Universidade de Aveiro Departamento de Ambiente e Ordenamento
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Avaliação de duas medidas na mitigação da erosão do solo após incêndio

Evaluation of two measures for soil erosion mitigation after wildfire

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Gestão e Políticas Ambientais, realizada sob a orientação científica da Dra. Maria de Fátima Lopes Alves, Professora Auxiliar com Agregação do Departamento de Ambiente e Ordenamento da Universidade de Aveiro, e sob coorientação científica do Doutor Jan Jacob Keizer, Investigador Principal do Centro de Estudos do Ambiente e Mar (CESAM) e do Doutor Flávio Gonzaga Castro Santos Silva, Estagiário de Pós-doutoramento do Centro de Estudos do Ambiente e do Mar (CESAM).

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Ao Professor Fernando Páscoa (*in memoriam*).

o júri

Presidente	Prof. Doutora Myriam Alexandra dos Santos Batalha Dias Nunes Lopes Professora Auxiliar do Departamento de Ambiente e Ordenamento da Universidade de Aveiro
Arguente Principal	Prof. Doutor António José Dinis Ferreira Professor Adjunto na Escola Superior Agrária de Coimbra do Instituto Politécnico de Coimbra
Orientador(a)	Professora Doutora Maria de Fátima Lopes Alves Professora Auxiliar com Agregação do Departamento de Ambiente e Ordenamento da Universidade de Aveiro

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palavras-chave lavragem; *mulching*; incêndios florestais; erosão hídrica; eficiência

resumo

Os incêndios florestais contribuem para a degradação do solo e aceleração dos processos de erosão. As medidas de emergência aplicadas após incêndio podem ser determinantes na mitigação da perda de solo e na preservação da fertilidade. Neste estudo, que decorreu em Semide, numa área ardida em Agosto de 2015, foram avaliadas duas medidas: lavragem e a aplicação de *mulching*. Ambas as medidas foram selecionadas pelos atores sociais interessados no decorrer do processo participativo desenvolvido no âmbito do projeto europeu RECARE. Considera-se a lavragem uma prática recorrente de gestão de terrenos florestais depois de um incêndio na preparação dos mesmos para plantação e/ou sementeira. A lavragem, implementada em Julho 2016, consistiu na análise de duas áreas contíguas, com parcelas lavradas e controlo. Foi monitorizada a perda de solo e matéria orgânica a duas escalas: MP ($0.25m^2$) e parcelas SF ($16\ m^2$). As perdas de solo nas parcelas SF foram similares entre tratamentos. Nas MP as perdas de solo foram três vezes mais altas nas parcelas lavradas. Ao nível das parcelas SF a eficiência foi positiva, com maior relevância na mitigação de perda de matéria orgânica (61%). Nas MP a lavragem revelou-se ineficiente na mitigação de perdas. A perda de solo e de matéria orgânica foi diminuindo ao longo do tempo de estudo. As parcelas lavradas revelaram, em ambas as escalas, maior cobertura de solo com pedras e menos vegetação, relativamente ao controlo. Contudo os resultados obtidos foram considerados inconclusivos dado o curto período de monitorização experimental (7 meses) e ao facto da lavragem ter sido implementada 11 meses após o incêndio. A monitorização do segundo ano da experiência de *mulching* visou avaliar a eficiência na proteção do solo à ação da precipitação, tendo os tratamentos derivado da aplicação do material a duas taxas: a taxa estandardizada na literatura como eficiente (8 $Mg\ ha^{-1}$), e a inovadora baixa aplicação (2.6 $Mg\ ha^{-1}$). Estas taxas foram aplicadas em três parcelas SF replicadas por três blocos. Foram ainda monitorizadas 6 MP, 2 por cada bloco, onde, para além da avaliação das perdas de solo e matéria orgânica, foi analisada a escorrência superficial. As parcelas SF com a aplicação da taxa de *mulch* mais alta revelaram perdas mais baixas de solo e de matéria orgânica que as parcelas com a aplicação da taxa mais baixa. As perdas mais elevadas foram obtidas no controlo. A eficiência na mitigação de perda de solo e matéria orgânica foi de 94% e 90%, respectivamente, nas parcelas com taxa de *mulch* mais alta, e 68% e 62%, respectivamente, nas parcelas com a taxa mais baixa. Nos três tratamentos as perdas de solo consideradas pela literatura como toleráveis (1 $Mg\ ha^{-1}\ ano^{-1}$). O desenvolvimento de nova vegetação foi mais elevado no controlo do que nas parcelas SF tratadas. As MP revelaram perdas intoleráveis de solo.

keywords ploughing; mulching; wildfires; water erosion; efficiency

abstract

Wildfires contribute for soil degradation and acceleration of erosion processes. Emergency measures applied after wildfire can be decisive in mitigating soil loss and preserving fertility. In this study, which was held in Semide in a area burned in August 2015, two measures were evaluated: ploughing and mulching. Both selected by the stakeholders during a participatory process developed under the RECARE European project. Ploughing is a recurrent practice of forestland management following a wildfire in order to prepare soil for planting and / or seedling. Ploughing was implemented in July 2016 and consisted on the analysis of two contiguous areas, with ploughed plots and control, respectively. Soil and organic matter losses were monitored at two scales: MP ($0.25m^2$) and SF plots ($16m^2$). Soil losses in the SF plots were quite similar between the both treatments. In the MP soil losses were three times higher in the ploughed plots. At the level of the SF plots the efficiency of the treatment was positive, with a more relevance in the mitigation of organic matter loss (61%). In the MP ploughing was inefficient in losses mitigation. Losses decreased over the study time. The ploughed plots revealed, at both scales, a higher cover of the soil surface by stones and less vegetation, when compared to the control. However, results obtained from the ploughing experience are considered inconclusive given the short period of experimental monitoring (7 months) and the fact that soils were ploughed 11 months after the wildfire. The second year of data monitoring of the mulching experience aimed to evaluate the efficiency of the treatments on soil protection against the direct impact of the raindrops. The treatments consisted in the application of the mulch at two rates: the standardized rate in the literature as efficient in soil protection (8 Mg ha^{-1}) and the innovative low rate (2.6 Mg ha^{-1}). The treatments were applied in three replicate SF plots, one per block. It was also monitored 6 MP, 2 for each block, where in addition to soil and organic matter was also evaluated the surface runoff. The SF plots with the application of the high mulch rate revealed lower losses of soil than the plots treated with the low mulch rate. The highest losses were obtained in the control SF plots. The efficiency of the treatments in soil and organic matter loss mitigation was 94% and 90%, respectively, in the SF plots with the high rate mulch, and 68% and 62%, respectively, in the SF plots with the lowest rate application. In the three treatments the soils losses area considered in the literature as tolerable (1 Mg ha^{-1} year $^{-1}$). The development of new vegetation was higher in the control SF plots than in the treated ones. The MP revealed intolerable soil losses.

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CHAPTER 1. INTRODUCTION

Fire is often identified as the main driver of soil erosion and land degradation by leading geomorphological changes. However, research on post-fire soil erosion is recent in the Mediterranean region. The first investigation outcomes appeared in the early 1980, aligned with the abrupt increase in the wildfires in Portugal (Shakesby, 2011). Orographic, climate and vegetation characteristics of the territory, as the socioeconomic reality of the country - mainly in central and northern regions, have shaped changes in the fire regime, especially by the massive introduction of extensive plantations with highly combustible species. In addition to this reality, climate changes such as the extension of hot and dry periods or the hot winds have contributed to an increase in the wildfires frequency (Ferreira *et al*., 2009).

According with Shakesby *et al.* (2006), the changes in soil properties after a fire are induced by high temperatures, such as the increase on surface repellency and the decrease of aggregate stability. Additionally, removal of the protective layer of vegetation and litter promotes surface runoff, since soils are bare and vulnerable to the direct action of rainfall (Shakesby *et al*., 2006; Ferreira *et al*., 2009; Prats *et al*., 2012; Prats *et al*., 2016). Runoff processes stems from the soils response to rainfall events. If the amount of rainfall exceeds the soil infiltration capacity or the events occur for a long period of time, the soil reaches its storage limit, and then the water flows along the surface following the natural slope. Usually there is an increase in soil erosion by water following a wildfire, thus resulting in threats to soil functions on-site such as loss of organic matter (fertility) and biodiversity decline, but also with potential impacts off-site, such as the increase on flood risk or downstream pollution of water bodies (Keizer *et al*., 2015). From these factors arise the urgent need for the application of post-fire mitigation measures for water erosion as an emergency treatment, for instance, the application of mulch to promote the effective soil cover (Robichaud *et al*., 2000; Prats *et al*., 2012). With the surface cover, the rainfall drops impact on the soil decreases as the surface runoff, since the organic material creates obstacles to the displacement of soil particles and increases infiltration (Bautísta *et al.,* 2009). Mulching has rarely been applied in recently burned areas in Portugal (Prats *et al*., 2012), mainly due the high costs of its application. Often the equipment logistics, manpower and unavailability of the organic material reach to prohibitive costs (Bautísta *et al.,* 2009). However this scenario may change mainly due to financial incentives at a European level, such as the Rural Development Program measures (PRODER, 2016). There are included sub-actions in these measures, such as sub-action 2.3.1.1 that promotes the recovery of potential productive areas affected by wildfires, or action 8.1.4 that supports the forest restoration affected by biotic or abiotic agents or by catastrophic events.

So far mulching has been a measure practically unknown in Portugal, since after the wildfire the remained wood is often logged and the land is ploughed. In turn, ploughing is a traditional land management practice used to prepare soils for replanting or seedling, to reduce competition by other plant species and also to improve accessibility (Malvar *et al*., 2015). Robichaud *et al*. (2009) and Ferreira *et al*. (2009) point out that this measure not only contributes to increase infiltration through the rupture of the impermeable water repellent layer, but also hinders sediment transport by overland flow. This measure is commonly seen as a soil degradation promoter since, in addition to the effects of the wildfires; the machinery used for ploughing produces marked changes in soil physical properties, such as breakdown of parental material, alterations on the particles size and soil hydraulic properties (Malvar *et al.,* 2015). On the other hand, the heavy machinery when is working on steep slopes may have increased difficulties on the surface work progression and some obstacles, such as roots, logs and stones, can make it harder for machines to operate. This can increase the operations costs in big areas (Ferreira *et al.,* 2010).

Alongside with this scenario, the RECARE project – "Preventing and remediating degradation of soil in Europe through land care", consists of a scientific research plan, which main objectives converge for development of solutions based on prevention, remediation and restoration of European soils. In an innovative way, this project has promoted the interaction between scientific partners and social stakeholders in sharing competences towards integrated solutions (RECARE, 2017). Aveiro University is included in this strategy as the Portuguese scientific partner of the project, and it has developed research on implementation of measures to mitigate water erosion of soils in post-fire scenarios.

The present dissertation is focused on the impact of two measures for mitigation of soil and organic matter losses after a wildfire. Both measures were selected by the stakeholders to be implemented in an experimental context, namely in two hillslopes of burnt eucalypt stands. One of the measures (mulching with eucalypt bark and cutting residues, applied at two contrasting rates) was implemented immediately after the wildfire, corresponding the presented results to the second year of monitoring, while the second measure (ploughing, as a current practice of soil management) was carried out 10 months after the wildfire and the results presented correspond to the first monitoring period. According with the study sites characteristics and aligned with the innovative nature of this project, with the stakeholders involvement for the selection of mitigating measures for post-fire erosion, this study aimed to answer to the following research questions: (i) which one of the selected measures (mulching and ploughing) is the most efficient in preventing soil and organic matter losses? (ii) a lower mulch application rate would be as efficient in mitigating erosion as a higher (and more expensive) rate?

CHAPTER 2. STATE-OF-THE-ART

2.1 Ecosystem services and soil functions

Food and Agriculture Organization of the United Nations defined soil as “a natural body consisting of layers (soil horizons) that are composed of weathered mineral material, organic material, air and water. Soil is the end product of the combined influence of climate, topography, organisms (flora, fauna and human) on parent materials (original rocks and minerals) over time” which in turn integrates a wider concept, land (FAO, 2016). Being considered a part of terrestrial ecosystems, soil provides services and functions not always properly valued.

According with the Common International Classification of Ecosystems Services (CICES) final ecosystem services are “the contribution that ecosystems make to human well-being and the outputs of ecosystems (whether natural, semi-natural or highly modified) that most affect the well-being of people. They retain a connection to the underlying ecosystem functions, processes and structures that generate them” (CICES, 2013). Thus CICES has recommended the following classification and hierarchical structure: (i) Provisional services (all nutritional, material and energetic outputs from living systems); (ii) Regulating and maintenance (covering all the ways in which living organisms can mediate or moderate the ambient environment that affects human performance and (iii) cultural services (covering all non-material, and normally non-consumptive, outputs of ecosystems that affect physical and mental states of people).

Therefore, it is noteworthy to conduct research that highlights the deleterious effects of fire in soils, as well as to promote systematic and informed measures that prevent soil degradation following the wildfires.

