Fire effects on soil and hydrology

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1 General introduction

1.1   Fire, land degradation and mitigation

Fire is part of the Mediterranean ecosystem. Yet, the frequency and intensity of fires has increased considerably over the last decades (Ferreira et al., 2009; Pausas, 2004; Silva et al., 2010). Throughout the Mediterranean, landscapes have become more flammable. Fuel loads have increased due to large scale depopulation of rural areas and associated land abandonment, and vegetation types have changed due to afforestation practices (Moreira et al., 2001; Moreira et al., 2010). Given the expected increase in periods of prolonged drought, higher temperatures, and stronger winds (IPCC, 2007), it is unlikely that the trend of increased fire occurrence will be countered in the near future.

In addition to causing extensive havoc to lives and property, increased fire frequency and intensity also has considerable ecological consequences. Fire can greatly increase the landscape's vulnerability to flooding and erosion events (Pierce et al., 2004), and cause a substantial threat to drinking water supplies downstream of burned areas (Cerdà and Robichaud, 2009). By removing vegetation, changing soil properties and inducing soil water repellency, fire increases the risk and erosivity of overland flow. Since removal of fertile topsoil is often much faster than soil formation by weathering, fires can contribute to long-lasting degradation and even desertification (Neary, 2009; Shakesby, 2011).

Mitigation of land degradation and flooding events after fire can help safeguard natural resources and protect lives, property and drinking water supplies downstream of burned areas. While mitigation efforts will be most effective if they target the causes of land degradation, the exact impact of fire on soils and hydrology and the drivers of post-fire land degradation are not fully understood. The aim of this thesis is to improve the understanding of the effects of fire on soils and hydrology in order to facilitate development of mitigation strategies and safeguard natural resources in burned areas. Laboratory studies and extensive fieldwork were conducted on the relation between fire, soil temperatures, soil changes and hydrology in order to find the drivers of post-fire runoff and erosion events. Taking a unique approach, this thesis presents the results of an experimental fire to determine the effects of fire at the catchment scale, in which data was gathered before, during and after the fire at different scales. This study therefore allows an integrated view of the various factors and processes involved, and provides an integrated insight into the environmental impacts of fire.

1.2   Fire behavior

In order to understand the effects of fire on ecosystems, it is crucial to understand fire itself. Vegetation fires are described in terms of fire behavior, namely the amount and

rate of heat released (fire intensity), the rate of spread, the residence time, and the fuel consumption (Alexander, 1982; Chandler et al., 1983a; Direcção Geral das Florestas, 2002). Fire behavior is determined by the interaction between weather, 'fuel' (all burnable living and dead plant material) and topography (Chandler et al., 1983a). As such, fire behavior varies with air temperature and relative humidity, both of which affect fuel ignitability, and with wind, which greatly influences fire spread. Furthermore, fire behavior varies greatly between ecosystems because of the variation in physical and chemical characteristics of fuel. Fuel moisture content controls the availability of fuel for burning (the consumability) (Dennison and Moritz, 2009; Hille and den Ouden, 2005; Rein et al., 2008), and determines, with factors like fuel load (amount), size, arrangement and heat content, fire ignition and propagation (Dimitrakopoulos and Papaioannou, 2001; Papió and Trabaud, 1990). Finally, topography influences fire intensity and rate of spread. For instance, fires move much more rapidly upslope, because fuels are pre-heated and dried before ignition, than downslope (Direcção Geral das Florestas, 2002). Although vegetation fires do have natural causes, such as lightning strike, in most ecosystems the majority are currently caused by humans - either intentionally (arson), or accidentally (Benavent-Corai et al., 2007; Catry et al., 2009; Silva et al., 2010).

Figure 1.1 Prescribed fire in a maritime pine (*Pinus pinaster*) stand, north-central Portugal.

Quite paradoxically, fire is also used as a very effective tool to manage fire-prone vegetation types. Using controlled fire in fire prevention and suppression, fire is fought by fire. Backfires are a useful method to stop otherwise uncontrollable wildfires (Chandler

et al., 1983b), and prescribed fires (also known as prescribed burns, fuel reduction burns or hazard reduction burns, Figure 1.1) are used under mild weather conditions to reduce fire risk by reducing fuel load and connectivity (Boer et al., 2009; Fernandes and Botelho, 2004). The use of fire is moreover a long-standing practice in range management and ecosystem restoration, as well as being commonly applied to stimulate biodiversity (Direcção Geral das Florestas, 2002; DiTomaso et al., 2006; Hancock et al., 2005). Although the environmental impact of prescribed fires is generally much lower than that of wildfire (Ferreira et al., 2009; Franklin et al., 2003), there is increased discussion about the sustainability of prescribed fire as a management tool (Ponder Jr et al., 2009; Shakesby, 2011; Shakesby et al., 2010b; Smith et al., 2010).

1.3   Fire effects on soils

Fire effects on ecosystems are related to the intensity and frequency of fires, the type of ecosystem and the resilience of the ecosystem to fire. The latter depends, among other things, on the degree to which the vegetation is adapted to fire (Buhk et al., 2007; Wright and Klemmedson, 1965). Fire impact is described in terms of 1) fire severity or burn severity, which refers to the direct impact of fire on soil and, particularly, vegetation; and 2) ecosystem responses, which refers to what happens after the fire, such as the impact of fire on erosion and flooding (Keeley, 2009). Since ecosystem responses are considered to depend more on soil changes than on vegetation changes, the term soil burn severity was recently introduced (Keeley, 2009; Robichaud et al., 2007), in order to improve prediction of ecosystem responses to fire.

Fire impact on soils can greatly affect belowground ecosystem functioning, as the heat of the fire can alter a range of biological, physical and chemical soil properties. The extent of the changes is generally determined to a large degree by the soil temperatures reached during the fire, and the length of time that high temperatures are sustained (Cerdà and Robichaud, 2009; Neary et al., 1999). Fire effects on soils can range from microbe and seed mortality to the development of soil water repellency (DeBano, 2000b), soil structural changes, and nutrient volatilization. While fire is known to impact soil organic matter content (Alauzis et al., 2004; García-Corona et al., 2004), bulk density (Andreu et al., 2001; Ferreira et al., 2009) and soil texture (Badía and Martí, 2003; Ulery and Graham, 1993), knowledge on the subsequent effects on soil hydrological properties is limited. For instance, despite the role of soil water retention in soil water availability and plant growth, understanding of the direct effect of fire on soil water retention characteristics remains limited and existing information is in many cases contradictory (Are et al., 2009; Mallik et al., 1984; Silva et al., 2006). In addition, the role of ash in the post-fire environment is poorly understood. While some researchers have reported

ash to reduce runoff by storing rainfall (Cerdà and Doerr, 2008; Woods and Balfour, 2008b), ash is also often regarded as a cause of increased surface runoff after fire (Kutiel et al., 1995; Onda et al., 2008; Woods and Balfour, 2008a). Yet, studies on the soil physical effects of ash following the first post-fire rains are scarce.

