at the three ploughed sites was sediment limited. In a recently rip-ploughed eucalypt site, Shakesby et al., (1994) found specific sediment losses as high as 3.27 g m^{-2} mm^{-1} rain. They also estimated that sediment losses decline rapidly following rip-ploughing due to the formation of a stone lag and the development of the protective vegetation and litter cover. The decline in sediment losses could also be related with the selective removal of the fine soil fraction by the initial soil erosions events (Walsh et al., 1995). However, unequivocal lower fine fraction or higher stone cover in all the ploughed compared to the unploughed sites was not observed. The time elapsed since ploughing (as much as 20 years or 2 eucalypt production cycles, judging by the remaining tree stumps) could be related with the low sediment rates registered on all the ploughed sites. So, sediment exhaustion was probably a consequence of severe initial erosion periods which occurred just after ploughing. The recorded sediment exhaustion, even under supposedly soil conservation practices (i.e. contour ploughing and terracing) well describes the threat of this type of land management. Even because, in commercial eucalypt stands, ground preparation involving uprooting the old stumps would be needed at least every 30-40 years (3-4 eucalypt cycles) (Shakesby et al., 1996) and recently is also often done after the fire. This ground preparation usually involves rip-ploughing (down-slope or contour) and even slope engineering (terracing), which compromise the soil conservation.

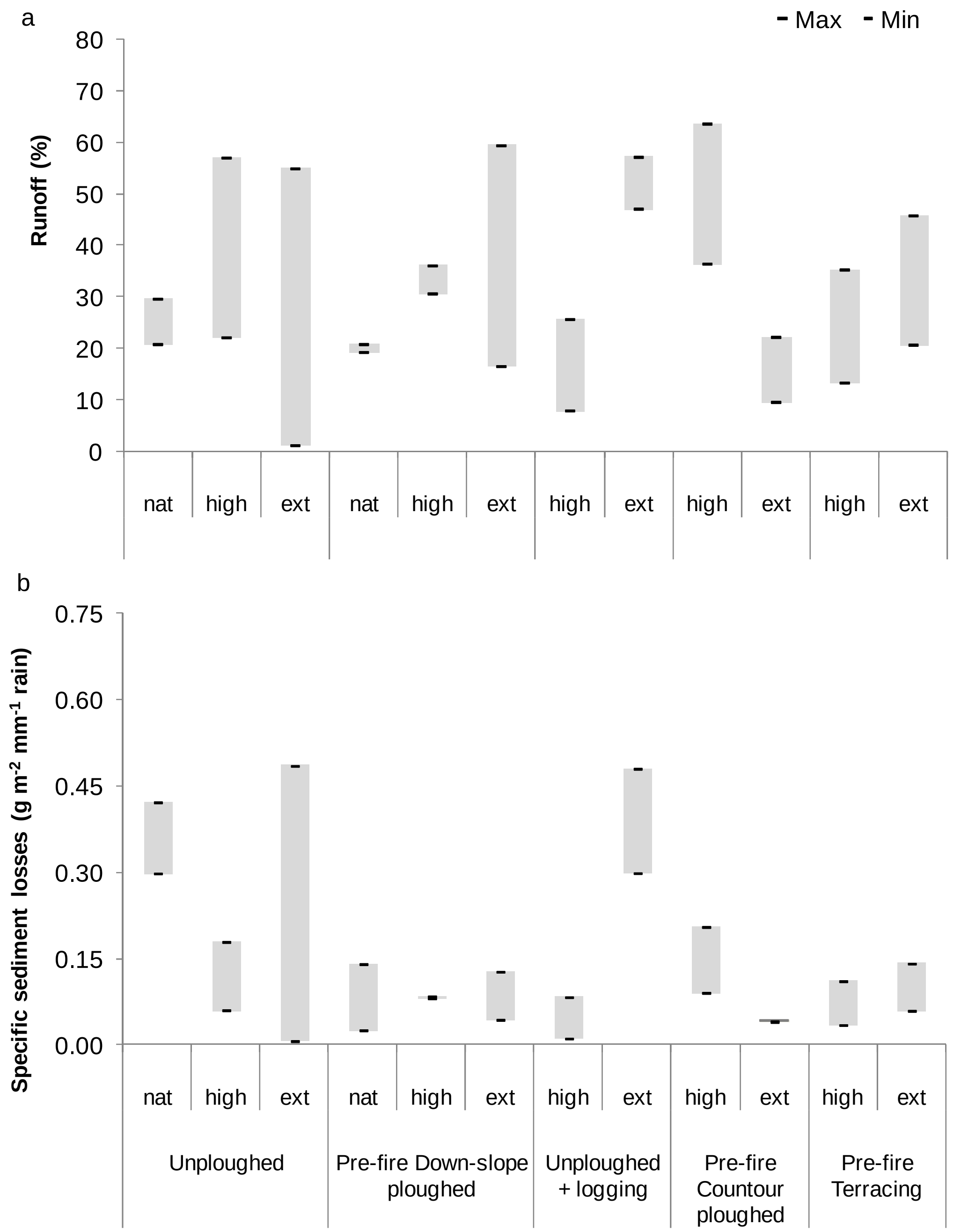

Figure 7. Overall maximum and minimum runoff (a) and specific sediment losses (b) measured during the two first post-fire years, at eucalypt sites managed with different pre-fire soil preparation techniques. Abbreviations located on the x-axis indicated the methodology used: natural rainfall ("nat."), high or extreme intensity rainfall simulation experiences ("high" or "ext." respectively).

In Portugal, post-fire runoff and soil erosion in eucalypt commercial plantations under natural rainfall, had been studied with larger plots (16 m^2) (Table 2; Prats et al., 2012; Thomas et al., 1999 and Shakesby et al., 1996) mainly at unploughed sites. The range of runoff generation reported in the former studies (6-30%) can be compared to both eucalypt sites (22%, Figure 5). However, the specific sediment losses range (0.07-0.33 g m^2 mm^{-1} rain) can only be compared with the most erosive unploughed site (0.40 g m^2 mm^{-1} rain), while the ploughed site (0.12 g m^2 mm^{-1} rain) corresponded to their minimum range. These results can suggest either that our measurements were comparatively low (plot size effect) or that our results can be compared. In the latter case, rill erosion did not take place on their 16 m^2 plots, inter-rill erosion being the main process in all the three studies. Outside Portugal, other post-fire studies carried out using 8 m^2 plots in burnt eucalypts stands in Australia showed higher erosion rates. Dragovich and Morris (2002) and Blong et al. (1982) found specific sediment losses of 0.39 g $m^{-2}mm^{-1}$ rain to 1.08 g $m^{-2}mm^{-1}$ rain (Table 2). Only the unploughed site values can be compared to their minimum range, although comparison is limited by differences in historic land use and the wild nature of eucalypt forest in Australia.