2.2 Wildfires in Portugal, reforestation policies and climate change

The human impact in landscape, on a local and/or regional scale, is potentially one of the most influent promoters of the propensity for wildfires and it was also identified as a main agent on soil erosion (Shakesby, 2011). Public policies, for forest management, implemented in Portugal at the beginning of the 20th century had, and still play, an important role on the fire regime, influencing the frequency, intensity, size, type and the time in which it occurs, thus also promoting the vulnerability for its occurrence and decreasing the resilience capacity (Fernandes, 2007). As an example, the action measures defined by the government and implemented with the National Forest Regime promulgated in 1903. These measures included for instance the afforestation of the dunes and all public lands, that in many cases comprise areas characterized by steep slopes; or the structuring of funds (e.g. World Bank Portuguese Forestry Project) in 1960, and the accession to the European Community, which ultimately encouraged the development of attractive financial mechanisms for private landowners (EFN, 2014). These mechanisms supported the substitution of native forest species by species with economic advantages, namely eucalypt and maritime pine. Such species are characterized by short life cycles and overlapped with the rupture and abandonment of agricultural and livestock practices (Fernandes, 2007). The Portuguese forest has been transformed over time into a flammable forest.

Partially reflecting the measures taken in the past, wildfires have become a huge problem in Portugal. The current climate changes and fire regime mutation reflect that Portugal is not adapted to the current climate reality (Ferreira *et al.*, 2009). These facts are mirrored in different information sources, such as the State of Europe´s Forests report, performed in 2015, where Portugal is referred as the European country with the highest average of burned area between 2006 and 2013, about 133 000 ha (FOREST EUROPE, 2015). The data available in 2006 on PORDATA statistical platform related with wildfires and respective burned area also reveals the lack of adaptation of Portugal to the climates changes that have been felt over years, such as the hot winds that occurred for long periods, possibly responsible for the wildfire peaks in 2003 and 2005 (Figure 1) (Ferreira *et al.*, 2009).

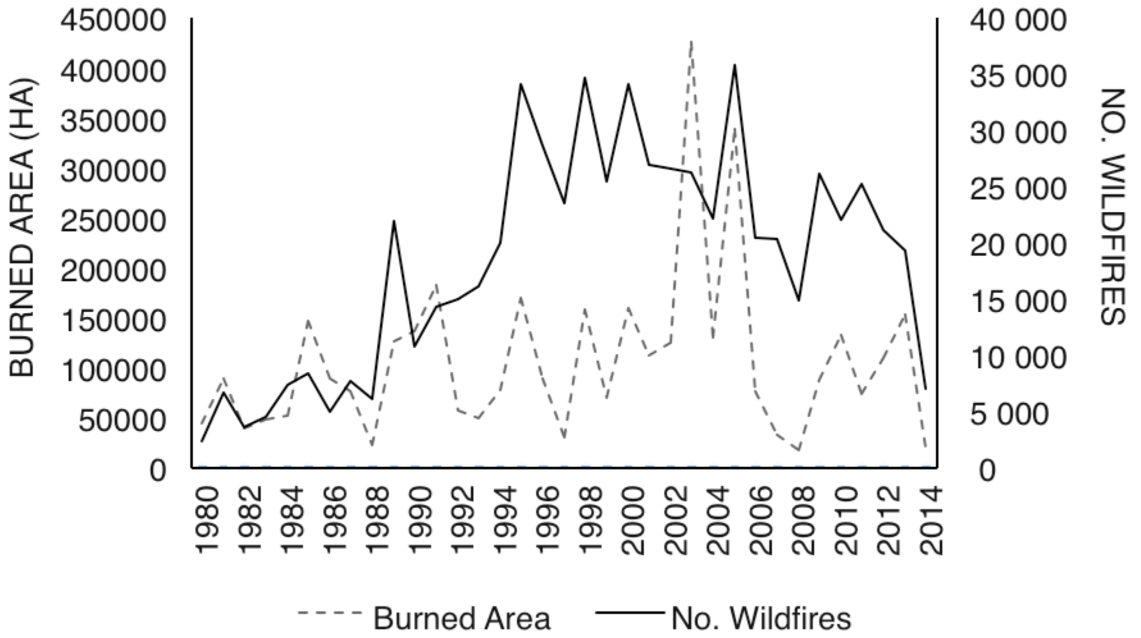

Figure 1. Wildfires number evolution / burned area in Portugal from 1980 to 2014. (Sources/Entities: ICNF/MA-MAFDR, PORDATA, 2016).

There are available some projections for climate evolution in Portugal across the 21st century. Based on IPCC (Intergovernmental Panel on Climate Change) scenarios some models were developed by the Portuguese Institute of the Sea and Atmosphere (IPMA), with the Dom Luiz Institute as investigation partner, included in a European consortium called EC-EARTH (IPMA, 2016). These models reflect a generalized increase in the average of annual temperature with potentially greater incidence in the inner part of the country. Additionally there is a high probability for increasing the amount of hot days (maximum temperatures above 35 °C) and the amount of tropical nights (minimum temperatures exceeding 20 °C), as well as the increase in frequency of heat waves. Regarding the rainfall, it is also pointed a generalized reduction during the spring, summer and autumn. All these facts lead to an increase on the meteorological fire risk and also the need for extension of the critical fire period (EFN, 2014). These projections follow the information presented by Shakesby (2011) regarding future predictions for the Mediterranean climate: higher temperatures, hotter and drier summers with an increase of heat waves, variable rainfall events and potential torrential storms. However, due the complex interaction between fire, vegetation and human actions, it is difficult to establish a linear connection between wildfires occurrences and climate changes, those that are felt in the present and those that are foreseen.

2.3 Impacts of wildfires on soil erosion

This dissertation deals with the threat of erosion by water due to its determinant role in degradation of soil functions after a wildfire. Morgan (2005) indicates that there are local and/or regional characteristics that are considered determinant in soil erosion, namely climate (rainfall amount and intensity), soil type (fragility and resistance to erodibility), vegetation and litter cover (protection and stability) and the surface slope, among other factors.

Rainfall is considered the main driver of soil erosion, being essential to determinate its total amount and intensity and connect this data with the sediments eroded. This information is decisive in understand the soil response after fire and to determinate post-fire restoration measure. A non-linear response is common in a system where the variables such as rainfall may produce more than one effect. In short time, rainfall can increase runoff but in long-term it also can increase vegetation density, which decreases runoff. Rainfall intensity is considered the driving factor in post-fire runoff (Moody and Martin, 2009). Several studies have shown that the effects of rainfall decrease after the first post-fire year due to: (i) development of new vegetation; (ii) decrease of soil water repellency and increase of infiltration rates; (iii) development of a surface resistant layer after the first erosive events; (iv) reduction of the amount of sediments available to be transported by erosive agents and (v) reduction of erodibility due the increase in soil organic matter content which promote the soil cohesion (Scott *et al.*, 2009).

Mediterranean soils, especially those in steep slopes, are in most cases rich in stones and the soil surface layer tends to be thin. According to Morgan (2005), bigger particles are more resistant to transport, being necessary to apply a stronger force to move them. Therefore, the high stone content in a soil can contribute to increase the structural support and protection of the smallest particles against erosion process (Shakesby, 2011). The same author (Shakesby, 2011) suggested that stones increase surface heterogeneity and roughness, thus limiting water action. He also refers several studies where it was verified greater aggregate stability under stones and under vegetation, during the same recovery frame after a wildfire.

When a forest wildfire consumes vegetation cover, it leaves the soil prone for the action of rainfall (erosion driver agent), so then more energy is directly transmitted to the soil surface. Thus, it is stated that the first rain events after a wildfire are typically those that cause more erosion. Increasing erosion can be connected with the early stages of the model developed by Sawson (1981), the so-called window of disturbance, which reflects wildfire impacts (Shakesby, 2011). This model showed that sediment losses rise steeply from a background level to a peak soon after burning, and then they decline gradually to return the background level over a period thought to range from months to years. The window of disturbance is considered to be largely controlled by vegetation recovery and sediment exhaustion. However, this model provides an overview of the soil erosion pattern and it has been recommended to take into consideration the regional variations and the influence of dominant factors (Shakesby and Doerr, 2006).

Forests play a key role in the protection of terrestrial ecosystems, especially regarding water and soil (FOREST EUROPE, 2015). By considering the evolution of wildfires, respective burned area (Figure 1) and the uncertain climate projections, there is a potential increase in the risk of soil degradation and associated threats (both on- and off-site) (Silva *et al.*, 2007). Keizer *et al.*, (2015) have identified some threats directly occurring in soils, such as loss of organic matter (fertility), sediments transport and biodiversity decline. On the other hand, some consequences can be reflected off-site, such as increased flood risk and pollution of downstream water lines.

The impact of soil erosion by water can be considered as natural (indirect or direct influence) or anthropic phenomena (indirect influence). The indirect natural impact is related with the influence of soil properties and vegetation cover, therefore affecting characteristics that are directly related to the soil hydrological response (infiltration capacity, texture, porosity and permeability) or those that are developed over time (superficial crust, aggregate stability or water repellency) identified as direct natural impacts. Morgan (2005) mentioned that the soil water erosion process could be explained through the occurrence of three distinct phases: (i) separation of individual particles from soil, (ii) transport of those particles by some erosive agent and, finally (iii) deposition of the particles when the erosive agent does not have enough energy to maintain the transport phase. Overland flow is directly related with the soil response to rainfall events (Keizer *et al.*, 2015). If the infiltration capacity of soil is exceeded, the ability of the soil to store water reaches to its limit, and the water from rainfall is not absorbed but flows on the surface.

The human influence on water erosion is driven by land use type and population expansion. The lack of land use planning contributes to hasten soil erosion (Keizer *et al.*, 2015). Besides that, the socioeconomic polities, such as those already mentioned and implemented in Portugal including reforestation and those that promoted soil preparation for the massive substitution of native species by profitable ones. These changes happen mainly during the 20 century (Shakesby, 2011).

2.3.1 Direct impacts

Vegetation and litter cover

According with Vega *et al*. (2013), vegetation response to a wildfire is highly dependent on the natural regeneration mechanisms of each species. However, other factors must be taken into account, such as fire severity, fire recurrence or weather patterns. Species with the ability to sprout from the trunk or roots have an important competitive advantage over those that germinate from seeds, since they have a higher growing speed and better ability to recoating the soil. In a short-term, vegetation plays a key role in reducing the impact of the raindrops on surface with a consequent decrease on erosion rate, due its protective capacity but also by stabilizing soil aggregates and promoting infiltration through root systems (Vega *et al*., 2013). Vegetation roots, as also stones, can act as bypass routes for overland flow in repellent soils allowing the migration in depth of water (Shakesby, 2011). In addition to these facts, the root systems of living vegetation also add stability to the soil profile, increasing the resistance to detachment by the action of an erosive agent (Scoot *et al*., 2009).

Soil organic matter

In Mediterranean soils, high amounts of organic matter are often concentrated in the topsoil or near the surface layer, being particularly vulnerable to major losses when the protective cover (vegetation and litter) is depleted or removed due a wildfire. After a wildfire, a large part of the nutrients available on surface is transferred to the ash layer. Large amounts of nutrients are mineralized at the same time that the ground cover and litter are consumed, thus, the surface ashes layer represent a substantial part of the nutrient pool. However a significant part of these ashes is transported with the first rainfall events and accumulated in ponds and water lines (Ferreira *et al*., 2009; Shakesby *et al*., 2011). If part of these nutrients is assimilated by the soil, they can contribute to increase soil quality. However, due to the Mediterranean soils characteristics (thin and high stone content), the probability of fertility depletion is high, leading to delays in vegetation recovery and promoting soil exposition to erosive agents for longer periods (Shakesby, 2011).

Organic matter also plays an important role in soil aggregation/cohesion, thereby reducing surface erodibility (Scoot *et al.,* 2009). Soils with high organic matter content are well structured due the presence of macrospores that will allow water movements in depth (infiltration) and its storage. These macrospores also allow roots to grow, thus leading to enhanced vegetation recovery (Ferreira *et al*., 2010). Therefore, organic matter losses are a part of soil erosion that leads to long-term loss of fertility and sustainability (Prats *et a*l., 2016). During the wildfire, the organic matter combustion and/or transformation will contribute to several changes on the physical, chemical and biological properties of the soil (DeBano, 1990). The vulnerability of soil to erosion is then enhanced: bare surface, less cohesion between particles and decreasing soil infiltration capacity, leading to higher organic matter losses on sediments transported (Scoot *et al.,* 2009).

As a result from the organic matter combustion is the formation of a repellent layer on surface that when combined with the loss of vegetation cover, leads to an increased runoff and erosion by the reducing the infiltration rate (Zavala *et al.*, 2014). This soil property called soil water repellency is dynamic and refers to the capacity of soils to resist on wetting at time scales ranging from seconds to weeks. Some research conducted in Mediterranean soils proved that soil water repellency is a common phenomenon, especially in soils that are dominated by several types of vegetation, whit some emphasis in eucalypt stands, burned or not (Malvar *et al.*, 2015).

However, human influence can play an important role in avoiding the most considerable soil loss, usually in the first year, through the application of measures against soil erosion in order to conserve soil properties and mitigate the action of erosive events when the soil is unprotected (Keizer *et al.*, 2015).

2.3.2 RECARE project overview

The project RECARE – "Preventing and remediating degradation of soils in Europe through land care" - is a scientific research project funded by the 7th Framework Program of European Commission, which main objectives converge towards the development of concrete solutions based at prevention, remediation and restoration of European degraded soils. By covering a total of 27 European institutions, it focuses on 17 case studies that cover a multiplicity of soil threats occurring through Europe, and which are marked by biophysical, socioeconomic and environmental differences. The innovation of this project is based on the involvement of the stakeholders in almost all phases of the research, stimulating communication and knowledge transfer. The central objective is the active involvement, being necessary to inform at the right moment and in the most appropriate language to encourage the implementation of the right measures (RECARE, 2015).