1.4   Factors controlling soil temperatures during fire

Despite the importance of soil heating during fire, relatively little is known about the subject. Soil temperatures are frequently not measured during fires, and since assessment of belowground temperatures is practically impossible for unplanned wildfires, data is restricted to planned prescribed and experimental fires. There is however an extensive body of literature covering soil thermal behavior (e.g. Karam, 2000; Parlange et al., 1998; Van Wijk, 1963; Wagner and Pruß, 2002), which can be used to understand belowground temperature dynamics during fire.

As in non-fire situations, soil temperatures during fire are determined by the heat input at the soil surface and the thermal properties of a soil. While the soil's mineralogy, structure and bulk density play a role (Abu-Hamdeh and Reeder, 2000; Clauser and Huenges, 1995; Côté and Konrad, 2005; Massman et al., 2008) , soil moisture content is particularly important, because of its pronounced effects on heat capacity and thermal conductivity (Abu-Hamdeh and Reeder, 2000). Soil moisture can considerably dampen the heat pulse into the soil (Busse et al., 2010; Campbell et al., 1994; Valette et al., 1994), which is one of the reasons why prescribed fires, mostly conducted when soils are moist, generally have a smaller impact on soils than wildfires (Ferreira et al., 2009; Franklin et al., 2003; Shakesby, 2011; Shakesby et al., 2010b), which usually occur when soils are dry. Rock fragments located in the soil and at the soil surface may have similar effects, because of their effects on soil thermal properties and because of their impact on diurnal soil temperature fluctuation (Childs and Flint, 1990; Mehuys et al., 1975). However, although fires in rocky areas are ubiquitous, surprisingly little is known about the effect of rock fragments on soil temperatures during fire.

While the large body of non-fire related soil thermal literature facilitates prediction of heat penetration from the soil surface downward, there is moreover a noticeable literature gap regarding what determines soil surface temperatures in the first place. Based on plot experiments, it is currently understood that soil temperatures during fires increase with increasing fuel load, fire intensity and residence time (Gimeno-Garcia et al., 2004b; Molina and Llinares, 2001a). However, fire impact on soils is not easily estimated from fire intensity alone (Hartford and Frandsen, 1992), which is illustrated by recent data from the more complex landscape scale. Despite their extreme intensity,

the 2009 Victorian wildfires in Australia had relatively little impact on the soil (Doerr et al., 2010). Improved understanding of the relationship between fire intensity and soil temperature will help land managers to more accurately predict areas at greatest risk for post-fire land degradation, and increase the efficiency of potential mitigation measures.

1.5   Implications of vegetation and litter removal

Vegetation cover protects soil from the elements. Firstly, it reduces raindrop impact on the soil surface, and therefore limits the risk of soil detachment by splash erosion (Andreu et al., 1998; Mati, 1994). Secondly, vegetation and, particularly, litter affect soil surface properties. By contributing to increased surface roughness, it therefore reduces the risk of overland flow generation (Govers et al., 2000). Thirdly, vegetation and litter cover reduces diurnal temperature changes in the soil (Chung and Horton, 1987), and protect the topsoil from heating up and drying out (Hulbert, 1969; Iverson and Hutchinson, 2002). Because soil moisture variation is an important driver of soil water repellency (Dekker et al., 2001), vegetation removal may play a large role in the evolution of soil water repellency in burned landscapes. However, the role of vegetation cover on soil water repellency has to date not been assessed, hampering the identification of the drivers of post-fire soil water repellency as well as the longevity of the fire impact.

In addition to the important role that vegetation cover plays in soil protection, it also plays a key role in the hydrological cycle because of the interception of rainfall and transpiration of soil water. Fire effects on ecosystems should therefore not be assessed from the perspective of soil changes alone. Interception of rainfall by the vegetation canopy can amount to 15-50% of total rainfall (Gerrits, 2010). By eliminating interception, vegetation removal can therefore greatly increase the amount of rainfall reaching the soil surface. Together with the elimination of transpiration, removal of vegetation cover has therefore been reported to significantly increase (peak) streamflow volumes in deforested catchments (Bosch and Hewlett, 1982; Brown et al., 2005; Jones, 2000). Yet, while an impressive body of literature exists regarding interception by forest canopies, interception by shrubs has received much less attention (Dunkerley, 2000).

1.6   Fire effects on hydrology and erosion

It is clear that the effects of fire-induced soil changes and vegetation removal can have considerable impact on hydrology and erosion processes. Researchers and media worldwide have reported severe flooding and erosion events originating from burned hillslopes (Shakesby and Doerr, 2006), and reports of destructive debris flows are also

common (Bisson et al., 2005; Cannon et al., 2001; Jordan and Covert, 2009; Nyman et al., 2011). Yet, assessment of the exact drivers of these events is limited, likely due to the complexity involved (Ferreira et al., 2008). Fire studies often lack pre- and post-fire unburned control data, and many focus on assessment of burned areas alone (e.g. Cerdà and Doerr, 2008; Malvar et al., 2011), ignoring the initial pre-fire situation. An example is the case of soil water repellency. While fire-induced soil water repellency is regularly considered to be the culprit for post-fire land degradation (DeBano, 2000a; Doerr et al., 2000), the often pervasive soil water repellency in unburned soils (DeBano, 2000b; Dekker et al., 2005) complicates identification of fire-related soil water repellency as the primary cause of the increased vulnerability to flooding and erosion events. This illustrates that comparison with unburned or pre-fire data can improve the understanding of post-fire land degradation.

Hydrology and erosion processes are highly affected by scale – both in burned and unburned systems. Decreased hydrological connectivity and increased storage at larger scales can facilitate downslope infiltration of runoff, reducing downstream flow and sediment volumes, and therefore mitigating pronounced changes at the catchment scale (Bracken and Croke, 2007; Cammeraat, 2002; Doerr et al., 2003; Ferreira et al., 1997; Smith et al., 2011). Changes observed at the plot-or hillslope scale therefore tend to overestimate changes occurring at catchment-scales (e.g. Prosser and Williams, 1998). Nested scale approaches are therefore valuable in terms of their added insight into the relations between processes acting at various scales. Because of the pronounced effect of scale, fire effects on flooding risk are best assessed at the catchment scale. Yet, as previously noted, catchment scale hydrological studies assessing fire impact are scarce (Shakesby, 2011; Shakesby and Doerr, 2006). Even though controlled fire experiments have the potential to give valuable insight into the drivers of fire-induced hydrological changes and effects of scale, to date catchment scale controlled fire experiments have not been performed and effects of scale are not often assessed.