RSE's in burnt eucalypt stands in Portugal were done only in one study by Leighton-Boyce et al., (2007). They used a similar set up as here (100 mm h^{-1} applied rainfall intensity in a ploughed site), although their study was done in a single moment after fire instead of the repeated RSE's approach used in the present thesis. The runoff coefficient reported by them (70 %) was 2-4 times higher than the measured range at the ploughed sites (15- 49 %), but their specific sediment losses (0.63 g m^{-2} mm^{-1} rain) were 5-10 times higher than the present study values (0.04 -0.15 g m^{-2} mm^{-1} rain; Table 2). Other RSE's studies in Portugal were done at pine sites (Ferreira et al., 2005a; Coelho et al., 2004 and Walsh et al., 1998) also in a unique moment after fire. Their runoff coefficients were comparable to the present study values (5-65%) but in terms of sediment losses, they showed much higher values than those registered at the unploughed and unploughed + logged sites (0.3 to 1.67 g $m^{-2}mm^{-1}$ rain vs. 0.31 -0.39 g $m^{-2}mm^{-1}$ rain; Table 2). Repeated RSE's after wildfires were carried out in Australia in eucalypt forests (Sheridan et al., 2007; during three years) and in Aleppo Pine in Eastern Spain (Cerdà and Doerr, 2005; during 11 years). To allow comparison, their results for the two first post-fire years have been summarized in Table 2. Although runoff generation between studies was comparable, even the highest specific sediment losses registered at the unploughed sites (0.4 g $m^{-2}mm^{-1}$ rain) were three times and roughly twelve times lower than the highest ones measured by Cerdà and Doerr, 2005 (1.32 g $m^{-2}mm^{-1}$ rain) and Sheridan et al., 2007 (4.88 g $m^{-2}mm^{-1}$ rain) respectively.

To summarize, the low recorded erosion rates coincide with the generally lower Mediterranean erosion rates as compared to other areas. This is mainly attributed to the high soil stoniness, shallow soils as well as long intensive land use (Shakesby 2011, Cerdan et al., 2010). The lower erosion rates do not necessarily mean that erosion is a lesser threat for the soil resource, as the soil is already thin, any additional loss may be considered detrimental (Cerdan et al., 2010).

On other hand, the organic matter fraction on the eroded sediments was high (40-60 %) when compared with its content on the top soil (5-10 %); independently of land use, pre and post-fire management, and measurement technique. The bulk of the studies do not present separate data on mineral and organic matter losses. However, Prats et al., (2012), Thomas et al., (1999) and Fernández et al., (2007) also found high organic matter losses (40-50 %). These high values can be related to moderate fire severity; once that the incomplete combustion could allow the presence of substantial amounts of charcoal over the soil surface. Furthermore, high organic matter contents in the sediments seemed to be consistent with low soil losses (Fernández et al., 2007). The large fraction of organic matter not only compromises the soil fertility, but also has consequences for off-site pollution (Campos et al., 2012; Vila-Escalé et al., 2007).

Table 2. Published micro to small plot post-wildfire soil erosion data under natural rainfall or simulated rainfall conditions with special emphasis in either Portuguese research or eucalypt stands data. Abbreviations are: C.lim., Cretaceous Limestone; Der., Acidic Eutrophic Red Dermosols; Euc.g, *Eucalyptus globulus*; Euc.s, *Eucalyptus spp.;* H., high fire severity; L., low fire severity; L.L., Leptosol & Luvisol; M., moderate fire severity; O.gneiss; Ordovician gneiss; P.schist, pre-cambrian schist; pine, *Pinus pinaster*; pinus.h, *Pinus halepensis*; Pt., Portugal; Q.schist, schists, quartz and quartzite fragments; RSE's; rainfall simulation experiments; SWR; soil water repellency; seed, new seedlings; Sp., Spain; U.L., umbric leptosol; unpl., unploughed; y., yes; -, not applicable or not mentioned.

Location, basin	Geology/Soil	SWR	Vegetation-Land Management.	Post-fire monitored time	Plots		Fire Severity	RSE's	Rainfall; RSE's intensity; RSE's duration	Runoff (min-max)		Sediment loss	O.M % in sed. loss	Specific Sediment loss		Authors
				months	m^2	nº		nº	mm; mm h^{-1}; min	mm	%	g m^2	%	g m^2 mm^{-1} rain	g m^2 mm^{-1} runoff	
Natural rainfall, bounded plots																
Pt., Vouga	P.schist/U.L.	y	Pine- unpl.	0-12	16	2	L	-	1684;-;-	116	11	38	55	0.02	0.32	Prats et al., 2012
Pt. Central,-		y	Pine- unpl.	0-12	16		-	-	982;- ;-	117	11.6	220	-	0.4	-	Ferreira et al. 2008
Pt., Agueda		y	Pine- unpl.	12-20	16	2	-	-	919.2;- ;-	-	6-16	86-152	-	0.09-0.16	-	Shakesby et al., 1996;Walsh et al., 1994
Pt., Vouga		y	Euc.g- unpl.	0-12	16	4	M	-	1684;- ;-	507	30	560	46	0.33	1.11	Prats et al., 2012
Pt, Agueda		y	Euc.g- unpl.	0-6	16	2	-	-	644.9;- ;-	40-55	6-9	46-192	34	0.07-0.29	1.15-3.4	Shakesby et al., 1996, Thomas et al., 1999
		y	Euc.g-rip–plough -seed	36-48 (7 months after ploughing)	16	1	-	-	1155;- ;-	-	-	3775	-	3.27		Shakesby et al., 1994
Pt. Central,-	P.schist/U.L.	y	Pine-unpl.-logged	0-12	0.25 &0.5	4	M	-	891;- ;-	503	56	594	49	0.66	1.18	Prats et al., accepted chapter 5
		y	Pine-unpl-logged	6-24	10	3	M	-	1746;- ;-	-	-	240-1000	58	0.14-0.57	-	
		y	Pine-unpl-logged-treated	6-24	0.25 &0.5	4	M	-	1746;- ;-	149-309	9-18	37-65	54	0.02-0.04	0.12-0.43	