The case study led by the Aveiro University has been focused on the implementation of mitigation measures for post-fire soil erosion by water after a wildfire that occurred in the Semide municipality on August 2015 (see Section 4.1). The measures selected consisted of mulching (at two contrasting application rates) and ploughing. The stakeholders have selected these measures during the first phase of the project as those with higher potential to be efficient in reducing soil erosion and, at the same time, about which they knew little. This selection reflect the two main strategies of emergency intervention in a post-fire scenario: (i) avoid or mitigate erosion through application of material that increases the surface cover and limit runoff, and (ii) development of water infiltration and sedimentation opportunities in order to reduce the magnitude of erosive processes (Ferreira *et al.*, 2005; Ferreira *et al.*, 2010).

In the Mediterranean region the dominant fire management policy has been the suppression of the wildfires by reducing fire severity through the application of measures to limit the available fuel amount (Shakesby, 2011). Considering wildfires negative impacts in soil that were discussed above, it became essential to apply post-fire stabilization and rehabilitation measures (Robichaud, 2009). However, most of these measures are relatively expensive and difficult to implement, reason why most forest owners are not receptive to invest in post-fire soil recovery, especially when it is associated with small incomes and high risks (Bento-Gonçalves *et al.*, 2013). This may be one of the reasons why most of the post-fire management of soil relies of common and traditional practices, such as logging and extraction of the remaining wood followed by reforest. In addition, reforestation is often preceded by soil mobilization, through ploughing rip-ploughing or terrace construction, which may contribute to additional increases in soil water erosion (Martins *et al.*, 2013).

Considering the global dimension assumed by the wildfire of 2005 that have affected areas of high sensitivity from the biophysical and landscape point of view or areas with great economic value for Portugal, was established in the ministers council Resolution n. º5/2006, 18 January, the need of adopt strategy guidelines for the recovery of burned areas. Thus, following the occurrence of a wildfire with considerable dimensions, or multiple wildfires in a region, Forests and Nature Conservation Institute (ICNF) prepare a report - Emergency stabilization report (REE), and thereafter the emergency stabilization measures that specific area are formalized. The treatments include the stabilization of slopes, water lines and paths. The detailed soil stabilization actions include mulching, seeding, erosion barriers, drainage along the contour lines and breaking the soil repellent layer. After this process the applications for funding can be submitted by entities, such as municipalities or associations, or individually, and the proposals may only be related with one type of treatment or intervention to apply in a small area than the total burned area. In the study area, addressed by the RECARE project, the REE proposed the installation of logger barriers (ICNF, 2015). The application for funding to implement the treatments was carried out by the municipality. The proposal was also complemented with mitigation measures for water lines and paths.

Under the experimental context, within the RECARE project, the measures selected by the stakeholders were implemented at plot scale (mulching with forest organic residues and ploughing).

2.3.3 Mitigation measures of soil erosion

According to Morgan (2005), preventing soil erosion, which means reducing the rate of soil loss rate to expected values to be achieved under natural conditions, is expected from the correct selection of mitigation measure, and for this is necessary to know erosion phenomenon.

Among all the existing emergency measures the reflection will focus on the mitigation measures considered on this study, namely the ploughing and the mulch application.

Ploughing

Soil ploughing was a recurrent as a traditional measure of land management in Portugal, during the 80´s and 90´s, used in the preparation of the soil for reforesting (Shakesby, 2011). This technique consists of mechanical action of turning the soil, leading to the formation of grooves and small ridges. The pits collect water and sediments, promoting water infiltration and sedimentation (Ferreira *et al.*, 2010; Ferreira *et al.*, 2015). However, the mobilization process could promote soil degradation, with a huge influence on soil erosion. This measure could change the sediment fluxes across the slope and continue to persist long after the emergency is over (Ferreira *et al.*, 2015).

Shakesby *et al.* (1994) have conducted a study focused on quantification of erosion in eucalypts and pine stands and its relation with the usual management practices after fire, including downslope rip-ploughing. A higher sediment loss was found in ploughing practice than that caused by wildfire itself. It was estimated that soil loss decreased considerably after the initial and seasonal rainfall peak (usually taking place after the dry summer period), but took several years to recover to background levels. Those authors also highlighted the lack of research in estimating erosion when these two disturbances –wildfire following ploughing, occur at the same time. Ferreira *et al.* (1997) conducted a research which main objective was to monitor soil degradation processes associated both disturbances, ploughing and wildfire, at plot and catchment scale. They observed higher erosion rates at plot scale when the soils were ploughed, as also found by Shakesby *et al* (1994). However, Ferreira et al. (1997) observed contrasting results when the catchment scale was considered, with lower erosion rates in the unploughed soils. This study reveals the importance of knowing the characteristics of the area that is surrounding the study area and its possible influence in the results. Malvar *et al.* (2015) also studied these two disturbance measures, however those soils had been ploughed 20 years before the wildfire occurred. Higher losses were found in the unploughed soil, perhaps due to soil exhaustion and sediment limitation to be transported. These and other studies, such as Alcázar *et al.* (2002), Figueiredo *et al.* (2012) and Martins *et al.* (2013), have demonstrated the susceptibility of soil to erosion after the application of soil mobilization techniques, such as ploughing and terracing construction, resulting in high losses of soil and organic matter, and thus constraining the productive features of the soil. Common to all the investigations mentioned on TABLE 5 are the intolerable losses of soil.

In 1996, Shakesby *et al.*, pointed out the importance of understand soil erosion processes when two disturbing events occur together - burned forests and ploughed soils, being a knowledge gap in this soil research area. This study lack still remains in our days; understand the interaction between these two disturbances and the soil response to them. In addition to the negative impact in soil degradation, this practice has other disadvantages. Ferreira *et al.* (2005, 2010) pointed out some disadvantages of this mechanical intervention, such as the difficulties of machinery progression on soil due the radicular system of trees remain in the ground, or the issues found when working in steep slopes. Ploughing of extensive areas has high costs associated due to manpower and fuel consumption. Thus, this practice reveals but itself difficult to implement and costly.

Some authors (Shakesby *et al.*, 1996; Cassol and Lime, 2003; Macdonald and Robichaud, 2007 all authors cited by Ferreira *et al.*, 2010) recommended, that in the forestry management (for plantation and seedling) after the soil mobilization, another measure should be applied, such as the mulching, in order to promote water infiltration, sediment retention and soil recovery through the regeneration of vegetation and soil structure rehabilitation.

Mulching

Emergency stabilization treatments, such as mulching, according with Robichaud (2009), should be conducted within a year of a wildfire to stabilize the burned area, protect public health and safety, and reduce the risk of additional damage to valued resources, such as water supply systems, aquatic habitats and roads. It is necessary to make the effort so that the treatments area applied before the first rainfall events after the wildfire has occurred.

The application of mulch as a post-fire emergency treatment began in the 80´s, when numerous rehabilitation measures were applied in areas severely affected by wildfires in the western United States of America. The main purpose of mulching is to reduce the energy impact of raindrops and surface runoff, thereby limiting the transport of soil particles and increasing the water infiltration (Bautísta *et a*l., 2009). Primarily, mulching is intended to provide soil cover and protection (Ferreira *et al.,* 2005).

The effectiveness of this treatment will depend on the mulching type as well as its application rate and technique used, but also can be influenced by local specific characteristics, such as type of soil, topography or vegetation recovery. In general, organic materials (straw, jute, wood excelsior, wood chips or wood shreds) are more effective in trapping soil particles, and in retaining moisture, than the inorganic materials (such as straw pellets that can contain binding materials like polyacrylamide-family flocculants). Mulches can be applied in the field by terrestrial means or helicopter, however terrestrial application is preferential in small areas as it can be carried out manually. An application by hand is less expensive than by helicopter but continues to have a significant cost associated, especially concerning the manpower and if there is no raw material locally available (Bautísta *et al*., 2009).

In 1996 Shakesby *et al*. conducted a study in Portugal that aimed to improve knowledge of wildfires impacts on soils in eucalypt and pine forests, and in the other hand, analyze the impact of the main types of post-fire land use practices, implemented on the study area, on soil erosion. In the study area there were three main post-fire land use practices following the manual logging of the remained timber, namely, (1) eucalyptus regrowth from the stumps, (2) pine seedling regeneration in scrub vegetation and (3) planting eucalyptus seedlings on ground prepared by rip-ploughing.

Another research performed in Portugal by Prats *et al*. (2012) was based on the application of different types of mulching, at different application rates, in distinct forest stands, namely pine and eucalypts, after wildfires. Later research evaluated different mitigation treatments (different types of mulching, hydromulching and polyacrylamides) for soil erosion, giving a worldwide view of their application (Prats *et* al., 2014). The most recent research by these authors assessed the scale effects of mulch application from micro-plots to slope-scale plots in a eucalypts stand (Prats et al., 2016).
Common to these studies was the high mulch rates application, equal or higher than 9 Mg ha^{-1}, demonstrated efficiencies close or superior to 90% (Shakesby *et al*., 1996; Prats *et al*., 2012; Prats *et al*., 2014; Prats *et al*., 2016), as can be observed on Table 6.

2.4 Objectives

The main objective of this dissertation is to contribute for the scientific work that has been developed in the framework of the RECARE European project. It intends to reinforce the knowledge on the efficiency of two measures – ploughing (implemented ten months after wildfire) and mulching (second year after wildfire) – for mitigation of post-fire soil erosion. In particular, the following research questions were raised:

- Which of the measures selected by the RECARE project stakeholders is the most efficient regarding the soil and organic matter losses?
- A reduced mulch application rate is as efficient as the standard application rate in mitigating soil erosion?

To address these questions, specific objectives comprised methodologies to quantify, correlate and evaluate, at two different scales:

- runoff generation and its relation with rainfall;
- soil and organic matter losses;
- ground cover dynamics.

CHAPTER 3. MATERIAL AND METHODS

3.1 Study area

The study was conducted at Segade, Semide, parish of Miranda do Corvo (40º 9.977’ N, 8º 19.506’ W), a village in the central Portugal, coinciding with a part of the Ceira river basin (Figure 2). This area is dominated by forest use, namely by eucalypt stands, and it was affected by a wildfire, starting on August 9th 2015, that resulted in a burned area of approximately 719ha (ICNF, 2015). For the implementation of the measures under study, two hillslopes were selected, distancing about 2 km from each other and presenting similar slope and exposure (A: 20 ± 5 º; B: 27 ± 2 º and A: NNE; B: ENE, respectively). However, the hillslopes presented contrasting conditions before the wildfire, in particular because the stands of slope A had been logged two weeks before the wildfire. Despite this difference, the severity of the fire appeared to have been similar in both slopes, presenting a complete combustion of the litter layer and with predominantly black ashes, thus suggesting a moderate severity according to Shakesby and Doerr (2006). The climate of the area is Mediterranean with oceanic influence and, according to Köppen climatic classification, it is characterized by a humid mesothermal (Csb) with dry and temperate summers (IPMA, 2016). The average annual temperature and precipitation is, according to the information at the nearest meteorological station (Carapinhal, 12 km distance), 12 ºC and 851 mm respectively (SNIRH, 2017). The parent material of the study area was pre-Ordovician schist of the Hesperic Massif (Pereira and Fitzpatrick, 1995) and the soils were classified as acidic loamy Epileptic umbrisol (WBR, 2014). The main characteristics of both slopes are summarized in Table 1.

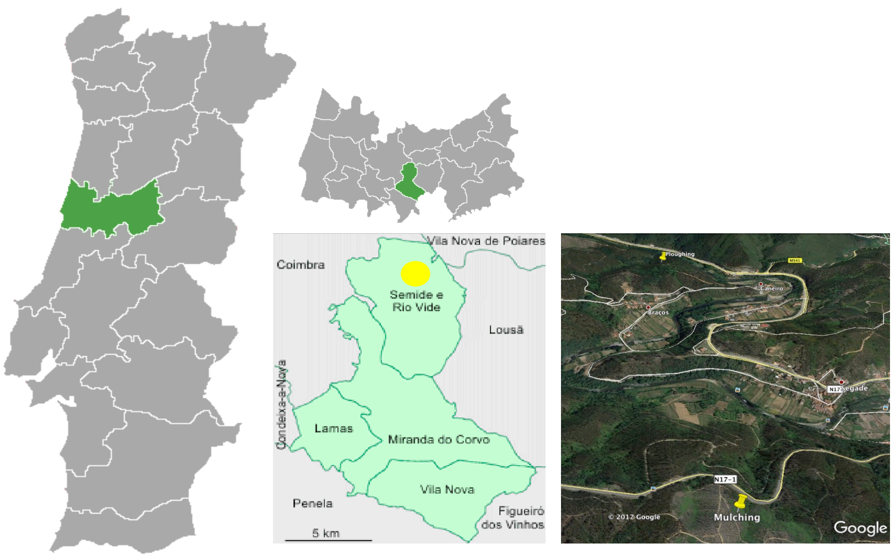

Figure 2. Geographical location of the study area.

Table 1. General characteristics of the study area (standard deviations between brackets; "*" indicates values after ploughing.

	Ploughing experience	*Mulching experience*
Previous vegetation	*Eucalyptus globulus* Labill.	*Eucalyptus globulus* Labill.
Fire severity	Moderate	Moderate
Soil characteristics		
Bulk density (g cm^{-3})	0.76(0.10) 0.83(0.14)*	0.90(0.11)
Stone content (g cm^{-3})	0.32(0.09) 0.28(0,07)*	0.42(0.09)
Organic matter content 0 – 5 cm (%)	13.10(1.79) 12.52(2.42)*	13.80(2.70)
Layout characteristics		
Slope angle (º)	20(5)	27(2)
Projected area (m^2)	14.73	15.13
No. Control/Treatment plots	6/6	9/6

3.2 Experimental setup

Eleven months after the wildfire, on July 22nd 2016, after the ploughing operation, were implemented over three erosion plots (8 x 2 m), three micro-plots (0.5 x 0.5 m) and one destructive plot per treatment in two contiguous areas (Figure 3 and Figure 4 - A). The six erosion plots (hereafter named as sediment fence plots – SF plots) were bounded by trenches and silt fence fabric, thus avoiding run-on into plots and allowing the retention of the eroded sediments at the base. The six micro-plots (hereafter named MP) were installed in the same way as SF plots. One of areas was ploughed and the other left unploughed. The ploughing operation was carried out at nearly 20 cm depth, consisting of soil revolving.