1.7   Objectives and research questions

The main objectives of this thesis are to identify the impact of fire on soil and hydrology in the Portuguese schist region, and to reveal the drivers of fire-induced land degradation. This thesis focuses on the relation between fire and soil temperatures, the interaction between soil temperature and soil properties, and the role that ash, surface properties, and vegetation removal play in changing hydrological processes and flooding and erosion risk (Figure 1.2).

The following research questions are addressed:

I.   What is the potential impact of soil heating and ash on soil physical properties?

II.   What determines soil temperatures during fire, regarding soil properties and fire behavior?

III.   What is the relation between fire intensity and fire impact, in terms of soil and surface properties, runoff and erosion risk?

IV.   Does fire alter the temporal evolution of soil water repellency, and what is the role of vegetation removal?

V.   Does fire result in increased runoff risk, and what is the cause of the related hydrological changes?
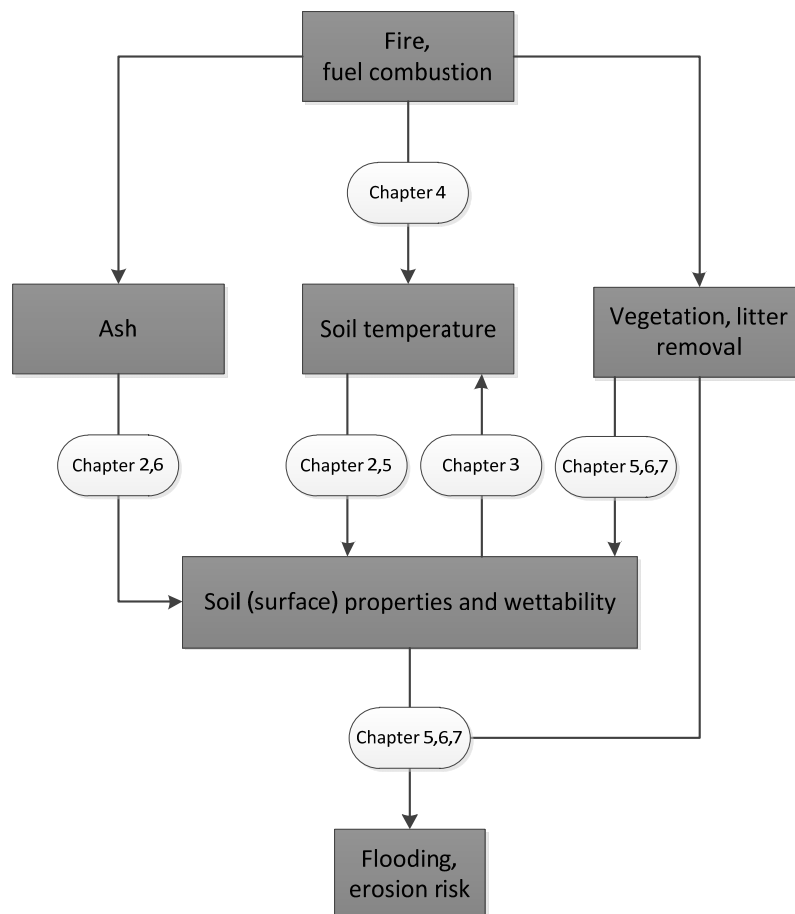
Figure 1.2 Thesis outline, indicating the chapters in which the different topics are studied and discussed.

1.8   Thesis outline

The research questions are addressed in the following six chapters (Chapter 2 to 7) and subsequently tied together in Chapter 8. Since all the chapters have been published in or submitted to international peer reviewed journals, they are all stand alone papers that

can be read independently. As a result, some repetition occurs in parts of the introduction and method sections of the different chapters.

Figure 1.2 summarizes the outline of this thesis and indicates the topics discussed in each chapter. Chapter 2 addresses the role of heating temperature in determining soil physical changes, in particular regarding soil water retention. This chapter moreover addresses the effects of ash, to evaluate the existence of its hypothesized pore-clogging effect.

Chapters 3 and 4 address the drivers of soil heating during fire. First, Chapter 3 analyzes the role of soil moisture and rock fragments in enhancing or reducing soil heating. Then, Chapter 4 examines how aboveground heating (fire behavior) controls belowground temperatures during fire at the catchment scale. For this purpose, a small catchment was burned by experimental fire in winter 2009.

Chapters 5, 6 and 7 concern the impact of the catchment scale experimental fire on soil and hydrology. The effect of fire on soil and surface properties is covered in Chapter 5, which also discusses the implications for runoff and erosion risk. Consequently, Chapter 6 deals with the natural and fire-induced soil water repellency in the catchment, and discusses the role of soil moisture, fire temperature and vegetation removal on the occurrence and persistence of soil water repellency. Chapter 7 addresses the impact of fire on hydrological processes, comparing pre- and post-fire time series of streamflow and soil moisture at different scales.

Finally, Chapter 8 presents a synthesis of the research findings outlining the new contributions they make to the research fields of fire, soil and water sciences. Furthermore, this chapter gives recommendations for sustainable fire use and post-fire land degradation mitigation, and concludes with directions for further research.

Figure 1.3 Valtorto catchment (treeless area) on the eastern flank of the quartzite crest that forms the Penedos de Góis, Serra da Lousã, Portugal.

1.9   Study area

The study area is located in the Serra da Lousã in north-central Portugal (Figure 1.3, 1.4, a region highly affected by fires and post-fire land degradation (Bermudez et al., 2009; Catry et al., 2009; Direcção Geral das Florestas, 2002). The climate in the region is Atlantic-Mediterranean, characterized by wet winters and dry summers with high wildfire risk.

The majority of the work was concentrated in the Valtorto catchment, where the impact of a catchment-scale experimental fire was assessed and from where the soil used for the laboratory experiments was taken. Additionally, the impact of a number of wildfires and prescribed fires was studied throughout north-central Portugal in order to place the insights gained into a broader context. The results of these wildfire and prescribed fire studies are only briefly mentioned in this thesis, and will be the subject of future papers.