Table 2. Continued

Location, basin	Geology/Soil	SWR	Vegetation-Land Management.	Post-fire monitored time	Plots		Fire Severity	RSE's	Rainfall; RSE's intensity; RSE's duration	Runoff (min-max)		Sediment loss	O.M % in sed. loss	Specific Sediment loss		Authors
				months	m^2	nº		nº	mm; mm h^{-1}; min	mm	%	g m^2	%	g m^2 mm^{-1} rain	g m^2 mm^{-1} runoff	
Pt. Central,-	P.schist/U.L.	y	Pine-unpl.-logged-treated	6-24	10	3	M	-	1746;- ;-	-	-	72-214	59	0.04-0.12	-	Prats et al., accepted chapter 5
Pt., Vouga		y	Euc.g- unpl-A1	0-12	0.28	4	M	-	1048;- ;-	228	22	415	52	0.4	1.82	Malvar et al., submitted chapter 4
		y	Euc.g-downslope rip plough-A2	0-12	0.28	4	M	-	1048;- ;-	228	22	125	37	0.12	0.55	
Australia	S./ Sandy	-	Euc.spp.	0-6	8	4	H, M	-	258;- ;-	-	-	102	-	0.39	-	Dragovich and Morris 2002
	S./ Sandy	-	Euc.spp .	0-6	8	-	-	-	450;- ;-	-	-	212-650	-	0.47-1.44	-	Blong et al., 1982
	S./ Sandy	-	Euc.spp .	0-12	8	-	-	-	736;- ;-	-	-	250-800	-	0.33-1.08	-	Blong et al., 1982
Simulated rainfall																
Pt, Agueda	P.schist/U.L.	y	Pine- unpl.	24	1	4	-	4	-;32-40; 60	2-9	5-26	6-66	-	0.39-1.67	1.5-7	Walsh et al., 1998
Pt. Central,-		y	Pine- unpl.	-	0.24	2	-	2	-;50.5;60	28-33	55-65	16-17	-	0.3-0.32	0.47-0.59	Coelho et al., 2004; Ferreira et al., 2005a
Pt, Agueda	Q.schist/U.L	y	Euc.g-rip plough	5	0.36	5	-	5	-;107;30	35	70	31	-	0.63	0.89	Leighton-Boyce et al., 2007
Pt., Vouga	P.schist/UL	y	Euc.g-unpl-A1	0-24	0.28	4	M	12	-;45;60	150	54	44	41	0.16	0.29	Malvar et al., 2011 chapter 2
		y	Euc.g-unpl-S1	0-24	0.28	4	M	12	-;45; 60	68	25	18	33	0.07	0.26	Malvar et al., 2013 chapter 3
		y	Euc.g-unpl-S2-logged	0-24	0.28	4	M	12	-;45;60	47	17	13	31	0.05	0.28	
		y	Euc.g-downslope rip plough-A2	0-24	0.28	4	M	12	-;45;60	94	34	24	42	0.09	0.26	

Table 2. Continued

Location, basin	Geology/Soil	SWR	Vegetation-Land Management.	Post-fire monitored time	Plots		Fire Severity	RSE's	Rainfall; RSE's intensity; RSE's duration	Runoff (min-max)		Sediment loss	O.M % in sed. loss	Specific Sediment loss		Authors
				months	m^2	nº		nº	mm; mm h^{-1}; min	mm	%	g m^2	%	g m^2 mm^{-1} rain	g m^2 mm^{-1} runoff	
Pt., Vouga	P.schist/U.L.	y	Euc.g-contour plough-J1	0-24	0.28	4	M	11	-;45;60	124	49	39	33	0.15	0.31	Malvar et al., 2013 chapter 3
		y	Euc.g-terrraced-J2	0-24	0.28	4	M	11	-;45;60	53	21	16	31	0.06	0.30	
		y	Euc.g-unpl-A1	0-24	0.28	4	M	12	-;85;60	265	55	150	38	0.31	0.57	
Pt., Vouga	P.schist/U.L.	y	Euc.g-unpl-S1	0-24	0.28	4	M	10	-;85;60	26	7	7	29	0.02	0.27	Malvar et al., 2013 chapter 3
		y	Euc.g-unpl-S2-logged	0-24	0.28	4	M	10	-;85;60	208	52	155	30	0.39	0.75	
		y	Euc.g-downslope rip plough-A2	0-24	0.28	4	M	10	-;85;60	154	38	35	40	0.09	0.23	
		y	Euc.g-contour plough-J1	0-24	0.28	4	M	11	-;85;60	69	15	19	47	0.04	0.28	
		y	Euc.g-terrraced-J2	0-24	0.28	4	M	9	-;85;60	134	37	40	38	0.11	0.30	
Sp. Eastern,	C.lim/L.L.	y	Pinus.h-unpl	0-24	0.24	2	H	8	-;55;60	-	33-44	151-292	-	0.68-1.32	2.07-3.03	Cerdà and Doerr,2005
Australia	O.gneiss/Der.	y	Euc.ssp-unpl	0-24	3	24	-	15	-;100;30	88-136	35-54	293-1221	-	1.17-4.88	3.33-8.98	Sheridan et al., 2007

7.2 Temporal patterns in runoff and erosion

A decline in post-fire runoff and sediment rates within the “window of disturbance” is generally assumed. The decreasing rates are due to the transition from transport- to sediment-limited erosion typically reported by post-fire erosion studies (see Shakesby, 2011; Shakesby and Doerr, 2006). The temporal variability had also been associated with inter and intra-annual rainfall variability and post-fire vegetation recovery (Shakesby et al., 1993; 1994, 1996). Independently of the land use, soil preparation technique and measurement methodology, the observed temporal patterns (two post-fire years) did not correspond to a simple decrease with time, but had a marked seasonal component. As a result, higher runoff coefficient and specific sediment losses values surrounding the driest seasons were observed. During these periods, at both eucalypt and pine sites, the weekly runoff and specific sediment losses were as high as the initial values measured immediately after the wildfire (see Chapter 2, 3, 4 and 5; Figures 3, 6, 4 and 5 and 3, respectively). The temporal patterns in the pine hydromulched plots were somewhat similar, but with smaller amplitudes. On the other hand, the hydromulch effectiveness to reduce runoff and sediment losses lasted for three post-fire years. Although the hydromulch cover decayed after the second winter, it was compensated for the vegetation recovery. At both logged sites, the logging disturbance impact over the sediment losses was larger than the time since fire. So, just after logging the specific sediment losses increased sharply, but two years after the fire the specific sediment losses reached similar figures to just after fire. Since RSE’s avoid the variability of natural rainfall, they were useful to compare results obtained at different moments in time after fire. The two prior studies that also employed repeated RSE’s to study post-fire runoff and erosion (Cerdà and Doerr, 2005; Sheridan et al., 2007), reported pronounced decreases in inter-rill erosion rates with time-since-fire. The decrease in overland flow and erodibility was related to the degree and type of vegetation cover as well as its influence over the soil hydrophobicity (Cerdà and Doerr, 2005). Equally, the repeated RSE’s carried out at six eucalypt sites confirmed the fact that time had a significant influence over the runoff and erosion response. However, RSE’s executed two years after the fire measured specific sediment losses as high as the initial RSE’s.

Consequently, for all seven sites and measurement techniques a risk of enhanced runoff and erosion response was observed two years after the fire, probably due to the soil water repellency effect increasing runoff generation and the observed slow and sparse post-fire vegetation recovery (mean vegetation cover two years after the fire was 28 % for untreated pine plots and about 40 % for the eucalypt sites).