About one month after the wildfire, on September 2015 at site B, were implemented over three SF plots per each treatment that were further randomly sorted over three blocks, plus a destructive plot per treatment. Were also installed two MP, per block and without any treatment, bounded by sheet metal and connected to tanks, thus allowing for runoff collection and sampling (Figure 3 and Figure 4 - B). The size of the plots at site B (SF plots and MP) was similar to the described for site A, with the difference that in site A was no runoff collection in the MP. The treatments over study were: no_mulch: control; low_mulch: 0.26 Mg ha^{-1} and high_mulch: 8.00 Mg ha^{-1}.

Each slope was instrumented with two rainfall gauges consisting of automatic tipping bucket type.

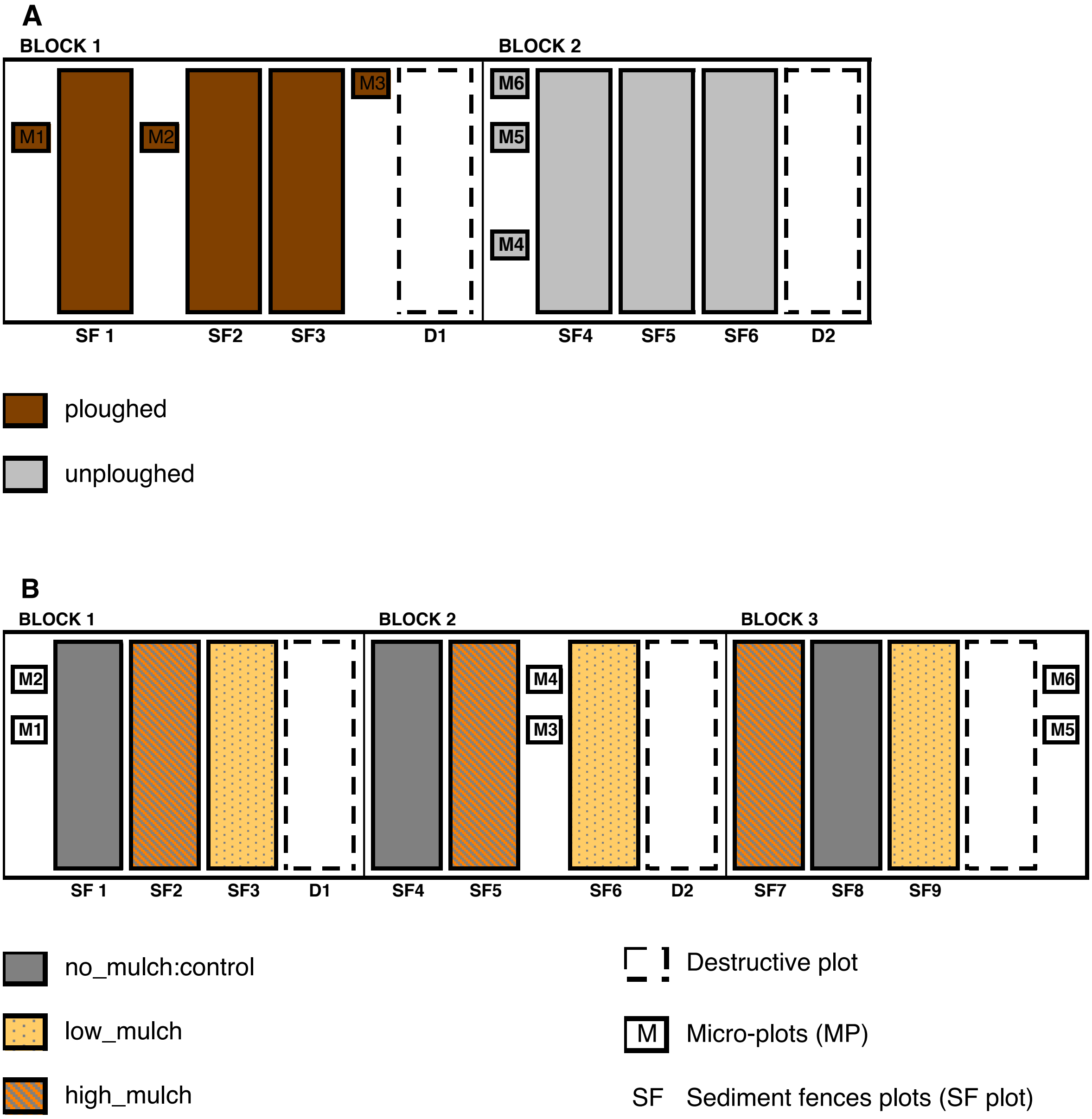

Figure 3. Experimental setups site A and site B.

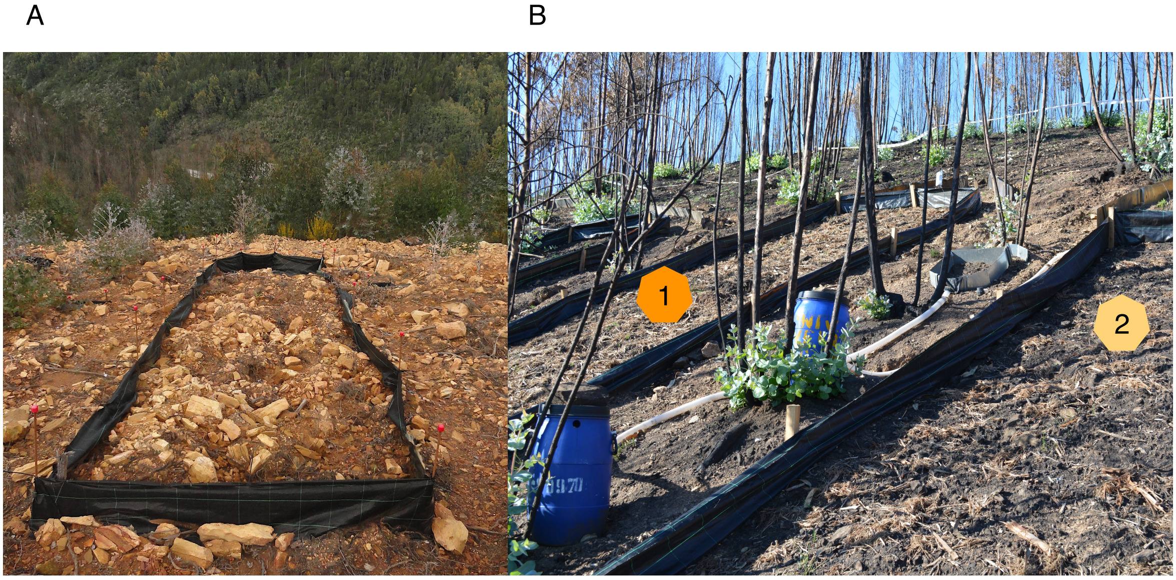

Figure 4. A - Ploughing experience; B - mulching experience: **1** – high_mulch, 2 – low_mulch.

3.3 Field measurement and sampling

Sampling campaigns were carried out with approximately weekly intervals, or at longer intervals when no rainfall occurred. A total of 11 read-outs were considered in the scope of this study, between September 2016 and March 2017. Each sampling campaign consisted of collecting sediments, measuring and sampling runoff (site B – MP), as well as collecting rainfall data. The monitoring of the SF plots (site A and site B) consisted in collecting the total amount of sediments eroded that were transported by water along the plots and stayed retained in the waterproof area. These sediments were in a later phase weighed for laboratory determination of moisture and organic matter content. The erosion monitoring of the MP, on site A, was conducted in the same way as in SF plots. In site B, sediment losses in SF plots was monitored in the same way as site A, while in the MP was analyzed by sampling runoff.

Runoff that occurred in the MP, on site B, was collected after measuring of the total volume stored in the sampling tanks (30 L). A runoff sample was collected from the tanks, in 1.5 L bottles, after thoroughly stirring of the tank, for further quantification of sediments and organic matter content. The runoff samples were filtered using 12-15 µm pore filters that were weighed after drying 24 h in an oven at 105 °C. After filtration, the filters were dried for 24 hours and weighed again for determination of dry matter content (APHA, 2005). Thereafter the dry sediments in the filter were scrapped to a crucible with known weight and ignited in a muffle at 550 °C for 4 h. Then the organic matter content was determined by loss on ignition (Pribyl, 2010).

For sediment samples, which total weigh was registered, a representative subsample of 2-5 g was collected to a crucible of known weight, and then dried for 24 h at

105 ºC and ignited for 4 h at 550 ºC, following the same determinations as previously described for runoff samples.

Ground cover was assessed on SF and MP (on both sites) on four occasions during the study period, with intervals of approximately two months. The evaluation was based on an individual picture taken (three per each SF: bottom, middle and top; one per each MP). For plots cover classification one virtual grid was drawn over each picture containing 100 intersections points for further assignment of one of seven cover categories (stone; litter, including mulch and debris; bare soil; new vegetation; moss; ashes and charcoal; fungi). Each grid corresponded approximately to 1 m^2 in the SF plots.

Rainfall was registered through the tips recorded in the automatic rainfall gauges. Each automatic gauge had its side a rainfall totalizer rainfall that would act as a backup in case of an equipment failure.

3.4 Data analysis

The data was analyzed in absolute terms of runoff (mm), soil and organic matter losses (Mg ha^{-1}), and expressed per unit area projected from each plot.

The total amount of rainfall was grouped for each period between sampling campaigns in order to relate erosion with the total rainfall occurred. For each of these periods the maximum 30-minutes rainfall intensity was calculated.

Soil loss scale ratios were defined as the SF plots value divided by the MP value for both control and treated plots, and treatment ratios were the value of soil, for each erosive event, from the treated plots divided by the value from the control plots (Prats *et al.*, 2016).

Statistical analysis consisted of a two-way ANOVA, by using sediment and organic matter losses as dependent variables and treatment and time since fire as fixed factors. Dependent variables were log-transformed to guarantee the assumptions of normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test). A significance level of 0.05 was considered throughout the tests.

CHAPTER 4. RESULTS

4.1 Rainfall

In terms of total rainfall amount registered in the monitoring period it may be considered that this year is being drier than the previous year of study (Silva *et al.*, 2016). Data monitoring took place from September 2016 to March 2017, where usually are included some of the typical seasonal peaks of rainfall, that happening in autumn, winter and early spring.

In the first seven months of monitoring of the study the accumulated average of rainfall, in both study sites, was around 555 mm (562.6 mm – Site A and 546.8 mm - Site B). The rainfall peaks were recorded between 24 November 2017 and 7 March 2017, with the event of 24 November 2017 recording the highest values of amount (92 mm - Site A and 107 mm – site B) and intensity (21.1 mm h^{-1}, site A and B) of rainfall (Figure 6).

4.2 Runoff

Runoff (mm) was only assessed at site B, on the six untreated MP, allowing the analysis of the direct impact of erosive events on a small scale. These MP produced an accumulated average runoff of 279 mm amounting to an overall average runoff coefficient of 49%. Runoff amount (mm) varied directly with the total amount of rainfall (mm) (Figure 5). On the other hand the variability of individual MP response to the erosive events, with runoff generation, was more pronounced when the amount of rainfall was higher (Figure 5).

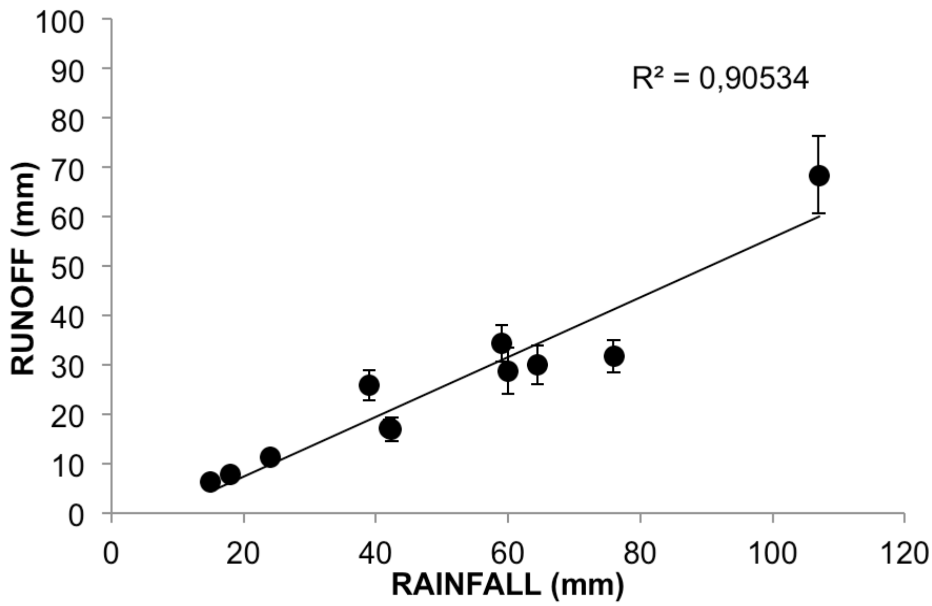

Figure 5. Relation of runoff (mm) with rainfall amount (mm) in the MP of site B.