The Valtorto catchment (Figure 1.3, 1.4) was selected because it is large enough to carry water for a large part of the year, and therefore suited for hydrological monitoring, yet still small enough for monitoring the variability in fire and soil characteristics. The catchment is located near the village of Vale Torto (Góis, Coimbra). It was completely burned when a wildfire swept the mountain flank in 1990. After a subsequent prescribed fire in April 1996, when fire breaks were constructed, the catchment was the subject of a short investigation into the effects on soil erosion (Coelho et al., 1998) for which two concrete weirs were installed. Although grazing by goats was common in the area at that time, this is currently no longer the case. Nine years after abandoning the site, the
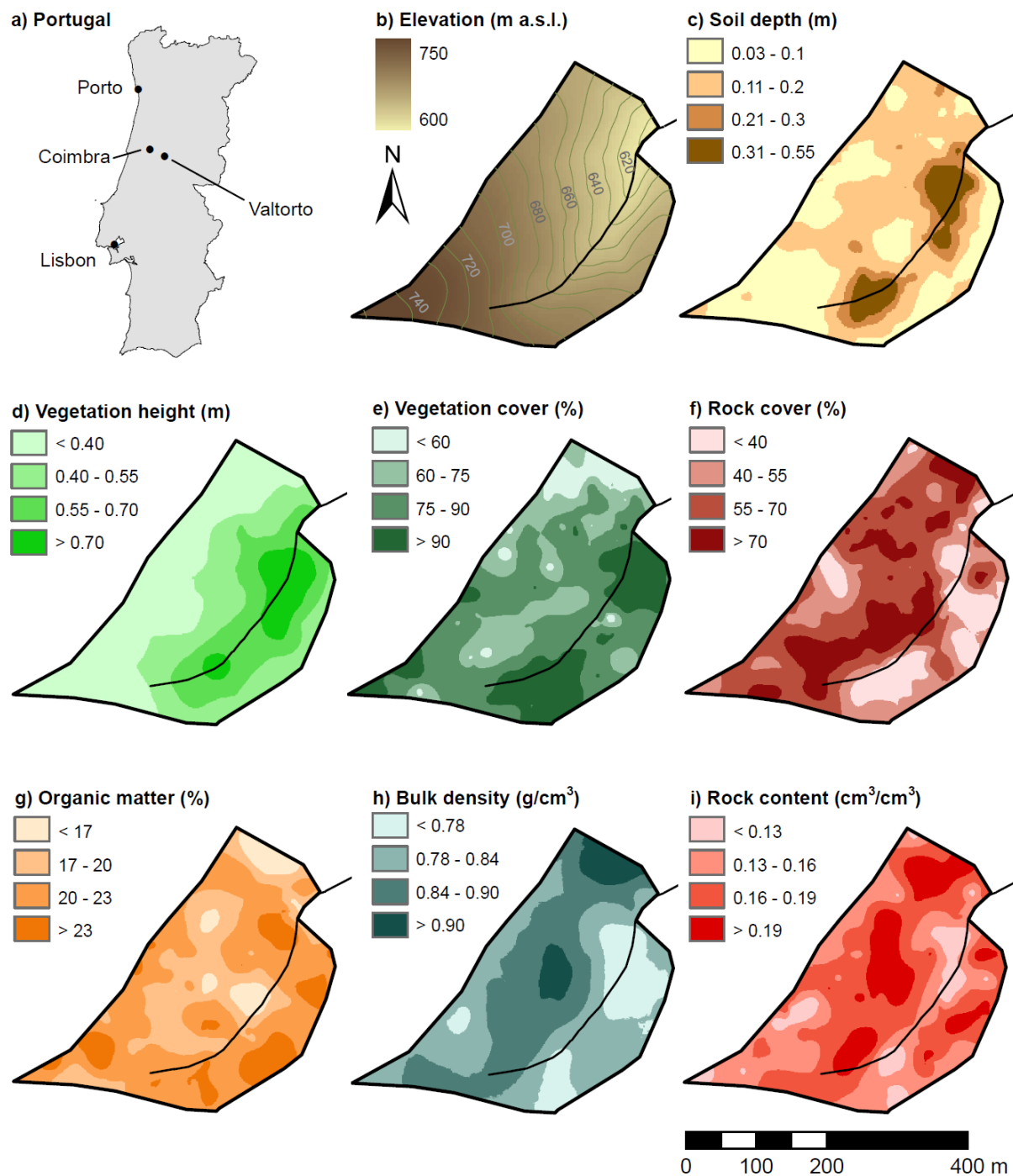
Figure 1.4 Location and characteristics of the Valtorto catchment, as mapped in summer 2007. Maps were interpolated by ordinary kriging using Vesper (Whelan et al., 2002); each map is based on 226 to 322 measurements, the exact number of which is given in Table 7.1.

catchment was reinstalled in summer 2007, when an extensive field campaign was started to map the soils and vegetation, and to (re)commence hydrological and erosion monitoring (Stoof et al., 2008). A second nearby research catchment, named Espinho, was installed in November 2007 and served as an unburned control treatment to

facilitate comparative assessment of the hydrological impact of fire. The Espinho catchment is located 3 km SE of the Valtorto catchment, and will be discussed further in Chapter 6.

Soils and vegetation in the Valtorto and Espinho catchments are typical for the region. Developed from schist and quartzite, soils are generally shallow gravelly loamy sands (USDA, 1993) with considerable rock fragment content and cover. Further detail about the soils in the Valtorto catchment can be found in Figure 1.4 and in the following chapters.

At the start of the study (May 2007), the vegetation in the Valtorto catchment consisted of dense shrubs regenerated after the 1996 prescribed fire. The catchment was dominated by heaths and heathers (Ericacea) such as *Erica umbellata, E. cinerea* and *Calluna vulgaris*, and several legumes (Leguminosae) such as gorse (*Ulex* sp.), "carqueja" (*Pterospartum tridentatum*) and broom (*Genista triacanthus*). In addition, grasses dominated by Poaceae such as *Brachypodium* sp., *Agrostis* sp. and *Dactylis* sp. were found in places where the shrub cover was less dense, and bracken (*Pteridium aquilinum*) was found in the valley bottom. Finally, some encroachments of maritime pine (*Pinus pinaster*) encircled the heathlands, being the remnants of former afforestation and not representative of the autochthonous woodlands of oak (*Quercus robur*) and cork oak (*Quercus suber*) that largely disappeared from the region.