7.3 Key factors explaining runoff and erosion

Overland flow generation analysis, and the role therein of several factors, represented a focus since the total sediment losses of the 132 RSE's, as well as the eucalypt and pine natural rainfall plots (n=1584), were strongly correlated to runoff volumes (Spearman's rank correlation coefficient 0.90–0.95; $p < 0.01$).

Multiple regression models for the weekly runoff measurements under natural rainfall, in the eucalypt (Chapter 4; Table 5) and in the untreated pine plots (Chapter 5; Table 4), revealed that rainfall amount was the main factor explaining runoff generation. This was followed by surface cover factors (litter, ash, vegetation) related either to an increase in the resistance to flow and or the interception capacity (Smets et al, 2008). A shift in the first descriptor from rainfall amount toward rainfall intensity was detected as surface cover increases over the plots. Differences between the partial regression models of the unploughed and down slope ploughed (with higher protective surface cover) eucalypt sites, as well as untreated and hydromulched plots highlighted that shift. Prats et al., (2012) described the same alteration on the first descriptor between eucalypt and pine plots (with high needle carpet cover) regression models. Equally, Vega et al., (2005) over plots with high vegetation cover (37% immediately after a prescribed fire) found rainfall energy (accumulated kinetic energy) to be the main factor for runoff generation.

The results confirm the effect of the seasonal and spatial variation of soil water repellency on runoff generation addressed by other authors in the same region (Prats et al., 2012; Malvar et al., 2011; Leighton-Boyce et al., 2007; Keizer 2005a; Ferreira et al., 2000). However, this effect on runoff generation is not consistent. The overall soil water repellency levels alone are not sufficient to assess the whole impact of repellency. Actually, the runoff coefficient was lower at the more hydrophobic eucalypt sites (frequency of not wettable measurements 70-80 %) compared to the untreated pine plots (frequency of not wettable measurements 20-40 %), (Figure 5 and Figure 6). Despite that, the regression model indicated that soil water repellency explained better runoff generation at the more hydrophobic sites. Soil water repellency represented the second factor explaining runoff variation (11%) at the eucalypt sites, whereas at the pine site was detected only through the negative sign in the soil moisture parameter estimate. At the eucalypt sites, further insight on the soil water repellency role was provided through the partial models of runoff generation under different repellency conditions. As the soil was more hydrophobic there was a shift from rainfall intensity to rainfall amount as the main factor controlling overland flow. At the same time, the importance in the protective-interception layer (litter+ ash) was decreasing. As a consequence, under repellent conditions, medium rainfall intensity events (I_{15} = 20 mm h^{-1}) were able to generate enough overland flow to transport sediments even with high protective cover.

In agreement with previous studies employing repeated RSE's (Cerdà and Doerr, 2005; Sheridan et al., 2007), the RSE's temporal patterns of overland flow cannot be attributed only to changes in soil water repellency. The observed changes in overland flow generation between RSE's campaigns coincided well with changes in soil water repellency assessed by means and/or with the frequency of extreme repellency (ethanol class>7) (see Chapter 3: Figures 6 and 7). However, there were exceptions in which low runoff generation was associated to strong soil water repellency levels. This could be attributed to the role of antecedent rainfall, enhancing the spatial variability in repellency and, thereby, creating opportunities for re-infiltration (e.g. Shakesby et al., 2000; Keizer et al., 2005a). This could also be attributed to the fact that the soil water repellency measurements were destructive and, thus, were not carried out in the RSE's plots themselves but in neighbouring plots. On the other hand, descriptors such as median ethanol class, its range or frequency of a soil water repellency class, might not fully capture the hydrological implications of soil water repellency, especially under heterogeneous repellency conditions.

At both eucalypt sites, multiple regression models showed that sediment losses were controlled mainly by rainfall intensity followed by litter cover. The relationship of sediment losses with runoff generation was represented by the presence of variables that were proved to affect runoff (soil water repellency, soil moisture, and ash cover). Previous studies have also reported the importance of rainfall intensity in determining post-fire sediment losses (Prats et al., 2012; Robichaud et al., 2008; Spigel and Robichaud 2007; Vega et al., 2005; Fernandez et al., 2004). In contrast, at the pine site, the first explaining factor was always a cover related variable, either organic cover (hydromulch + litter + vegetation) or bare soil depending in the treatment specific models. The results enhance the importance of increasing the soil cover for a successful control of soil erosion. Bare soil exposure related to fire intensity (Benavides-Solorio and MacDonald, 2005) or post-fire logging operations (Fernández et al., 2007) had previously been found to explain sediment losses variability. In agreement with that, the increase after logging in specific sediment losses by plot of 5 to 10-fold, at the pine and the eucalypt sites respectively, was related to the marked decrease in litter cover after logging disturbance. Although increments in sediment losses after clear-cutting had been reported for unburnt forest (e.g. Croke et al., 1999; Powers, 2002; Hartanto et al., 2003), the research on post-fire logging is less frequent (Fernandez et al., 2007). Independently of the origin (low fire intensity, post-fire treatment) the contribution to reducing soil erosion of the cover-related variables has already been documented (Bautista et al., 1996; Prats et al., 2012; Robichaud et al., 2000; Shakesby et al., 1996; Wagenbrenner et al., 2006). The results agree well with those findings highlighting the importance of surface cover variables to mitigate post-fire soil erosion. As a consequence, from a soil conservation point of view, land managers are strongly encouraged to cautiously carry out logging activities, taking into account the importance of keeping the needles and the logging litter over the soil.

7.4 Natural versus simulated rainfall

Natural and simulated rainfall experiment measurements were equal in terms of study sites, post-fire monitored period, plot size and plot experimental design (Chapters 2 and 4). Since total rainfall amount and intensity were very different between both methodologies, the absolute runoff and erosion values can hardly be contrasted (Table 3). However, relative differences between them were well represented, both natural and simulated rainfall results reported that both sites had comparable runoff amounts but the sediment losses at the pre-fire ploughed site were significantly lower. On the other hand, the organic matter fraction of the eroded sediments was around 40-50%, independently of the site and methodology. Once divided by rainfall amount, both techniques results could be better assessed. At both sites, the runoff coefficient was consistently higher (roughly double) under simulated compared to natural rainfall, possibly reflecting the higher simulated rainfall intensity (Table 3). Sediment exhaustion at the ploughed site was pointed out as the cause underlying the lack of differences in specific sediment losses between natural, extreme and high intensity RSE's (ca. 0.07 g m^2 mm^{-1} rain) (Figure 8). Similarly, sediment exhaustion at the other ploughed eucalypt sites was also recorded by the RSE's erosion results. The specific sediment losses ranged from 0.05 to 0.20 g m^2 mm^{-1} rain, and varied very little between high and extreme intensity RSE's (see Figure

7b). In contrast, when sediments are available, the extreme intensity RSE's recorded comparatively high sediment losses. So, at the unploughed site the extreme intensity RSE's (0.31 g m^2 mm^{-1} rain) were able to capture similar specific sediment losses compared to the natural rainfall plots (0.35 g m^2 mm^{-1} rain) (Figure 8). Equally, extreme intensity RSE's at the logged eucalypt site captured the values recorded with natural rainfall plots at the logged pine site (ca. 0.50 g m^2 mm^{-1} rain; see Figure 5b and Figure 7b).