Runoff coefficient reached the peak on 29 November 2016 with the value of 67% (Figure 6) where was registered 26 mm of runoff. In this moment it was registered the rainfall amount of 39 mm and an intensity of 6.2 mm ha^{-1}. In the read-out performed few days before, namely on 24 November 2016, the value of the runoff coefficient was quite similar (64%) however the runoff reached to its highest average value (68 mm) that could be related with the most relevant rainfall event in terms of quantity (107 mm) and intensity (21.1 mm h^{-1}) (Figure 6).

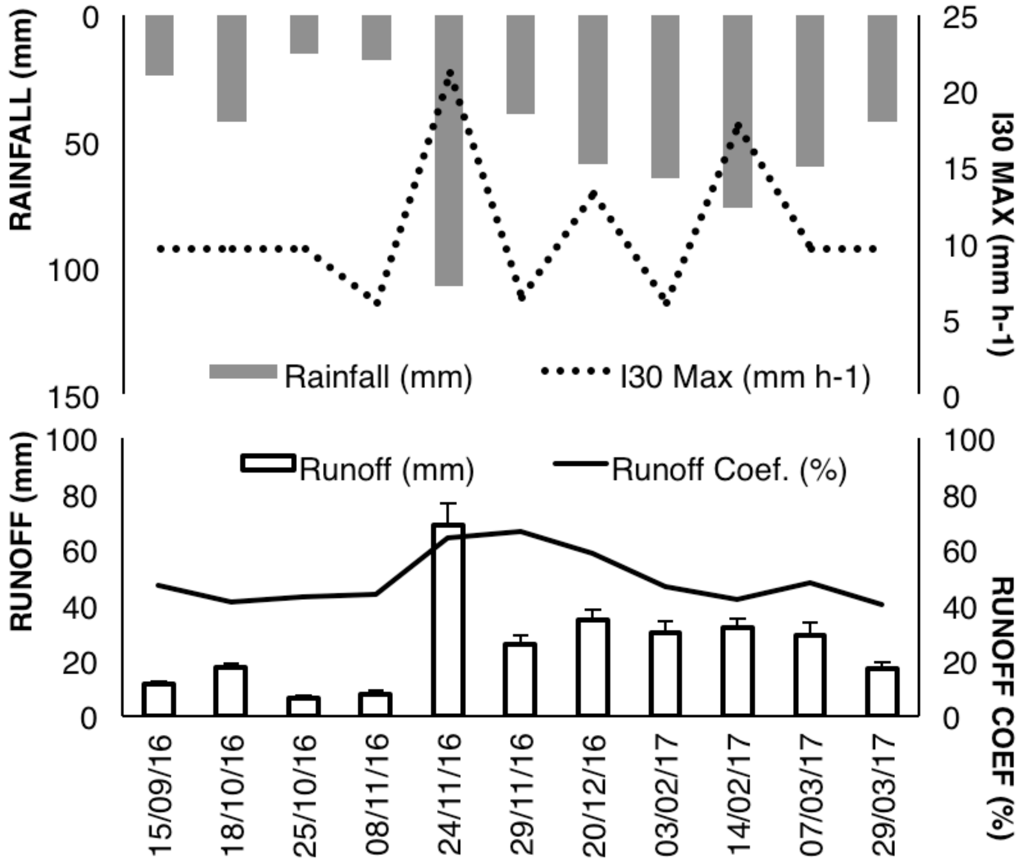

Figure 6. Relation between erosive events and the average runoff generated.

4.3 Soil erosion

Total losses

The data collected during 7 months in the ploughing experience, showed similar soil losses at SF plot scale on unploughed and ploughed plots (1.249 Mg ha^{-1} and 1.178 Mg ha^{-1}, respectively). In the MP, the soil lost in the ploughed plots was almost 4 times higher (12.582 Mg ha^{-1}) than in the unploughed plots (3.235 Mg ha^{-1}). Regarding the total amounts of organic matter loss, at SF plot scale the loss was 3 times higher in the unploughed plots (0.357 Mg ha^{-1}) than in ploughed plots (0.138 Mg ha-1), and in the MP the loss was more than 3 times higher in the ploughed plots (1.689 Mg ha-^{1}) than in the control ones (0.531 Mg ha^{-1}) (Table 2).

Regarding the mulching experience, the soil losses observed in the treatments, low_mulch and high_mulch, reached to low values (0.162 Mg ha^{-1} and 0.031 Mg ha^{-1}, respectively), when compared with untreated SF plots (0.499 Mg ha^{-1}) (Table 2). The amount of soil lost in the low_mulch was five times higher than the amount lost in the high_mulch. Untreated MP revealed high losses (2.934 Mg ha-1). On the other hand, the loss of organic matter was four times higher in the MP (0.328 Mg ha^{-1}) than in the SF plot scale (0.078 Mg ha^{-1}) (Table 2).

Table 2. Cumulated losses of soil and organic matter in both experiences during the second year after fire, with the values in between brackets corresponding to the standard deviations.

Total losses (Mg ha^{-1})								
	Ploughing				**Mulching**			
Treatment	unploughed		ploughed		no_mulch		low_mulch	high_mulch
Scale	MP	SF plot	MP	SF plot	MP	SF plot	SF plot	SF plot
n	3	3	3	3	6	3	3	3
Soil loss	3.235	1.249	12.582	1.178	2.934	0.499	0.162	0.031
	(0.854)	(0.215)	(4.378)	(0.731)	(1.848)	(0.814)	(0.161)	(0.013)
Organic	0.531	0.357	1.689	0.138	0.328	0.078	0.030	0.008
matter loss	(0.094)	(0.038)	(0.518)	(0.080)	(0.188)	(0.078)	(0.025)	(0.002)

4.4.1 Loss patterns

Ploughing

Soil and organic matter losses were monitored on site A for 7 months showing the cumulated average losses that occurred in each read-out in a SF plot scale and in a MP scale (Figure 7).

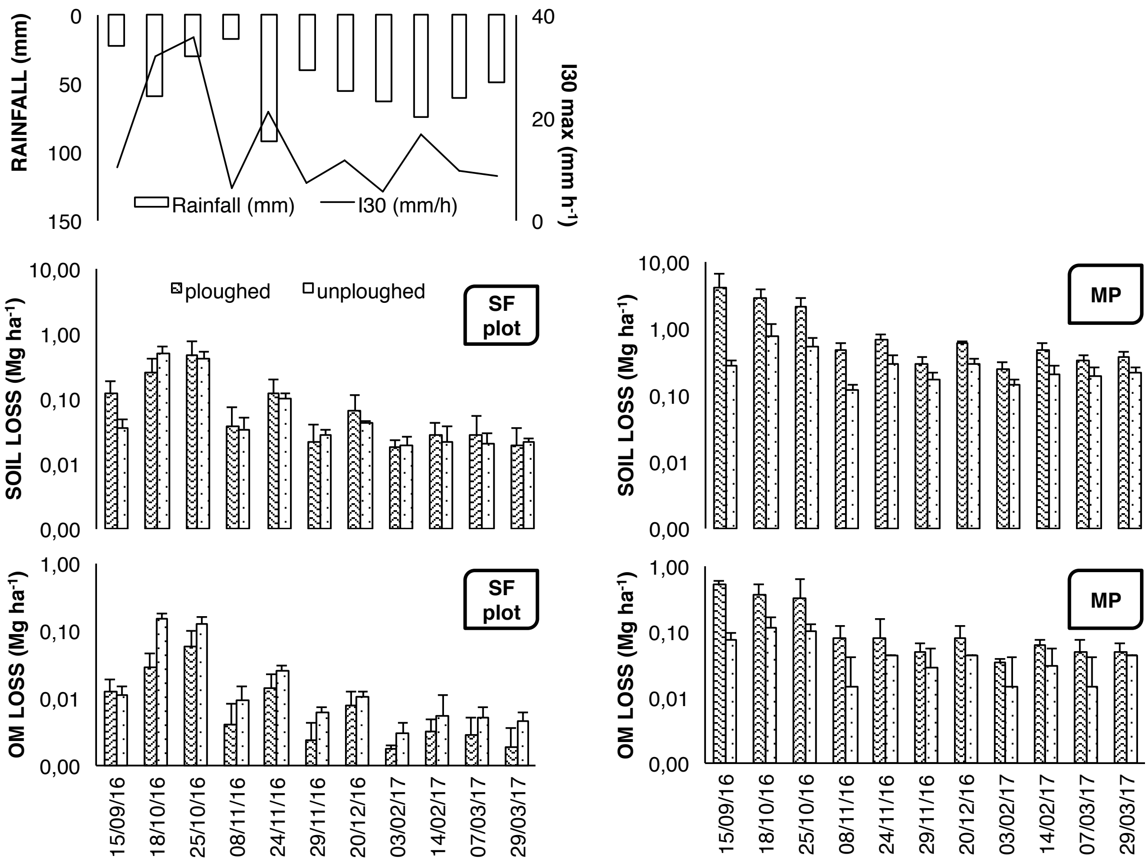

Figure 7. Average soil and organic matter (MO) losses in the ploughing experience.

Regarding this experience, soil losses were more pronounced in the first three read-outs, on both treatments (unploughed and ploughed), at both scales. After these moments the loss values reached to apparent stable values (Figure 7). This fact reveals the importance of the factor time, since the wildfire, on soil loss (p<0.001) (Table 3). In the SF plots, the soil loss increase over these first three moments, while in the MP the losses decreased. The organic matter losses closely follow soil losses, being relatively proportional (Figure 7).

Considering the amount lost in the three first moments in relation to the total loss in unploughed and ploughed SF plots (1.249 Mg ha^{-1} and 1.178 Mg ha^{-1}, respectively), more than 70% of the losses were concentrated in firsts moments, in both treatments (71% and 77%, respectively). Regarding the similar total amounts of soil lost at this scale, treatment (ploughing) has not a significant role (p=0.805) (Table 3).

The ploughed MP, 72% of the total amount of soil lost (12.582 Mg ha^{-1}) occurred in the first three erosive moments while in the unploughed MP 49% of the total lost (3.235 Mg ha^{-1}) (Table 2) occurred in those moments. At this scale, also the treatment (ploughing) had a significant impact on soil loss (p<0.001) (Table 3). Soil losses were continually high in MP, namely in the untreated plots (Figure 8 a) and b)).

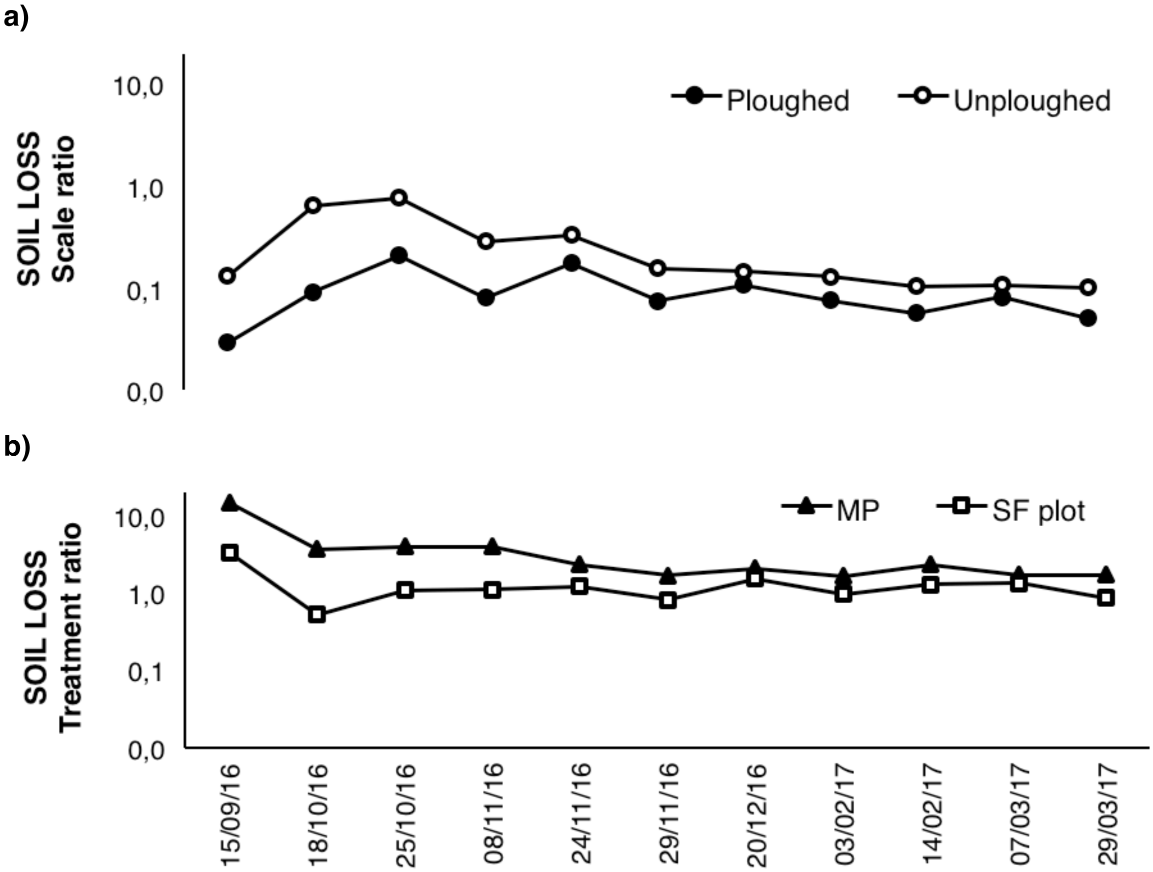

Figure 8. a) Soil loss scale ratio (SF value divided by the MP value) for each erosive event considered along the monitoring period; b) Soil loss treatment ratio (SF value divided by the control value).