2   Soil properties:
effects of soil heating and ash

Abstract

Despite the pronounced effect of fire on soil hydrological systems, information on the direct effect of fire on soil water retention characteristics is limited and contradictory. To increase understanding in this area, the effect of fire on soil water retention was evaluated using laboratory burning and heating experiments. In addition, ash-infiltration and ash-incorporation experiments were performed to evaluate the effect of ash on soil water retention. While heating soil to 200°C and below did not change soil properties, burning and heating to 300°C and above increased bulk density, clay and silt content, and decreased organic matter and sand content. Burning and heating above 200°C decreased the amount of water stored at the nine tensions considered, although the effect on soil water retention did not always increase with increasing temperature. Changes were largest for low tensions, i.e. between saturation and field capacity (10 kPa). Heating to 200°C decreased the amount of plant available water, but despite reducing the amount of water stored at evaluated tensions, burning and heating to 300°C and above increased the amount of plant available water. This may be caused by more complete combustion of organic matter at the higher temperatures and the production of ash. Direct incorporation of ash into soils did not alter soil texture but increased water retention from saturation to 310 kPa tension. Ash infiltration experiments interestingly had a similar effect, despite the fact that very little ash washed into the samples. Results from these experiments contribute to understanding post-fire changes in hydrological and erosion processes.

2.1 Introduction

Wildfires can increase a landscape's vulnerability to extreme flooding and erosion events. By removing plant cover, changing soil properties and inducing soil water repellency, fire can increase runoff which can lead to floods and erosion (DeBano, 2000a; González-Pérez et al., 2004; Shakesby and Doerr, 2006). Despite the pronounced effect of fire on flooding and erosion processes and the role of water retention capacity in post-fire plant regeneration, understanding of the direct effect of fire on soil water retention characteristics remains limited and existing information is in many cases contradictory. Soil water retention is a major governing factor for soil water movement. It is a measure of the amount of water that can be stored in a soil, and together with infiltration, determines the fate of precipitation. Precipitation can be more optimally used by soils with high retention capacity because more water can be stored until it is either a) used by plants, b) evaporated, c) percolated into deeper layers, or d) lost by saturated overland flow. Soil water retention can therefore be an important factor in post-fire plant regeneration. In combination with (un)saturated hydraulic conductivity, soil water retention characteristics govern the rate of water flow through soils and impact a soil's vulnerability to saturated overland flow. It is therefore an important parameter in process-based hydrologic and erosion models (De Roo et al., 1996; Van Dam et al., 1997; Wesseling et al., 2009a).

Soil water retention characteristics are largely determined by texture, structure, organic matter content and bulk density (Minasny and McBratney, 2007; Rubio et al., 2008; Vereecken et al., 1989). The amount of moisture retained at a given tension increases with decreasing particle size and with increasing organic matter content (Wesseling et al., 2009b). It therefore varies with soil type (Batjes, 1996), land use (Bormann and Klaassen, 2008; Heiskanen et al., 2007), management (Ahuja et al., 1998; Katsvairo et al., 2002) and topographical position (Pachepsky et al., 2001). Soil water retention largely determines the amount of water available for plant growth, and is therefore for instance known to be related to seed germination (Zeng et al., 2010) and tree height growth (Piedallu et al., 2011). Plant available water refers to the volume fraction of water present in the soil between field capacity (10 kPa) and wilting point (1550 kPa) (Van der Valk and Stakman, 1969). Outside of this range, soil water is generally not available for plants: between saturation and field capacity, roots can suffer from low oxygen levels, and soil water is readily lost to deeper layers because of gravitational forces. Beyond wilting point, water is so strongly bound to the soil particles that uptake by plants is very limited.

Fires are known to alter soil properties that influence soil water retention. They have been reported to decrease organic matter content (Alauzis et al., 2004; García-Corona et al., 2004) increase bulk density (Andreu et al., 2001; Ferreira et al., 2009), change soil texture (Badía and Martí, 2003; Ulery and Graham, 1993) and induce soil water repellency (DeBano, 2000b). Temperature plays a major role regarding the magnitude of these changes (e.g. Badía and Martí, 2003; García-Corona et al., 2004). Several authors have reported on the effect of fire on soil water retention, but reports are inconclusive. Two laboratory studies found decreases in moisture content at field capacity and wilting point upon heating, depending on soil type and heating temperature (Badía and Martí, 2003; García-Corona et al., 2004). Most field studies found burning to decrease the amount of water stored at saturation, field capacity and wilting point (Alauzis et al., 2004; Boix Fayos, 1997; Kitzberger et al., 2005; Mallik et al., 1984; Silva et al., 2006). Increased moisture content at these tensions has however been found by Mallik et al. (1984), while Are et al. (2009) found no change. In the field, spatial variability of soil properties and fire dynamics often make it difficult to draw hard conclusions. While the largest changes can be expected from hot wildfires, planned pre- and post-fire sampling at the same site is only possible with generally cooler experimental and prescribed fires.

In addition to effects from heating, the presence of ash can play a major role in flow and transport processes after fire. The effect of ash on soil water retention is recognized by the sports industry which uses fly ash (a by-product from the coal industry) as a soil amendment (Adriano and Weber, 2001). Addition of the ash increases soil water retention and nutrient status but decreases hydraulic conductivity (Campbell et al., 1983; Chang et al., 1977; Khanna et al., 1994). In wildfire research, ash has often been considered to be a cause of increased runoff and erosion rates after fire (Kutiel et al., 1995; Onda et al., 2008; Woods and Balfour, 2008a). It is suggested that ash washes or infiltrates into the soil, thereby clogging soil pores and consequently limiting infiltration rates (Etiégni and Campbell, 1991; Woods and Balfour, 2006), explaining increased soil water retention (Mallik et al., 1984). However, studies on the soil physical effects of ash following the first rains after fires are scarce.

The objective of this research was to evaluate the effects of fire and ash on soil water retention. By performing experiments under controlled laboratory conditions, this study rules out effects of the spatial variability of soils and fire intensity dynamics that are often encountered under field conditions.