Table 3. Natural and simulated rainfall experiences (RSE's) measurements characteristics and overall runoff and interrill erosion results at micro-plot scale (0.28 m^2) in two eucalypt sites during two post-fire years.

Site and Methodology	Unploughed Natural	Unploughed High RSE's	Unploughed Extreme RSE's	Down-slope rip-ploughed Natural	Down-slope rip-ploughed High RSE's	Down-slope rip-ploughed Extreme RSE's
Code	UP_Natural	UP_Rse_H	UP_Rse_Ext	DP_Natural	DP_Rse_H	DP_Rse_Ext
Methodology characteristic						
Number total observations	320	12	12	320	12	10
Number observations runoff>0 ml	244	12	12	230	10	8
Plot number	4	2	2	4	2	2
Field work days	71	6	6	71	6	5
Runoff samples number *	202	60	60	187	50	40
Overall results						
Rainfall (mm)	2656	277	486	2656	277	404
I_{15} maximum (mm h^{-1})	71	47	84	71	47	84
Runoff (mm)	654	150	265	538	94	154
Runoff (%)	25	54	55	20	34	38
Sediment rate (g m^{-2})	930	44	150	179	24	35
Specific Sed. losses (g m^{-2} mm^{-1} rain)	0.35	0.16	0.31	0.07	0.08	0.08
Organic matter (%)	56	41	38	39	42	40

* Runoff samples with volume < 250 ml were not analyzed

Other studies reporting post-fire runoff and soil erosion from RSE's and natural rainfall plots were carried out with different objectives than the comparison of methodologies. Therefore, high dissimilarities between techniques were present. For example, at the burnt pine stands in Portugal, Ferreira et al., 2008 also reported higher runoff coefficient but lower sediment losses in RSE's than in natural rainfall plots. Besides inherent differences between methods, the comparison is also restricted by differences in plot size (0.24 vs. 16 m^2), the slope and plot position and because the RSE's were done at a single moment after fire.

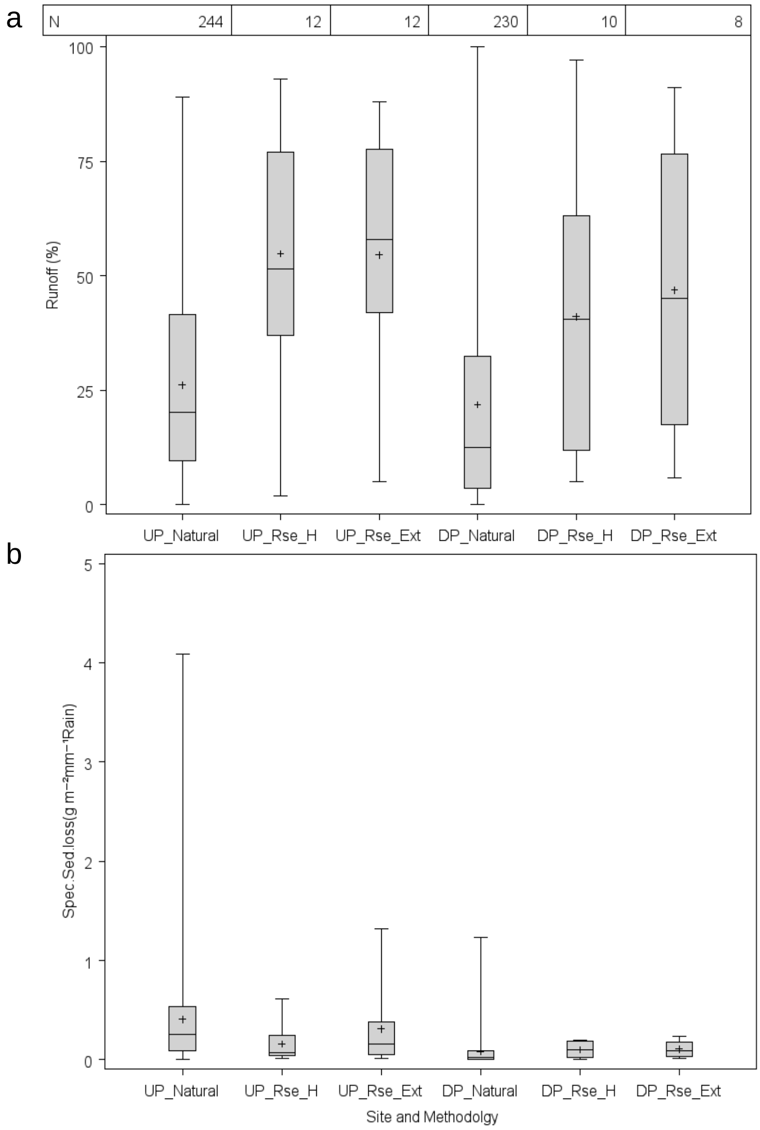

Figure 8. Box plots of runoff (a) and specific sediment losses (b) produced by the natural rainfall plots and the repeated rainfall simulation experiments (six field campaigns) in two post-fire years. Number (N) of observations is indicated on the top, see Table 3 for site and methodology codes.

The temporal trend described by the repeated RSE's were similar to those of the same months natural rainfall results in two aspects (

Figure **9**): (i) a marked seasonal component with higher runoff coefficient and specific sediment losses surrounding the driest seasons as consequence of the soil water repellency effect was registered, and; (ii) runoff coefficient and specific sediment losses as high as one month after the fire were also measured two years after the fire.