Total organic matter loss was higher in the unploughed SF plots (0.357 Mg ha^{-1}) than in the ploughed plots (0.138 Mg ha^{-1}) (Table 2). Such as in soil loss; the values obtained in the first three read-outs corresponded to the highest values of organic matter loss. On those moments the amount losses obtained in the unploughed plots were three times higher that in the ploughed plots (0.3 Mg ha^{-1} and 0.1 Mg ha^{-1}, respectively). Thus, unploughed SF plots lost 80% of the total amount of organic matter lost (0.357 Mg ha^{-1}) in the beginning of the monitoring period while in the ploughed SF plots 72% of the total amount loss (0.357 Mg ha^{-1}) occurred in the first three read-outs.

At micro scale was verified the higher loss of organic matter, namely in the ploughed plots (1.689 Mg ha^{-1}) while the unploughed plots the loss was three times lower (0.531 Mg ha-1) (Table 2). Ploughed MP lost 72% of the total amount in the first three monitored moments and in the unploughed MP the lost in those moments was 55% of the total amount of organic matter loss. These organic matter loss values revealed the significant of the treatment applied such as the time since the perturbation (*p*<0.001) (Table 3).

Table 3. Two-way ANOVA tests presenting the F-values after a transformation of the ploughing data (soil and organic matter losses (Mg ha^{-1})) using a logarithmic function (log10). "*" Indicates the interaction between the two independent variables tested (treatment and time since fire). (*p*-value<0.05); (*p*-value<0.001) indicate a significant effect of the factor(s).

Treatments	Scale	Source	Log10 (Soil losses)		Log10 (Organic matter losses)	
			F-value	*p*-value	F-value	*p*-value
Ploughing unploughed ploughed	SF plot	Interception	1330.339	<0.001	3533.605	<0.001
		Fixed factor(s)				
		Treatment	0.062	0.805	24.674	<0.001
		Time since fire	16.122	<0.001	20.867	<0.001
		Treat*Time	0.819	0.612	0.945	0.503
	MP	Interception	481.672	<0.001	1005.307	<0.001
		Fixed factor(s)				
		Treatment	156.547	<0.001	19.105	<0.001
		Time since fire	26.890	<0.001	5.638	<0.001
		Treat*Time	5.018	<0.001	1.163	0.349

Regarding treatment effectiveness the ploughing results presented opposite trends, when were considered both scales. At SF scale the measure showed to be more efficient in organic matter conservation (61%) than in the soil conservation (6%). When considering MP the efficiencies of ploughing, relatively to the control, were negative. At micro scale the measure was inefficient in the soil and organic matter lost mitigation (Figure 11).

Mulching

Soil and organic matter losses were monitored on site B for 7 months showing the cumulated average losses that occurred in each read-out in both scales under study (Figure 9).

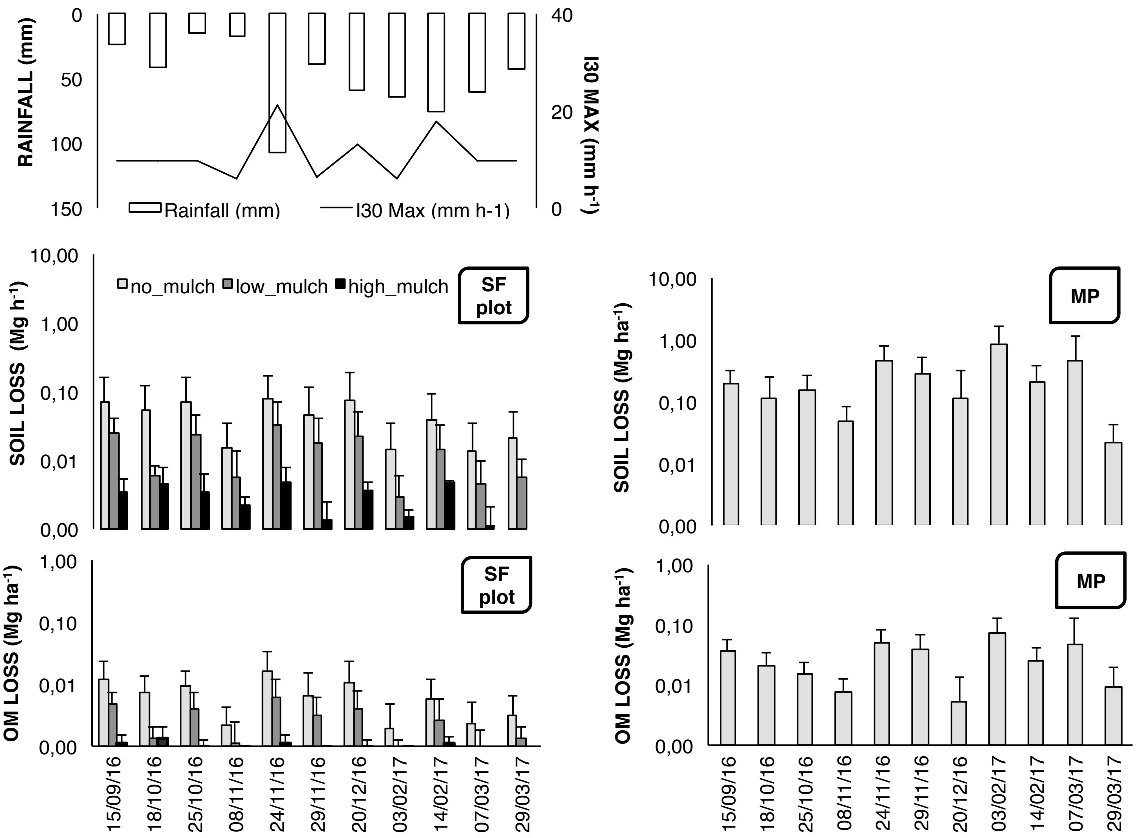

Figure 9. Average soil and organic matter (MO) losses in the mulching experience.

At SF plot scale the higher soil loss values were obtained in the no_mulch plots (0.499 Mg ha^{-1}) regarding the losses registered in the treatments (0.162 Mg ha^{-1} and 0.031 Mg ha^{-1}), low_mulch and high_mulch, respectively (Figure 9). The treatment, when considered by it self, influenced the losses obtained (p<0.001) (Table 4).

At this scale soil losses were relatively constant over the time of sampling in all three treatments (Figure 9), revealing that time since the wildfire had no significant effect on soil that was lost (p= 0.173) (Table 4). In all read-outs performed, the soil loss scale ratio obtained (< 1) reflected the constant higher losses in the untreated MP (Figure 10).

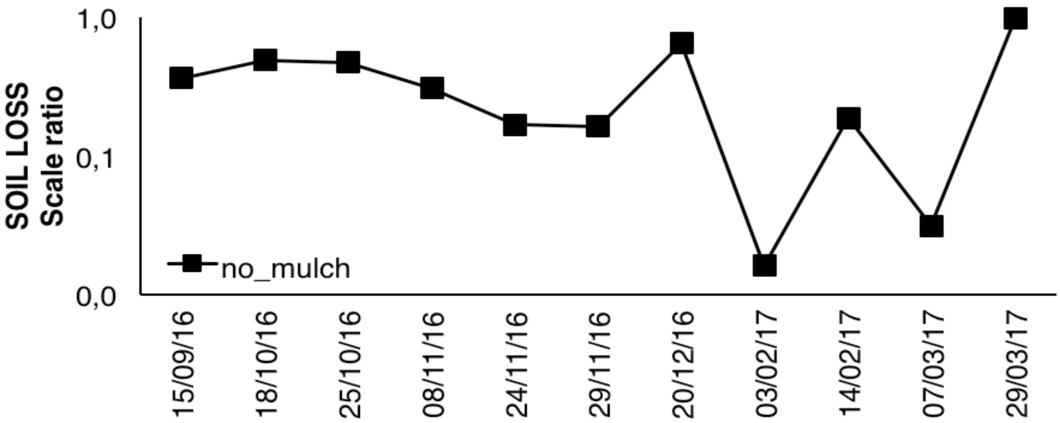

Figure 10. Soil loss scale ratio for no_mulch plots (SF value divided by the MP value) for each read-out of the monitoring period**.**

Soil loss in the SF plots, in all treatments, was more relevant when was registered highest amount and intensity of rainfall, such as the one verified at 24 November 2016, (107 mm; 21.2 mm h^{-1}) and the one recorded at 14 February 2017 (76 mm and 17.7 mm h^{-1}, respectively) (Figure 9). However the exception remains especially in the first three read-outs were the amount (24 mm; 42 mm; 15 mm) and intensity (9.6 mm h^{-1}) of rainfall were lower but were still registered relevant losses in all treatments. This was specially observed in the high_mulch treatment, corresponding the amount lost in the three first moments to 38% of the total amount of soil lost, while in the other treatments the relevance of the lost was around 20% from the total amount lost. At this scale organic matter loss vary along time as soil loss, being the lost more representative in the first three reads and in intermediate ones. These moments were more relevant in loss scope for the no_mulch and low_mulch treatments (Figure 9).
Regarding the organic matter loss patterns closely follows the variations of the soil losses, and remained relatively constant over the time of study (Figure 9). The treatment had a relevant role in the occurred losses (p<0.001) (Table 4).

Table 4. Two-way ANOVA tests presenting the F-values after a transformation of the mulching data (soil and organic matter losses (Mg ha^{-1})) using a logarithmic function (log10). "*" Indicates the interaction between the two independent variables tested (treatment and time since fire). (p-value<0.05); (p-value<0.001) indicate a significant effect of the factor(s).

Treatments	Scale	Source	Log10 (Soil losses)		Log10 (Organic matter losses)	
			F-value	*p*-value	F-value	*p*-value
Mulching no_mulch low_mulch high_mulch	SF plot	Interception	1441.931	<0.001	3380.383	<0.001
		Fixed factor(s)				
		Treatment	18.910	<0.001	20.013	<0.001
		Time since fire	1.473	0.173	1.694	0.106
		Treat*Time	0.239	0.999	0.416	0.979

In the MP, soil loss follows the rainfall characteristics, higher amount of rainfall, higher soils losses (Figure 9), however with some exceptions such as the one verified at 3 February or 7 March 2017 where the loss values were the highest recorded (0.874 Mg ha^{-1} and 0.451 Mg ha^{-1}, respectively). On these moments rainfall the amount was 64.4 mm and 60 mm and rainfall intensity 6 mm ha^{-1} and 9.6 mm h^{-1} (Figure 9). Organic matter loss at this scale, accomplished the soil loss, with the same most relevant moment of lost were the losses were 0.071 Mg ha^{-1} and 0.046 Mg ha-^{1}, respectively.

Treatments (low_mulch and high_mulch) effectiveness relatively to control (no_mulch) it was observed that high_mulch is about 27% more efficient than the low_mulch in preventing soil and organic matter. At SF plot scale was verified efficiencies in the mitigation on soil loss of 68% when applied low_mulch treatment and 94% in the case of high_mulch application. On the other hand, low_mulch was 62% efficient in reducing organic matter losses while high_mulch reached to an effectiveness of 90% (Figure 11).

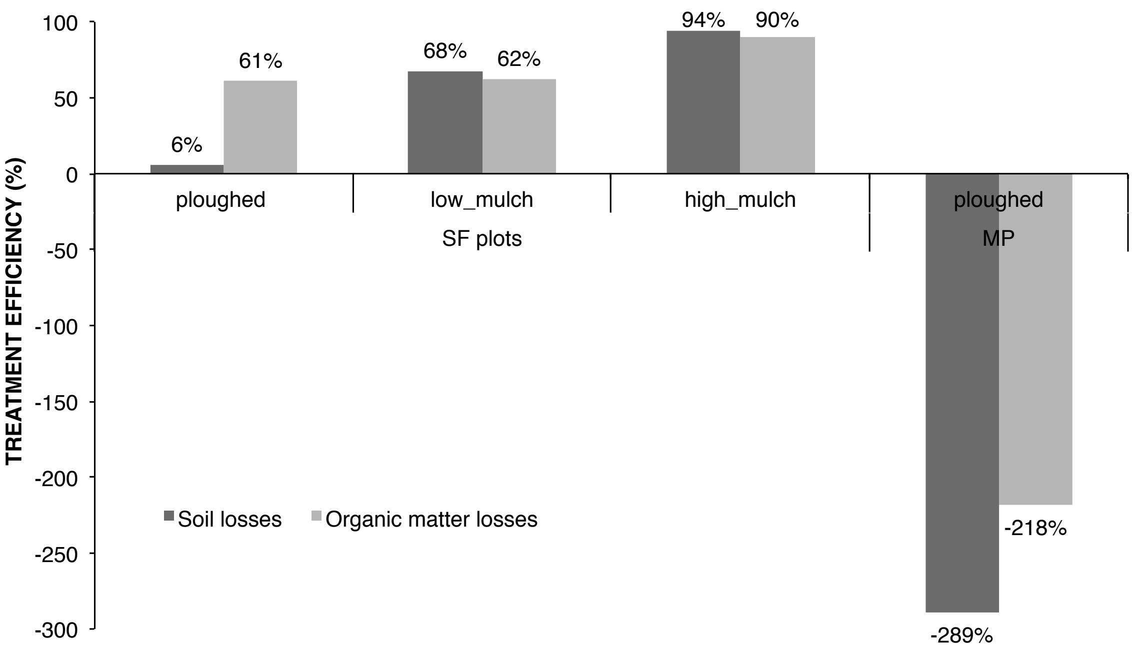

Figure 11. Treatment efficiency, regarding the control, on the mitigation of soil and organic matter loss.