2.2   Material and Methods

2.2.1 Fire and ash experiments

Five controlled laboratory experiments were performed: two fire experiments and three ash experiments. The fire experiments evaluate the effect of fire on soil water retention using two different heating methods (Figure 2.1). The first method used a propane burner to burn the soil surface, with the second method soils were heated to different temperatures in a muffle furnace. Several laboratory studies have evaluated the effect of fire on soil properties using heating experiments (e.g. Badía and Martí, 2003; Doerr, 2004; Glass et al., 2008), although heating does not account for direct effects of flames. The experimental setup of this study, which combines burning and heating, consequently allows comparison of the two processes.
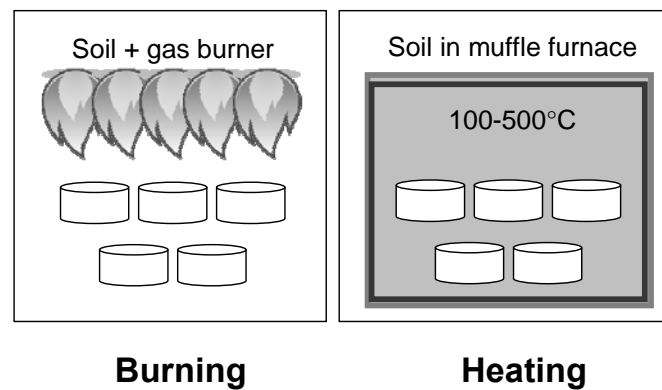
Figure 2.1 Setup of fire experiments, the number of rings representing the number of replicates
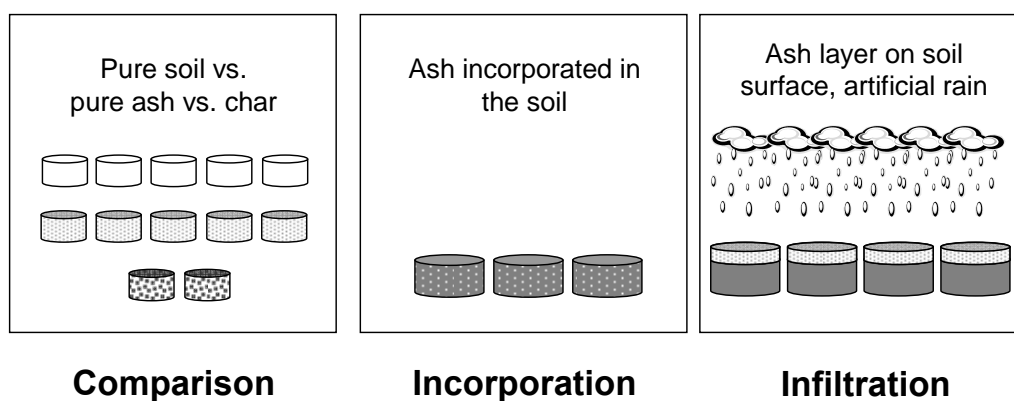
Figure 2.2 Setup of ash experiments, the number of rings representing the number of replicates

The ash experiments evaluate the effect of ash on soil water retention in three different ways (Figure 2.2). Firstly, properties of pure soil and ash were compared, and the effect

of degree of combustion was evaluated by determining and comparing properties of fully combusted ash and partly combusted char. In the second experiment, ash and unburned soil were manually mixed, while in the third experiment, ash was washed into unburned soil during a rainfall simulation.

2.2.2 Soil and ash properties

The soil used in these experiments is a soil often found in the fire-affected region of north-central Portugal: an organic matter rich topsoil derived from schist. It was air dried (0.04 cm^3/cm^3 moisture content) and then sieved at 2 mm to remove coarse fragments. The soil originates from the Valtorto catchment in north-central Portugal, which is subject of a large-scale field investigation of fire effects on hydrology and erosion (Shakesby et al., 2009; this thesis). Stainless steel cylinders (50 mm in diameter, 25 mm in height) were manually filled with the sieved soil, attempting to ensure uniform density.

In the ash experiments, cylinders were lined with cheesecloth before filling, while in the fire experiments cylinders were placed on a metal plate before filling and only lined with cheesecloth after the respective burning and heating treatments. The amount of soil needed to fill the cylinders was calculated using target bulk densities representative of the soil in the Valtorto catchment (0.72 to 0.88 g/cm^3). The ash used in the experiments was derived from *Pinus* wood burned in a fireplace that was sieved at 2 mm to separate the fully combusted ash (< 2 mm) from the partly combusted char (2-5 mm). The amount of ash needed was calculated using an ash bulk density of 0.30 g/cm^3. This value is representative of undisturbed wood ash found after a wildfire near Pampilhosa da Serra (Portugal) in August 2007 (personal observation), and lies within the range of ash bulk densities reported by Cerdà and Doerr (2008).

2.2.3 Fire treatments

For the burning experiment (Figure 2.1), samples were heated from above using a propane burner placed 20 cm above the soil surface. Temperature recording in this particular experiment failed, but soil surface temperature was around 900°C during a burning experiment performed under similar conditions (Chapter 3). A burning time of 5 min was used as representative of typical shrub understory fires (Chandler et al., 1983a; Glass et al., 2008). An unburned control treatment was included, and five replicates were performed per treatment.

For the heating experiment, five treatments were performed with five replicates each. Samples were heated in a muffle furnace pre-heated at 100, 200, 300, 400 and 500°C and compared to unheated controls. A heating time of 30 min was used, which is representative of burning small dry logs (Chandler et al., 1983a). Prior to burning, the

soil was slightly water repellent (water drop penetration time, WDPT (Letey, 1969), < 1 min). While heating at 100 and 200°C did not considerably affect WDPT, burning and heating at 300 and 400°C caused a substantial increase (WDPT > 10 min). Heating at 500°C removed the water repellency completely: samples heated at this temperature were highly wettable (WDPT = 0 s).

Samples were left to cool 24 h and then saturated. To be able to start the experiment with saturated soil, water repellency was eliminated before wetting the soil with water. First, 96% ethanol was used to quickly wet all samples from below. Samples were then left to drain and consequently slowly saturated with water from below five times to wash away the ethanol. Finally, saturated water-filled samples were used in further analyses.

Sample volume was calculated from the post-treatment sample height, because part of the dry soil was blown away by the flames during the burning treatment, and some soil material was consumed during burning and heating. After treatment, sample height was therefore up to 32% lower than before. The post-treatment sample volume was consequently used in further calculations of volumetric soil moisture content and bulk density.

2.2.4 Ash treatments

To compare the soil physical properties of soil and ash and evaluate the effect of degree of combustion, unburned soil was compared with pure ash (< 2 mm) and char (2-5 mm) (Figure 2). While the unburned soil had to be slightly compressed in order to achieve the desired bulk density, ash did not have to be compressed at all. Both ash and char were therefore very loosely packed. In the case of soil and ash, five replicates were used. Due to the small amount of material remaining after sieving the ash, there were only two replicates for the char.

For the ash incorporation experiment (Figure 2.2), the equivalent of 1 cm of ash was manually mixed with soil, to simulate an ash depth found at the base of burned plants in the Portuguese schist region (personal observations). This corresponded with 15.5% by weight. Three replicates were used, and a non-amended control was included.