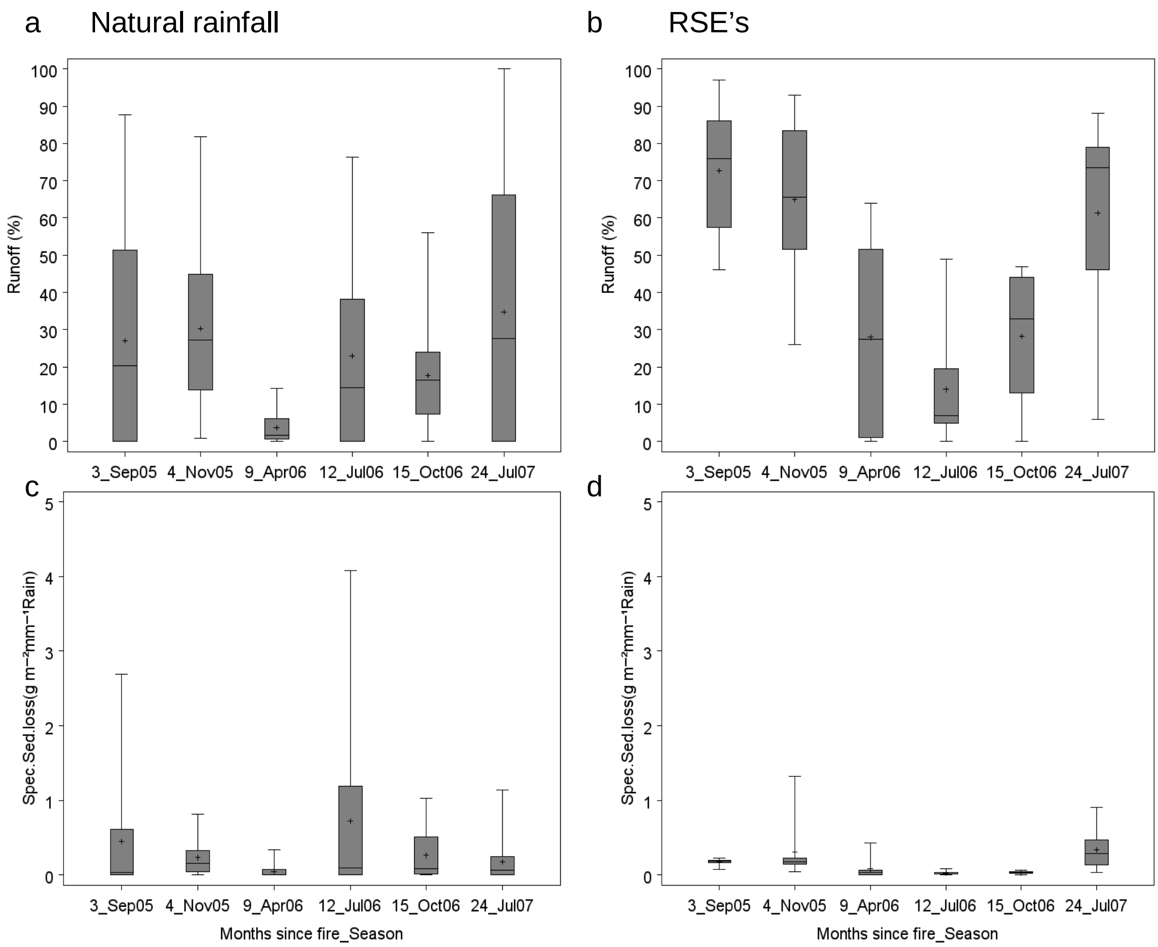

Figure 9. Box plots of natural rainfall (a, c) and rainfall simulation experiences (RSE's) (b, c) of runoff (a, b) and specific sediment losses (c, d) at six subsequent field campaigns in the two post-fire years (natural rainfall results are the values registered at the same month that the field RSE's campaigns were executed).

The extreme RSE's represented well the specific erosion rates, as well as the temporal trend in runoff coefficient and specific sediment losses. Equally, the RSE's captured the differences in sediment losses between sites and ground preparation techniques. Compared to the natural runoff plots, which required 71 field work days and analyzed roughly 500 samples, the extreme intensity RSE`s required only six field work days and 100 runoff samples for assessing runoff and soil erosion during two years following a wildfire (Table 3). These facts converted this methodology into a suitable alternative for assessing the post-fire erosion risk. Furthermore, they can be used to calibrate or validate predictive soil erosion models (Prats, 2007), which was the primary goal of the FCT-funded EROSFIRE project (Keizer et al., 2006, 2007).

7.5 Soil water repellency

Soil water repellency measurements were carried out simultaneously during the six RSE's field campaigns in the first and second post-fire years. The different soil preparation techniques did not show a clear trend in soil water repellency levels (Figure 10). Although some caution is required in comparing the data because the sites' sampling dates were not the same, the lack of relationship between the ploughing and soil water repellency levels was probably related to the time elapsed since ploughing. In the same region, Shakesby et al. (1993) suggested that deep-ploughing can render previously hydrophobic soils hydrophilic. Doerr et al. (1998) found that the hydrophilic nature of the soil recently ploughed was only temporary (as short as two years) until the planted eucalyptus trees grow and provide inputs of hydrophobic substances from the litter and root development. Further research in the area suggested that recently rip-ploughed areas can become repellent in a period as short as six months (Leighton-Boyce et al., 2005). Soil burning could also affect the soil water repellency levels, but the effects of burning can be highly variable, depending mainly on the type of organic matter consumed, the soil heating and the amount of oxygen available during burning (Doerr et al., 2009a). Besides this, eucalypt stands constitute a somewhat unusual case in which the long unburned stands can show similar repellency levels compared to the recently burned stands (Doerr et al., 1998). On the other hand, since fire severity was classified as moderate in all the eucalypt stands, to attribute the observed post-fire water repellency spatial pattern to a fire-related component was not possible. Although, wildfire severity was classified through the use of simple indicators such as canopy and shrub twigs consumption, ash colour, etc (see Chapter 3, Table 1).

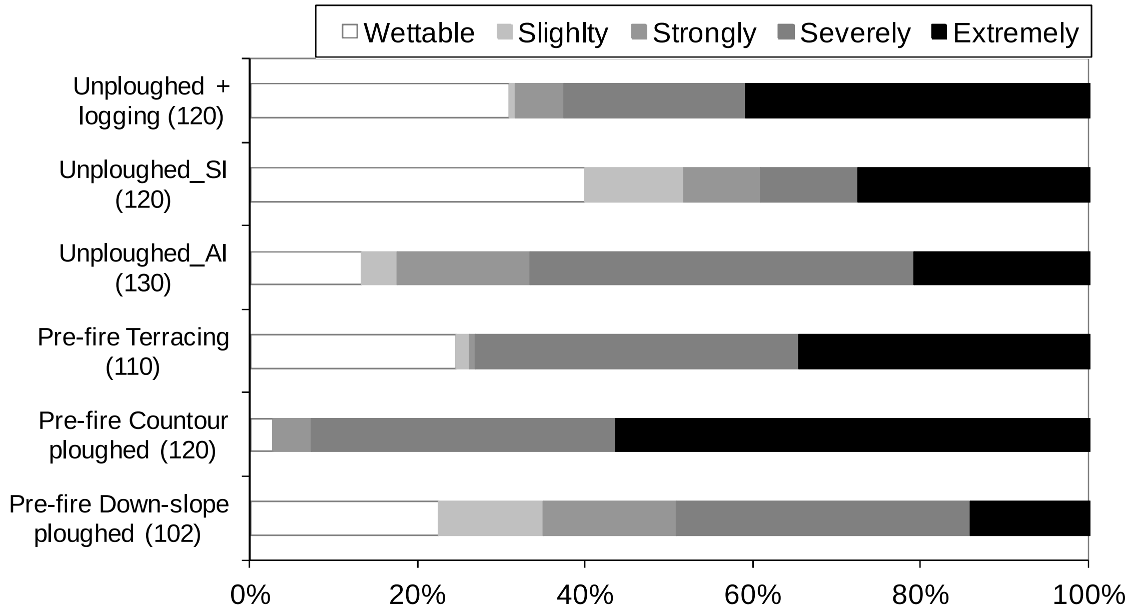

Figure 10. Frequency of topsoil (soil surface + 2-3 cm) water repellency levels at six eucalypt sites managed with different pre-fire soil preparation techniques. Measurements were done at six field campaigns carried out in two post-fire years or one post-fire year in the case of unploughed + logging and unploughed_SI sites. Number of observations is shown in brackets.