4.4 Ground cover

Ground cover was assessed on both study sites (A - ploughing and B - mulching) on four monitoring times allowing the evaluation of the evolution of the soil surface cover through the study time (Figure 12).

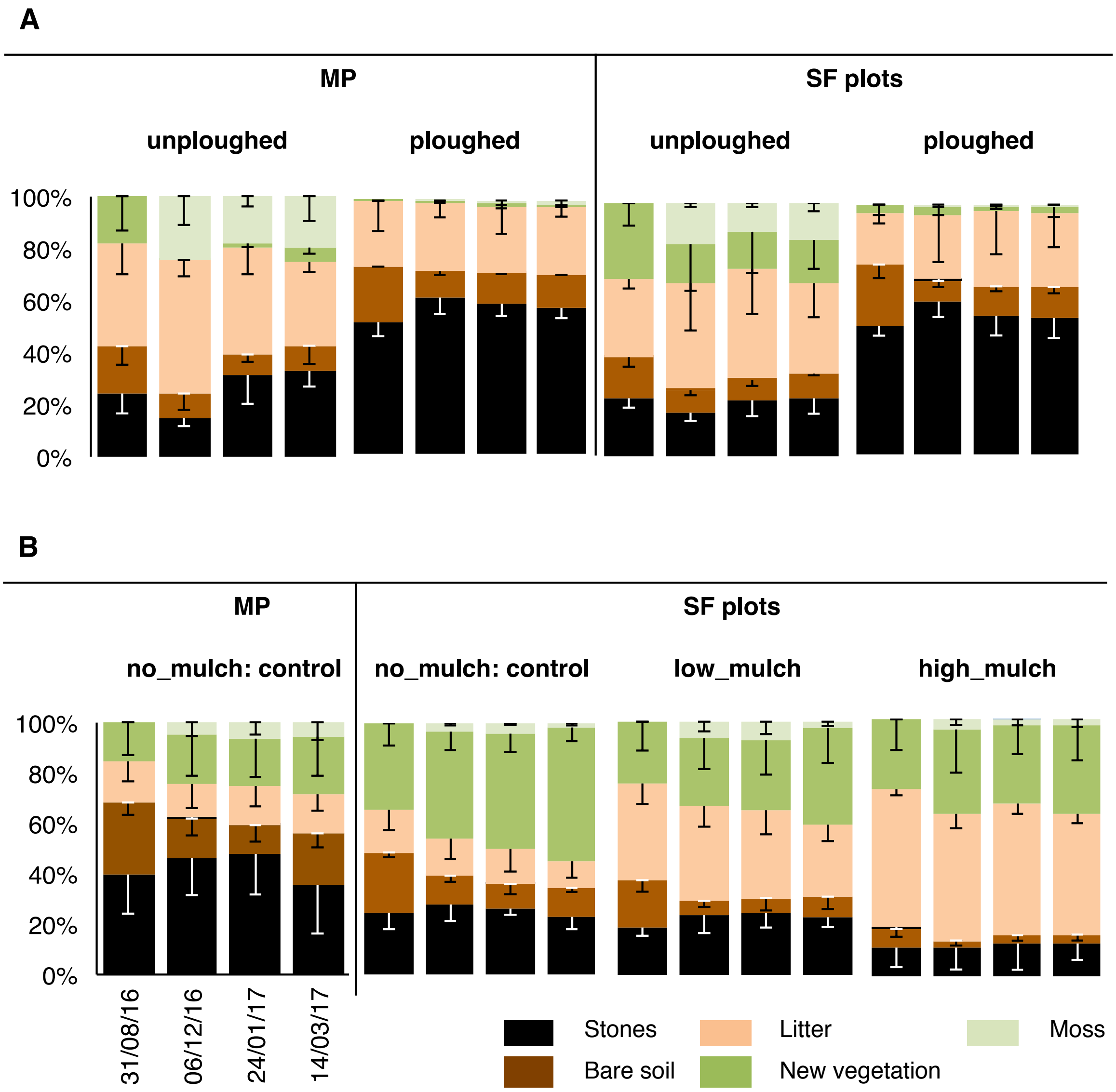

Figure 12. Average soil cover (%) verified in the treatments under study: A - Ploughing experience; B - Mulching experience.

In the ploughing experience the new vegetation growth and moss development was more evident in the unploughed plots. At SF plots the values obtained were 19% and 10%, respectively, and in the MP, 6 and 16%, respectively, against values that rounded 1% in the ploughed plots, at both scales. Moss had a more relevant developed in

untreated plots, appearing in the winter (first observation on 6 December 2016) and remaining relatively constant over the following classification dates (Figure 12).
Regarding the litter cover, the unploughed plots (SF plots and MP) had a higher percentage of cover (38% and 41%, respectively) than the ploughed plots (27% and 26%, respectively). Thus, considering vegetation, moss and litter categories, the protective soil cover reached to values higher than 60% in the unploughed SF plots and MP (67% and 63%, respectively), while in the ploughed plots the values were roughly half (31% and 28%, respectively).
On the other hand, stone surface cover was higher in the ploughed plots; in the SF plots reached to 56% and in the MP was 58%. The unploughed plots values reached to an average of 24% of soil stone cover. Stone surface cover was about 2.5 times higher when the soil was ploughed (Figure 12) at a depth of 20cm.

Regarding the mulching experience, SF plots showed a more pronounced development of new vegetation in the control plots (no_mulch) than in the mulched plots (Figure 12), amounting to an average of 44% as opposed to about 30-31%.
The litter cover was higher in the low_mulch and high_mulch SF plots (35% and 51%, respectively) than in the control SF plots (14%). When the experience was implemented (first year) the mulch application covered the soil surface up to 48% in the low rate while in the high rate the surface covered was 77%.
After the first cover classification (30 August 2016) bare soil cover decrease reaching to an apparent stable level in all the treatments at both scales (Figure 12). Still comparing results obtained between scales, in the control plots, a higher stone cover was verified in the MP plots than in the SF plots (42% and 26%, respectively) but also a lower vegetation cover (19% and 44%, respectively).

CHAPTER 5. DISCUSSION

5.1 Rainfall

In 2016 the nearest meteorological station as recorded an average rainfall of 851 mm (SNIRH, 2017) and the field monitoring of the automatic gauges recorded an average rainfall of 1332 mm. During the monitoring period of study (2017) the total amount of rainfall registered on site A was 562.6 mm and on site B 546.8 mm. Considering that in this time scale were included most of the common seasonal peaks of rainfall is possible to consider this year as drier.

5.2 Post-fire erosion

5.2.1 Impacts of ploughing

Micro-scale

Unprotected soils allowed the direct impact of raindrops (Bautísta *et al.*, 2009), and the rainsplash erosion process. Was verified that the first three erosive, mainly, were those that had the greatest impact in soil and organic matter loss. Malvar *et al.* (2015) states that the first events, after the wildfire, generate more surface runoff, and consequently more erosion and sediments transport. The same authors also refer that this fact may due the existence of a hydrophobic layer, stimulated by the hot and dry season, that not allow the infiltration of the first rains. However at this scale, the results highlight the erosive agent impact and process (rainsplash) that include the detachment of the particles process (Morgan, 2005), leading to intolerable soil losses (Verheijen *et al.*, 2009).

Other studies, on soil losses after mobilization, reported also intolerable soil losses (Verheijen *et al.*, 2009) in the first year such as the present study (Table 2). However the studies carried out in this scope, at micro-plot scale, showed differences in the implementation that could have some influence in the final results. The study conducted by Malvar *et al.* (2015) reveal in the first year of data three times more soil loss in the unploughed plots. These results were opposite to those obtained in the present study. However, this difference may be justified with the fact that the ploughing was carried out 20 years after the wildfire and the soils could be exhausted and with little sediments to transport in the ploughed plots. Another study conducted at this scale was performed by Martins *et al.* (2013) where the treated plots revealed high amounts of soil loss in the second year. The main difference of this study with the present one is that the mobilization technique applied was different, corresponding to the soils terracing, and the results were related with two years of study and in the present study the results derive from 7 months of monitoring. On the other hand, total rainfall amount observed in the studies used, in reference, was higher (Table 5).

Ploughing was performed 11 months after the wildfire allowing the development of vegetation and moss and leading to a gradual recovery (Shakesby, 1996). This fact is reflected in the unploughed plots.

The 26% classified as litter in the ploughed MP could be mainly due the dead roots exposed to the surface with the soil mobilization. The origin of these roots could be from the vegetation that existed before the wildfire or from the vegetation that growth between the two disturbance moments, wildfire and ploughing. In the unploughed MP 41% of ground cover was classified as litter and this may be related with the decline, and life cycle, of the vegetation during the autumn and winter. In other hand, some of the litter could result from the post-fire logging operations.

The results obtained on stone surface cover content (2.5 times higher in the ploughed plots) may due to the mobilization intervention during the ploughing operations, exposing the stone layer to the surface. These results could be a reflection of the Mediterranean soils characteristics that tends to be thin and rich in stones (Morgan, 2005). Shakesby (2011) and Urbanek and Shakesby (2014) pointed out that these roots and stone fragments could act as a sink for the water, promoting the infiltration through impermeable soil layers and limiting the erosion rate.

SF plot scale

The first three read-outs revealed the higher values of soil and organic matter losses, with more impact in the unploughed plots. In the SF the total soil losses values were quite similar in untreated and treated plots. According with Shakesby (2011), stones may increase surface roughness and heterogeneity limiting the water action. The same author refers that stones may protect the smallest particles under them avoiding their transport.

Regarding the organic matter was verified more than two times less losses in the ploughed plots. This situation may be due to the fact that the ploughing had been carried out 11 months after the fire and the monitoring of the depend variables began to late in relation to the initial erosive events. Thus, we can consider that the soil was not exhausted and possibly with sediments available to be transported by erosive agents.

On the other hand, it is expected that the ploughed soils will have a smaller amount of organic material to be transported due the soil mobilization process (Silva *et al.*, 2007; Ferreira *et al.*, 2010), and in this study was verified less 11% of litter cover on the ploughed soils regarding the control. Possible for these reasons, the efficiency of the treatment applied in the SF plots was higher than 60% in relation to the organic matter losses than the untreated plots.

Malvar *et al.* (2013) suggest that this difference may be related to soil exhaustion and the limited amount of sediments available on the surface to be transported. The reduced losses, of soil and organic matter, in the ploughed SF could be related to the formation of a very pronounced micro-topography during the mobilization actions, promoting the accumulation of sediments and water and preventing them from being transported by surface runoff (Silva *et al.*, 2007; Ferreira *et al.*, 2010). Additionally, roots and stones exposed on the surface can function as water sinks and crossed impermeable soil layers (Shakesby, 2011).

Comparing the loss results obtained in the present study with those obtained in other studies it is common losses considered intolerable by the literature (Verheijen *et al.*, 2009). At SF plot scale, Shakesby *et al.* (1994) reported higher losses in the ploughed plots and less in the unploughed. However a relevant difference of this study with respect to the present, that may had a strong impact in the final results, was the fact that ploughing was performed downslope and not along the contour lines. This technique used to implement the measure could justify the difference of results between Shakesby *et al.* (1994) study and the present one. Regarding the work conducted by Ferreira *et al.* (1997) in the first year losses were higher than the present study, being more relevant in the treated plots, just like Shakesby et al., (1994) results. Common to both these studies is the fact that the measure was implemented 2 and 3 years, respectively, after the wildfire and the total amount of rainfall registered in the monitoring period was higher (Table 5) than the one registered in the present data. However, all the mentioned studies indicate that this technique may be a promoter agent of soil erodibility, given the disturbances performed at a coverage surface and soil profile.

Soil cover results at SF plots were similar to the MP ones in relation to litter and stone cover. In the ploughed plots 27% of soil cover was litter, mainly roots that result from the mobilization process. On the other hand, unploughed SF plots, reveal 38% of litter with the possible same origin that in MP. Stone surface content was also similar to the one founded at micro scale, 2.5 times higher in ploughed plots.

5.2.2 Impacts of mulching

Micro-plot scale

Runoff amount variation was explained though rainfall amount as described by Prats et al. (2012, 2016). The runoff values registered in the initial four read-outs were smaller than the following read-out data moments; however, generate a runoff coefficient around 50%. This fact must probably due to the repellent soil layer induced by the dry season (Doerr *et al.*, 2009; Malvar *et al.*, 2015) that not allow the infiltration of the first rainfall and promote the surface flow. Runoff coefficient is directly related with plot dimension, so the total runoff reflects the direct impact of the first erosive events in a small area (Bautísta *et al.*, 2009; Morgan, 2005).

Comparing soil losses between untreated plots, SF plots and MP, were about six times less in the second year. In the untreated plots, plot size was a significant factor (p<0.001), while the time since the wildfire (p=0.167) and the interaction of these both factors (p=0.753) was apparently insignificant on soil loss at both scales.

Losses were always higher in the MP so the effect of the spatial scale it could be connected with the plot sizes and the soil erosion process, that was mainly due the rainsplash impact in the MP and in the SF plots due the rainsplash and surface overflow that transport the sediments (Prats *et al.*, 2016).