For the ash infiltration experiment, a 1-cm layer of ash contained in a metal cylinder was placed on top of the soil sample, and 5 mm of water was sprayed on the ash for over a period of five minutes to imitate rainfall. After all water applied had percolated, the ash left on the surface was removed before further analyses of the soil samples. Four replicates were used and a non-amended control was again included. It is interesting to note that water rapidly ponded on the ash, but outflow at the bottom of the sample

verified that percolation did occur. The ash, however, did not seem to infiltrate at all (Figure 2.3).
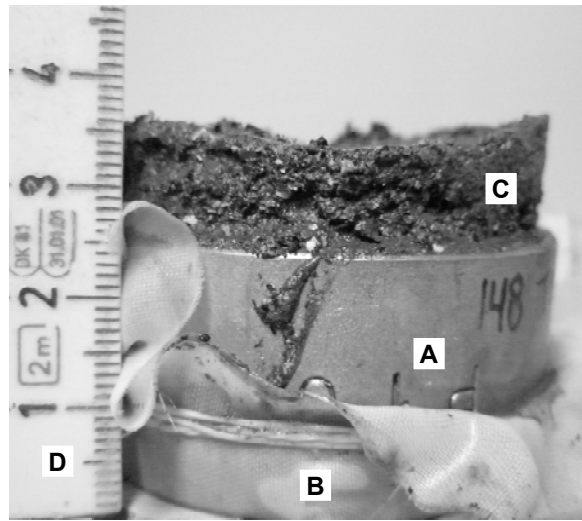
Figure 2.3 Soil core (a) lined with cheesecloth (b) showing a thick layer of ash remaining on the soil surface (c) after the infiltration experiment. A ruler (d) shows a centimeter-scale subdivided in millimeters.

Because the samples showed no signs of water repellency, no alcohol was used to saturate the samples, and all samples were slowly saturated with water from below. Because of the swelling nature of ash, ash-amended samples slightly increased in volume after wetting, increasing sample thickness by up to 4%. The height of all samples was therefore determined after wetting, and the resulting soil volume was used in further calculations.

2.2.5 Laboratory analyses

Upon saturation, samples were weighed to determine their moisture content. The drying branch of the water retention characteristic was obtained using a sandbox apparatus (Van der Harst and Stakman, 1961) and a pressure plate device (Stolte, 1997) at nine tensions between saturation and wilting point (h= 1550 kPa, Table 2.1). Samples were weighed to determine moisture content after hydrostatic equilibrium was reached at each tension, which generally took five to seven days. Because two pressure plates failed at tensions of 31 and 100 kPa, moisture contents corresponding to these tensions are missing for the burning experiment and for the 300 and 400°C heating treatments. One char sample was excluded from the analyses for tensions of 31 to 1550 kPa. Its moisture content decreased and increased with increasing tension, which was likely caused by poor contact between the pressure plate and the irregularly shaped char-particles.

For all treatments, the potential water storage was calculated for four tension ranges: 0 to 10 kPa ('gravitational'), 10 to 1550 kPa ('available'), beyond 1550 kPa ('unavailable'), and 0 kPa to ∞ ('total'). It is a measure of the volume of water that can be retained in a 10-cm high soil profile. Furthermore, water retention curves were fitted to the data using the program RETC (Van Genuchten et al., 1991) to facilitate the use of the presented data in hydrological models. Curves were fitted to all data points per treatment, resulting in one set of Van Genuchten parameters for each treatment (Appendix 2.1).

All experiments were performed in a climate-controlled laboratory with air temperature ranging between 16 and 17°C and relative humidity between 65 and 70%. At the end of the experiments, samples were oven-dried for 24 h at 105°C to determine final soil water content. Thereafter, organic matter content was determined by loss on ignition at 550°C for 4 h. Particle size distribution was determined by dry sieving (125 to 2000 μm) and by using a LS230 Beckman Coulter Laser Particle Size Instrument with the Variable Speed Liquid Module (up to 125 μm). Samples were not treated to remove carbonates or organic matter. Particle size distributions are given as fractions clay (< 2 μm), silt (2-50 μm) and sand (50-2000 μm).

Table 2.1 Overview of methods used and tensions at which moisture content was determined between saturation (0 kPa) and wilting point (1550 kPa).

Method	Tension (kPa)
Saturation trays	0
Sandbox	0.3, 1, 3.1, 10
Pressure plates	31, 100, 310, 1550

2.2.6 Statistical analyses

Results were statistically analyzed using the software package SPSS for Windows (version 15.0). First, a mixed-design ANOVA was used to test the main effects of the treatments and the tensions, as well as the interactions between treatments and tensions. Since Mauchly's test indicated that the assumption of sphericity had been violated in all cases, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity. Because all treatments had significant effects on soil water retention, one-way independent ANOVA's were used to test the effect of treatments at specific tensions. One-way independent ANOVA's were also used to test treatment effects on bulk density, organic matter content, particle size distribution and water retention capacity.

2.3   Results

2.3.1 Effect of fire treatment: burning

Burning increased dry bulk density, decreased soil organic matter content, and significantly changed soil texture by increasing clay and silt content and decreasing sand content (Table 2.2). Furthermore, it had a main effect on soil moisture content (F=99.38, p=0.000). Because two pressure plates failed at tensions of 31 and 100 kPa, moisture contents for these tensions are missing. At all other tensions, burning decreased moisture content (Figure 2.4). The decrease was significant for all but one tension (field capacity). The significant interaction between burning and tension (F=30.28 and p=0.000) indicates that the magnitude of the burning effect varied depending on the tension considered. In other words, soil moisture did not respond the same way to burning for each tension value. Because of the absence of a significant effect at field capacity, burning significantly increased plant available water (Table 2.2). It however decreased the total amount of water that can be stored in the soil, and thus soil porosity (Table 2.2, Figure 2.4).

Table 2.2 Bulk density (ρ_d), organic matter content (OM), particle size distribution and potential water storage of burned samples. Potential water storage is given for gravitational (0 to 10 kPa), available (10 to 1550 kPa), unavailable (beyond 1550 kPa), and total water (0 kPa to ∞). Values are averages over the replicates of the treatments (n=5), standard deviations are given between parentheses. Values not sharing the same letter in each column are statistically different at p<0.05.