A seasonal cycle of low soil water repellency conditions during the wet winter and greater repellency during the dry periods have been reported for unburnt and burnt eucalypt plantations in Portugal (Doerr and Thomas 2000; Ferreira et al., 2000; Keizer et al., 2005a; Leighton-Boyce et al., 2005; Prats et al., 2012) and for other vegetation types around the world (Doerr et al., 2000). All six eucalypt sites showed overall strong to extreme soil water repellency median values, but non-repellent conditions also occurred, revealing rainfall-related seasonal variations (see Chapter 3; Figure 7). The more frequent (2-weekly interval) soil water repellency measurements, at 2-3 and 7-8 cm depth, in the unploughed_AI and down-slope ploughed eucalypt site also showed a seasonal pattern (see Chapter 6; Figure 2). Although it was not possible to give the precise time required for repellency to break down or become re-established, strong changes in repellency level were observed within a period of two weeks. At the unploughed_A1 site, spatially homogenous transitions, i.e. from entirely extreme repellent (median ethanol class 8; inter-quartile range =0) to entirely wettable (median ethanol class 0; inter-quartile range =0) occurred within 22 days. The opposite, i.e. change from entirely non-repellent (median ethanol class 0; inter-quartile range =0) to entirely extreme repellent conditions (median ethanol class 8; inter-quartile range =0) occurred within 15 days. It appears that non-spatially homogenous re-establishment of soil water repellency was even shorter (6 days). Relatively rapid changes in water repellency under eucalypts have previously been reported by Keizer et al. (2005b: 3–4 weeks) and Leighton-Boyce et al. (2005: 22 days) and Crockford et al. (1991: 6–9 days). The rapid change over such short time intervals implies that an adequate description of the temporal dynamics of water repellency under field conditions requires frequent sampling, especially during soil wetting and drying phases, and when the assessment of the hydrological soil water repellency impact is a goal.

In addition to the temporal dynamics, the spatial variability between sites was irregular in time, and poorly related to overall values. In spite of the overall very strong repellency levels in the unploughed and ploughed eucalypt sites, there was a shift from less soil water repellency in the unploughed site in the first post-fire year, to more repellent during the second year (Figure 11). Since fire severity was moderate in both cases and rainfall patterns were the same, the spatial differences in soil moisture content can be the cause underlying the observed differences between sites. Overall soil moisture content was higher at the less repellent unploughed than ploughed site (7.3 vs. 5.8 vol. %) during the first year, whereas the opposite was true during the second (6.7 vs. 9.4 vol. %). However, the soil moisture alone is insufficient to explain the observed temporal fluctuations and/or spatial differences in water repellency levels. An inverse relationship of soil moisture and soil water repellency had been observed for eucalypt sites in the region (Walsh et al., 1994; Doerr and Thomas 2000; Coelho et al., 2005; Keizer et al., 2005a; Leighton-Boyce et al., 2005). Above a certain moisture content (i.e. critical threshold), a repellent soil becomes entirely wettable (Dekker and Ritsema 1994; Soto et al. 1994; Doerr et al. 2009). Afterwards, Dekker et al. (2001) revised the concept suggesting that, a transition zone could be more appropriate, rather than a distinct threshold separating wettable and repellent conditions. The transition zone detected in this study for the two post-fire years was at lower soil moisture content at the unploughed than ploughed site (8-12 vs. 10-14 vol. %; Figure 12). These results implied that the unploughed site maintained hydrophilic conditions at lower soil moisture figures than the ploughed site. In both cases, the soil moisture range was narrower than the 14-27 vol. % described by Leighton-Boyce et al., 2005 in a mature eucalypt site of the region. The results agree with previous findings in the detection of a transition zone (Doerr et al., 2000; Dekker et al., 2001; Leighton-Boyce et al., 2005) and also with the fact that temporal and spatial water repellency patterns cannot be explained only by the soil moisture content.

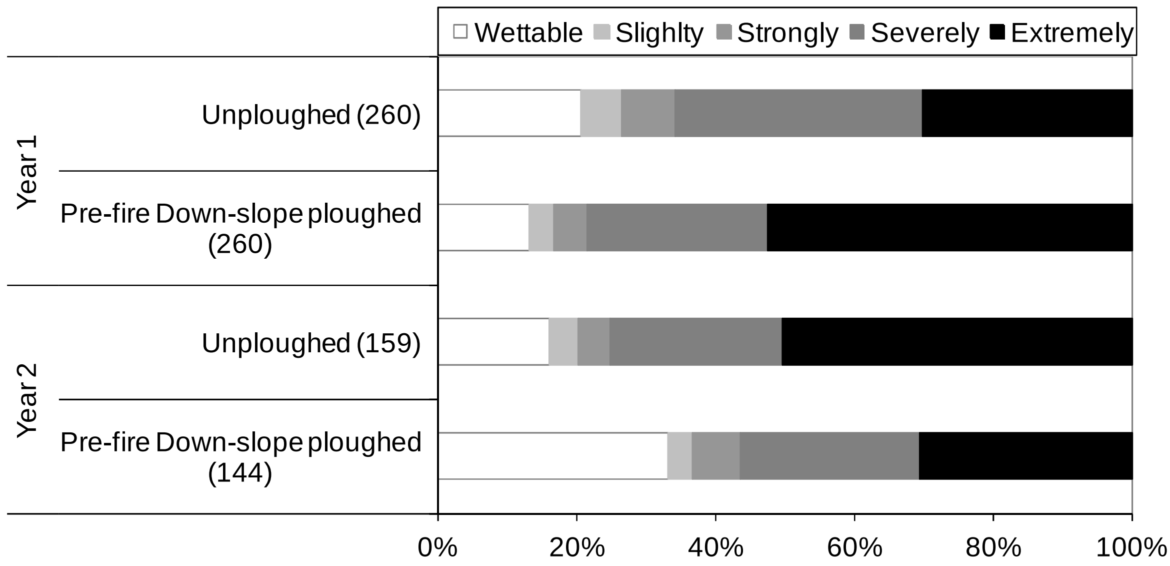

Figure 11. Frequency of below the soil surface (2-3 cm depth) water repellency levels at the unploughed and ploughed eucalypt sites during two post-fire years. Number of observations is shown in brackets.