According to Morgan (2005), at micro-scale the erosion is largely controlled by the stability of soil aggregates, with a pronounced influence of soil moisture, organic matter content and fauna activity on soil. Since the aggregation breakdown is largely a result of the rain impact, the frequency and erosivity of individual erosive events control the erosion rate through the rate of soil particle detachment. In an area with this dimension, the type of soil, slope and the cover are fairly uniform, so the founded differences can be used to demarcate different micro-scale units. It was possible to verify in the MP under study considerable data variability in the generated total runoff amounts, possibly reflecting the spatial distribution on the study blocks and the possible influence of the surrounding environment, such as vegetation with high development which can function as protection factor to the plots, or the moss development in some plots reflecting lower soil loss.

Regarding a study conducted by Prats et al. (2014) with results of soil losses at untreated (control) MP, the values were three times higher than the values obtained in the present study. However, it must be considered that these values resulted from the first year of experiment (Table 6).

Through the soil surface cover evaluation was verified that the sum of stone content and bare soil reached to more than 50% soil cover, even in the second year after the wildfire. Thus the soil remains unprotected allowing the direct action of raindrops. In addition, litter cover was about 15%, not enough to reduce runoff generation and as consequence, reduce erosion. Covert (2010) defended that at least vegetation cover should be 30% to mitigate erosion, however on these plots the average was 19%. This may justify the erosion values obtained in the MP, exceeding almost three times the values defined in the literature, by Verheijen *et al.* (2009), as the tolerable soil loss (1 Mg ha^{-1}).

SF plot scale

Comparing the soil losses results obtained in this second year of with those achieved in the first year of sampling (soil losses were 8 Mg ha-1, 1.1 Mg ha^{-1} and 0.3 Mg ha^{-1} in no_mulch, low_mulch and high_mulch, respectively (Silva *et al.*, 2016)) could reveal possibly soil stabilization (Shakesby and Doerr, 2006). The decrease of total losses showed the importance of mulching application in the erosion mitigation (Shakesby *et al.*, 1996; Prats *et al.*, 2012; Prats *et al.*, 2016) and the significance of the treatment in soil loss mitigation. The efficiency, relatively to the control, observed in this study, namely in high_mulch treatment, was slightly higher than in the first year of data collection, with an increase of approximately 10% of efficiency in mitigation of soil loss. In the low_mulch treatment the efficiency remained relatively constant. It was observed that the high_mulch is about 27% more efficient than the low_mulch in preventing soil and organic matter loss in both years of study. This data may suggest relevance of the mulching application, early after the wildfire, on soil lost, and the importance that still maintain in the second year of after the wildfire (Robichaud, 2009).

High_mulch treatment has an effectiveness of 94%, following the results obtained in the studies presented on Table 6 where the mulch rates applications were equal or higher than 9 Mg ha^{-1}, have demonstrated efficiencies close or superior to 90%, in the second year of data monitoring in SF plot scale. High mulch soil cover rates reflect a higher effectiveness in soil erosion mitigation (Bautísta et al., 2009; Robichaud, 2009).

The studies performed in Portugal on high mulch application (≥ 9 Mg ha^{-1}), show in the second year of study, in the control plots than in the mulched ones (Shakesby *et al.*, 1996; Prats et al., 2012; Prats et al., 2016), such as the present study, when relating control with high_mulch treatment. However, when comparing soil losses from the applied treatment, it is verified the values were lowest. The same happens when are related the losses of the studies with the low_mulch application from the present study, lower losses were obtained than those reached in the study of Shakesby *et al.* (1996) and Prats et al. (2012). This fact could be related with the high amount of rainfall (Table 6) felt during those experiments in relation to the low rainfall amount of the present study

None of the studies used as reference used such low mulch. Only with 1/3 of the material being used in the highest rate was applied. In the literature there is no evidence of a mulch rate application at such a low rate. The total losses of organic matter accompany the soil losses, when is verified a higher loss of soil the result is a higher amount of organic matter loss. Treatment effectiveness on organic matter mitigation on low_mulch and high_mulch reached to similar values than in soil loss (62% and 90% respectively). The total amount lost may be a reflection of the amount of material (litter) available on the surface to be transported along the plots. This material may result from the experimental context but also from the vegetation existing on the plots or the surrounding area.

Regarding soil surface cover evaluation, it was verified a development over time of new vegetation in the three treatments. However this development is more pronounced in the control plots than in the low_mulch and high_mulch plots. Thornes (1990) refer that the vegetation cover verified in the treatments is enough to protect the soil from water erosion, with a minimum value of 30%. Considering this fact, all treatments in study reveal the vegetation cover needed to reduce water erosion.

The dominant specie of the study areas is eucalypt, characterized by its vegetative regeneration capacity and high competition ability for the light with other species, namely the native ones (shrubs and herbaceous sub-cover) or species with other regeneration process. These characteristics can be determinant in the vegetation regeneration scenarios after a wildfire (Pereira, 2007; Vega *et al.*, 2013), and also could justify the high new vegetation growth on the control plots.

New vegetation development was less pronounced in the application of mulching, being slightly higher in the high rate than in the low rate. Some authors, such as Bautísta *et al.* (2009) and Cover (2010), report the importance of the study on the impact of mulching on vegetation and its ecological response, since it could be responsible for the inhibition of vegetation growth. Robichaud *et al.* (2010) and Bautísta *et al.* (2009), also mention that the mulch may have a side effect on the plants germination and the thickness of the mulch layer may play an important role in the development of new vegetation, inhibiting natural recovery. Covert (2010) identified, in an experimental context, 19% of ground cover in plots with 60-70% mulch cover while in the control plots the vegetation had a development of 50% within a year. However the author assume that this should be systematically addressed in subsequent studies.

Litter cover was 31% and 37% higher in the mulched SF plots, low_mulch and high_mulch, than the control plots. These values may reflect the mulch rate applied in the beginning of the study (48% and 77% cover for low_mulch and high_mulch, respectively) (Silva *et al*., 2016). The amount of material applied in the first year of study could be related, even after transport over time, with the quantity of material that is still available on soil cover. In addition to this fact, litter cover could also contain the material that fall from the tree crowns that exist in the surrounding area of the plots.

On the other hand it is in the control plots where is verified a higher percentage of bare soil which reflects not only the lack of sub-cover but also the fact that the soil and organic matter losses were higher due the direct impact of the raindrops on soil (Bautísta *et al.*, 2009).

According to Scoot *et al.* (2009) root systems of living vegetation add stability to the soil profile, increasing the resistance to detachment by the action of an erosive agent, and on the other hand, soil covered by litter observed in the plots, could be determinant factors in losses obtained in this experience.

Table 5. Compilation of several studies performed in Portugal where the treatment applied after wildfire consisted on soil mobilization and disturbance and where was evaluated soil losses (Mg ha^{-1}).

Study area	Forest type (pre-fire)	Fire severity	Rainfall (mm)	Plot size (m^2)	Treatment	Monitoring period	Control (Mg ha^{-1})	Treatment (Mg ha^{-1})	References	Observations
Águeda	EUC	nd	1155	16	Rip-ploughing (downslope) + plantation Performed March 1988	Oct 1989	0.002	1.610	Shakesby *et al.* (1994)	Wildfire 1986; Control (Eucalyptus stump regrowth); soil erosion according with the post-fire land management practice; soil loss variation with seasonal rainfall
						Oct 1989 - Feb 1990	0.011	2.659		
						Feb 1990 - Apr 1990	0.005	0.122		
Águeda (Caramulo)	P / P-EUC	nd	1300-1900	16	Rip-ploughing and eucalyptus plantation Performed 1989	1989 - 1990	< 3	> 51	Ferreira *et al.* (1997)	Wildfire 1986; Rip-ploughing / Wildfire; plot / catchment scale
Albergaria-a-Velha	EUC	M	1048	0.25	Rip-ploughing Performed 20 years before wildfire	Oct 2005 - Sep 2006	3.780	1.120	Malvar *et al.* (2015)	Wildfire 2005; Half of the eroded sediments was organic matter; stock depletion of the sediments available to transport in the ploughed plots
						Oct 2006 - Jul 2007	5.520	0.670		
Sever do Vouga	EUC / P	M	1412	0.25	Terracing Performed after wildfire	Aug 2010 - Feb 2012	0.18	36	Martins *et al.* (2013)	Wildfire July 2010; soil losses on the EU plots
Segade (Semide)	EUC	M	563	0.25	Ploughing	Sep 2016 - Mar 2017	3.235	12.582	(Present study)	Ploughing technique was the one used by the forest owners in the region
				16			1.249	1.178		

Table 6. Compilation of several studies performed in Portugal where mulching was used as a treatment to evaluate soil losses (Mg ha^{-1}).

Study area	Forest type (pre-fire)	Fire severity	Rainfall (mm)	Plot size (m^2)	Treatment	Application rate (Mg ha^{-1})	Cover rate (%)	Year	Control (Mg ha^{-1})	Treatment (Mg ha^{-1})	Efficiency (%)	References
Águeda	EUC	M	1470	16	Eucalyptus residues resulting from cutting	46	89	2	4.900	0.400	92	Shakesby *et al.* (1996)
Pessegueiro	EUC	M	1540	16	Eucalyptus bark	8.7	67	2	5.400	0.700	87	Prats *et al.* (2012)
Ermida	EUC	H-M	1419	0.25	Eucalyptus bark	11	85	1	8.500	0.600	93	Prats *et al.* (2014)
Ermida	EUC	H-M	1186	100	Eucalyptus bark	14	77	1	4.620	0.190	96	Prats *et al.* (2016)
								2	0.920	0.080	91	
Segade (Semide)	EUC	M	851	16	Eucalyptus residues resulting from cutting	8	77	1	8.000	0.300	85	(1st year: Silva et al. (2016); 2nd year: Present study September 2016 - March 2017)
								2	0.499	0.031	94	
			547			2.6	48	1	8.000	1.100	69	
								2	0.499	0.162	68	

5.3 Ploughing and mulching as post-fire land management options

With scientific ambitions, RECARE European project was installed in the burned area. Two measures selected by the stakeholders during the project implementation and their first study cases performed in Serra do Caramulo (Águeda). The measures, mulching and ploughing, were selected as the ones that were possible more efficient in soil erosion mitigation. The same measures were implemented in the second study case of the project, in Semide parish.

Ploughing, as a current soil mobilization practice applied, by landowners and forest managers, after fire for the preparation of the land for planting and/or seedling. On the other hand, the mulching selection represented a choice based on the need to extend knowledge about a measure still unknown in Portugal.

Ploughing results showed intolerable soils losses (Verheijen *et al.*, 2009), following other studies in this scope presented in the literature (Shakesby *et al.* 1994; Ferreira et al., 1997; Martins *et al.*, 2013; Malvar et al., 2015). Still, in other to obtain more accurate results of the interaction between the two soil disturbances (wildfire and ploughing) the soil mobilization experience should be conducted just after the wildfire and monitored for a long period. The study performed by Shakesby *et al.* (1994) also reveal that usually soil losses increase in the second year after the intervention and may take a long period of time to soil stabilization. It is a consensus between authors that from the post-fire erosion control point of view; soil ploughing should not be carried out (Ferreira *et al.* 2015). As a management measure, could lead to soil exhaustion, either by the loss of sediment available to erode or by loss of the productive capacity.

Second year mulching results could reflect the soil erosion stabilization due the vegetation regeneration (Shakesby and Doerr, 2006) with lower soil losses than those registered in the first year (Silva *et al.*, 2016). As reported in the literature application of mulch at a high rate is efficient in mitigating soil erosion (Shakesby *et al.*, 1996; Prats et al., 2012, Prats et al., 2014; Prats *et al.*, 2016), however with high cost associated, regarding the material and the application by itself (Silva *et al.*, 2007; Prats *et al.*, 2014). The results obtained with the application of the low_mulch rate may change the way of looking to this measure. In the second year, low_mulch continues to be efficient in soil protection, keeping the efficiency registered in the first year and resulting in tolerable losses (Verheijen *et al.*, 2009), as happened in the first year (Silva *et al.*, 2016). The application of a low_mulch rate (2.6 Mg ha^{-1}) has associated a considerable cost reduction, regarding the material cost values presented by Prats *et al.*, (2014), 30 euros/ tone. With the low mulch rate application will be 162 euros cheaper protect one hectare of soil. Depending on the erodibility of the soil of the area to be treated, the low_mulch is preferable to the strategy of not acting, allowing the achievement of results that would benefit the stakeholders not only in relation to the costs but also due the positive values of efficiency on soil erosion mitigation and productivity preservation.

CHAPTER 6. CONCLUSIONS

The main conclusions obtained in this study were:

- **Ploughing**

i) Soil and organic matter losses obtained with the ploughing implementation are a promising contribution the literature, however have some limitations due the fact that the study area was only monitored for 7 months, requiring a longer monitoring period, and was implemented 11 months after the wildfire;

ii) Time since fire was relevant in the total amount of soil lost;

iii) Ploughed plots registered and average of 33% more stones on soil surface than the control;

- **Mulching**

iv) Time was irrelevant in the total amount of soil lost;

v) Treatment, even in the second year after fire, was important on the losses obtained in the mulching treatments;

vi) Low soil and organic matter losses in the mulching experience reveal the probable soil stabilization;

vii) Low_mulch treatment has a more acceptable cost-benefit ratio than high-mulch treatment, since the material costs reduction per hectare, and the positive efficiency values which are maintained over a long term.

6.1 Reflection on future research

- evaluation of the interaction between disturbances, of ploughing right after the wildfire occurrence, being a lack in the literature;
- monitoring of the ploughing for a longer and continuous period;
- runoff evaluation in other to compare this variable generation at MP and SF plot scale;
- access the effect of different mulching rates on vegetation regeneration after wildfire. The existing studies in the literature require more scientific support.

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