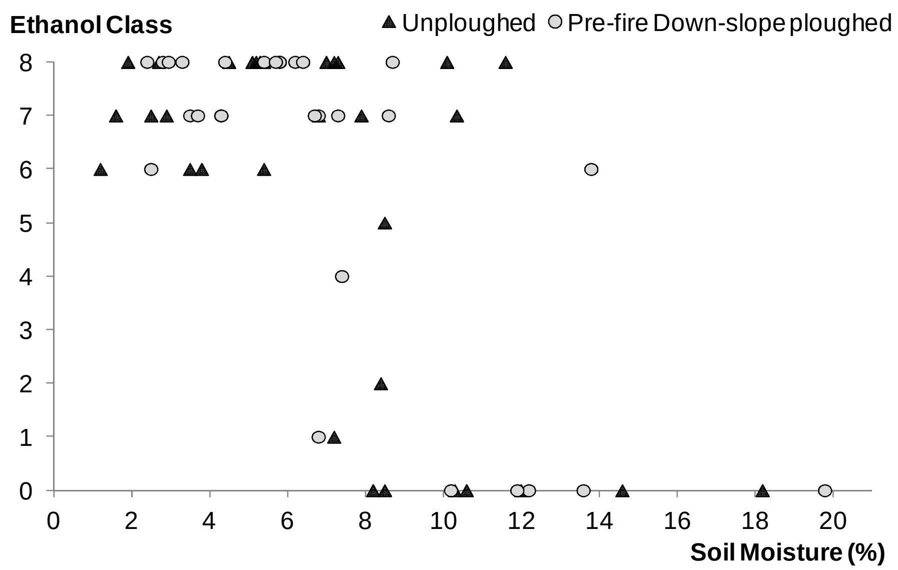

Figure 12. Relationship between median soil moisture contents (vol.%) and median ethanol class at 2-3 cm depth for two eucalypt sites during two post-fire year period.

7.6 General conclusions

The main conclusions of the present PhD study into the hydrological and erosion response of recently burnt forest plantations in north-central Portugal were as follows:

1. Post-fire runoff amounts at the seven study sites tended to be comparable to those reported by other studies in and outside Portugal. The associated sediment losses, however, were low compared to those found by earlier studies, not only in Portugal but especially in other parts of the world. Even so, the present sediment losses must be appreciated against a background of typically shallow soils, presumably, reflecting a long history of intensive land use and, in recent decades, a high recurrence of wildfires. The organic matter contents of the eroded sediments were consistently high (50%), both across the various study sites and throughout the 1- to 2-year study periods. Whilst organic matter losses by post-fire runoff have received little research attention, they do seem of crucial importance for fire-induced soil fertility losses and pollution of downstream aquatic habitats.

2. Contrary to what was expected based on prior research, the pine study site generated more overland flow than the unploughed eucalypt site but similar sediment losses. The present results, however, did not allow clarifying whether this was due to differences in land cover (pine vs. eucalypt) or in post-fire forestry operations (salvage logging vs. natural regeneration). Even so, salvage logging did increase sediment losses at the pine site, as was also suggested by the rainfall simulation experiments that were carried out at another eucalypt study site. These increases in sediment losses after logging could be explained by disturbance of the protective litter cover and the resulting increase in bare soil cover. As a precautionary principle, post-fire logging activities should therefore pay due attention to maintaining or promoting a protective litter cover, as for example provided by the needle cast from scorched pine canopies or by logging residues.

3. The three eucalypt study sites that had been ploughed (prior to the last wildfire) produced similar amounts of overland flow but lower sediment losses than the three eucalypt study sites that appeared never to have been ploughed. This difference in sediment losses was attributed to sediment exhaustion, resulting from enhanced erosion following ploughing. At the same time, however, post-fire sediment losses did not differ markedly between the three types of ploughing operations studied here. This was somewhat surprising, as contour ploughing and terracing are commonly advocated as soil

conservation techniques, whilst down-slope ploughing has been found to markedly increase erosion rates. A probable reason was that the erosion impacts of ploughing were shorter-lived than the time that had elapsed since the ploughing. Since especially terracing is becoming an increasingly widespread practice in the study region, it would seem urgent to address in more detail its implications for land-use sustainability.

4. Hydro-mulching was highly effective in reducing runoff and sediment losses during the first 19 months following its application in a recently logged pine stand. The key factor explaining this effectiveness was the elevated protective soil cover that was first provided by the hydro-mulch alone but, in later stages, in combination with litter and vegetation cover. Besides litter and vegetation cover, hydro-mulching has an effect on topsoil moisture content and topsoil water repellency, these changes also played a role in reducing runoff.

5. During the first two years after the wildfires, time-since-fire had a marked effect on overland flow generation and the associated sediment losses. This effect was observed at all study sites, independent of their land cover or pre-fire land management, and for both measurement techniques (rainfall simulation experiments and runoff-erosion plots). The observed temporal patterns, however, did not correspond to a simple decrease in runoff or erosion with time-since-fire. In general, clear peaks in runoff and erosion occurred following dry seasons or dry spells. These peaks could often be explained by elevated levels of soil water repellency, associated to dry soil conditions and in the absence of a vigorous regeneration of the understory and ground vegetation.

6. Rainfall amount and ground cover were the main factors explaining runoff volumes, respectively for the eucalypt and pine sites. However, the specific models - carried out independently at the ploughed and unploughed eucalypt sites, control and hydromulch plots at the pine site- revealed that the first factors were rainfall amount or intensity. Rainfall amount was the first variable on sites with low ground cover or during periods of high soil water repellency, whereas rainfall intensity became the main factor on sites with high ground cover or during low soil water repellency conditions.

7. In general, sediment losses at the study sites were strongly correlated with runoff volumes. In terms of independent variables, however, they could be explained best by rainfall intensity followed by cover-related parameters.

8. Comparison of post-fire runoff and erosion rates produced by simulated and natural rain indicated that rainfall simulation experiments (RSE's) captured well key

aspects such as the difference between a ploughed and an unploughed eucalypt plantations, their specific sediment losses (i.e. per mm of runoff), and the organic matter content of the eroded sediments. Repeated RSE's furthermore evidenced the marked seasonal variations in runoff and sediment losses, and the apparent role therein of soil water repellency.

9. Overall levels of soil water repellency during two years following a wildfire did not reveal an obvious impact of ploughing for two neighbouring eucalypt plantations, one ploughed and one unploughed, possibly because the ploughing had occurred several years before the wildfire. Differences in water repellency were observed between the two study sites but they were highly irregular through time. Furthermore, temporal patterns in water repellency proved hard to capture, since significant changes were detected over time intervals as short as 6 to 7 days. Soil water repellency levels were less strongly correlated with antecedent rainfall than with soil moisture content, but the latter relationship is clearly of less import for the purpose of predicting water repellency.

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