Treat-ment	ρ_d (g/cm^3)	OM (%)	Particle distribution (%)			Potential water storage (mm)			
			clay	silt	sand	gravi-tational	available	un-available	total
Control	0.87 a (0.01)	16.2 a (0.3)	1.4 a (0.2)	17.9 a (0.9)	80.7 a (1.1)	16.6 a (1.6)	32.4 a (1.6)	18.5 a (1.0)	67.6 a (1.5)
Burned	1.00 b (0.05)	11.8 b (0.9)	2.9 b (0.6)	24.9 b (1.6)	72.1 b (2.2)	7.3 b (0.8)	35.4 b (0.8)	16.2 b (0.4)	58.9 b (0.9)
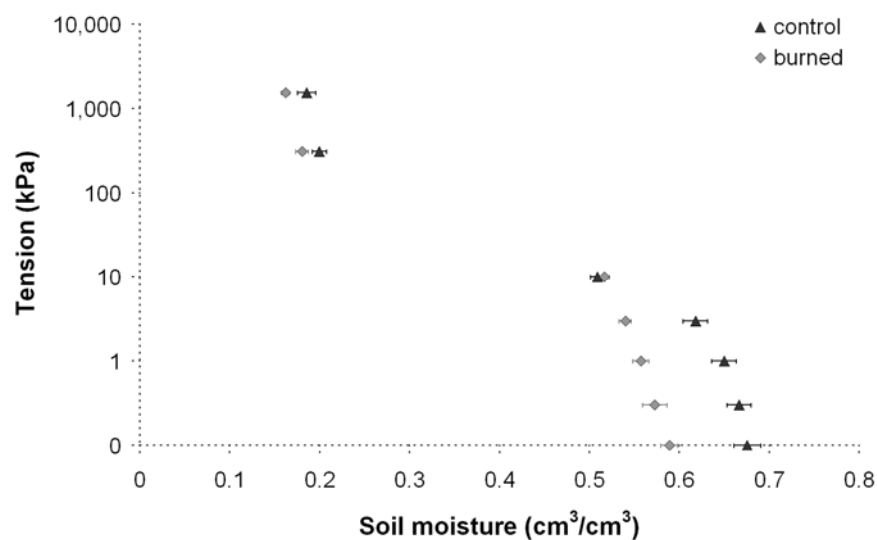
Figure 2.4 Water retention characteristics for burned soil and unburned control soil. Values are averages over the replicates of the treatments (n=5).

2.3.2   Effect of fire treatment: heating

Heating soils at temperatures up to 200°C did not alter dry bulk density or organic matter content. At higher temperatures, bulk density of soils significantly increased with increasing temperature. This effect was highest at 300 and 400°C. Organic matter content showed a more consistent response to heating at 300°C and above, significantly decreasing with increasing temperature (Table 2.3). Particle size distribution was likewise affected: for temperatures up to 200°C, no significant changes were observed. For soils heated to 300°C and higher, clay content slightly increased, silt content significantly increased and sand content significantly decreased (Table 2.3).

Similar to the results from burning, we found a main effect of heating on soil moisture content (F=11.63, p=0.000). In general, oven heating decreased soil moisture content at a given tension, but this effect was not always positively correlated with either temperature or tension (Figure 2.5). This is also indicated by the significant interaction between tension and heating (F=18.36, p=0.000). Table 2.4 and Figure 2.5 show that heating samples in a muffle furnace pre-heated at 100°C did not affect moisture content at any evaluated tension, while heating at 200 and 300°C decreased moisture content at all tensions compared to the unheated control. Heating at 400 and 500°C decreased moisture contents at low and high tensions while slightly increasing moisture contents at medium tensions (10 kPa for the 400°C treatment, 10 to 100 kPa for the 500°C treatment). Note that standard deviations of the moisture contents presented in Figure 2.5 are given in Appendix 2.2.

Table 2.3 Bulk density, organic matter content, particle size distribution and potential water storage of heated samples. Potential water storage is given for gravitational (0 to 10 kPa), available (10 to 1550 kPa), unavailable (beyond 1550 kPa), and total water (0 kPa to ∞). Values are averages over the replicates of the treatments (n=5), standard deviations are given between parentheses. Values not sharing the same letter in each column are statistically different at p<0.05.

Treat-ment	ρ_d (g/cm^3)	OM (%)	Particle distribution (%)			Potential water storage (mm)			
			clay	silt	sand	gravi-tational	available	un-available	total
Control	0.87 ab (0.01)	16.2 a (0.3)	1.4 a (0.2)	17.9 a (0.9)	80.7 a (1.1)	16.6 ab (1.6)	32.4 a (1.6)	18.5 a (1.0)	67.6 a (1.5)
100°C	0.89 ab (0.03)	15.8 a (0.7)	2.3 ab (0.6)	20.5 ab (2.2)	77.2 ab (2.8)	17.0 a (0.7)	31.7 a (0.9)	18.5 ab (1.1)	67.3 a (1.1)
200°C	0.87 a (0.01)	15.5 a (0.4)	2.2 ab (0.8)	20.2 a (3.8)	77.6 ab (4.6)	19.8 a (1.1)	25.9 b (1.7)	17.1 ab (0.7)	62.8 b (1.4)
300°C	1.04 c (0.04)	11.3 b (0.5)	2.6 b (0.7)	25.2 bc (3.3)	72.2 bc (3.9)	5.6 c (0.9)	34.5 ac (3.0)	16.3 ab (1.6)	56.4 c (1.7)
400°C	1.11 c (0.04)	9.7 c (0.3)	3.0 b (0.1)	28.1 c (0.6)	68.8 c (0.7)	7.8 c (1.0)	36.7 c (1.7)	16.8 ab (2.4)	61.3 b (0.9)
500°C	0.94 b (0.07)	7.9 d (0.3)	2.7 b (0.3)	27.5 c (0.7)	69.9 c (0.7)	13.4 b (3.7)	36.7 c (2.0)	14.4 b (2.3)	64.6 ab (3.9)

Interestingly, soils responded differently to heating at low tensions than at medium or high tensions. For low tensions (0 to 3.1 kPa), the decrease in moisture content increased with temperature increases up to 300°C, but diminished for soils heated at higher temperatures. In this low tension range, heating at 400°C had more impact than heating at 200°C, but heating at 500°C only had a minor impact (Table 2.4, Figure 2.5). At field capacity, the effects of heating were greatest at 200°C rather than at 300°C. Moisture content of soils heated to higher temperatures did not decrease at medium tensions (10 to 100 kPa) compared to the unburned control but slightly increased, though this increase was not always significant (Table 2.4). In the high tension range (310 kPa and above), the moisture contents generally decreased with increasing temperature, but effects were significant at the highest temperature only.

It is noteworthy to mention that soils in all heating treatments had a rather high moisture content at saturation, i.e. a rather high porosity (0.564 to 0.676 cm^3/cm^3, Table 2.3, Figure 2.5). Roughly half of the total amount of water that can be stored in this soil is available for plant growth (Table 2.3). Heating soils at 200°C negatively affected the amount of plant available water. This is in contrast to heating at higher temperatures, which had a positive effect on plant available water. The remainder of the total soil water storage is unavailable to plants and is divided between gravitational and

unavailable water. In general, heating decreased both the amount of gravitational water and the amount of unavailable water (Table 2.3).
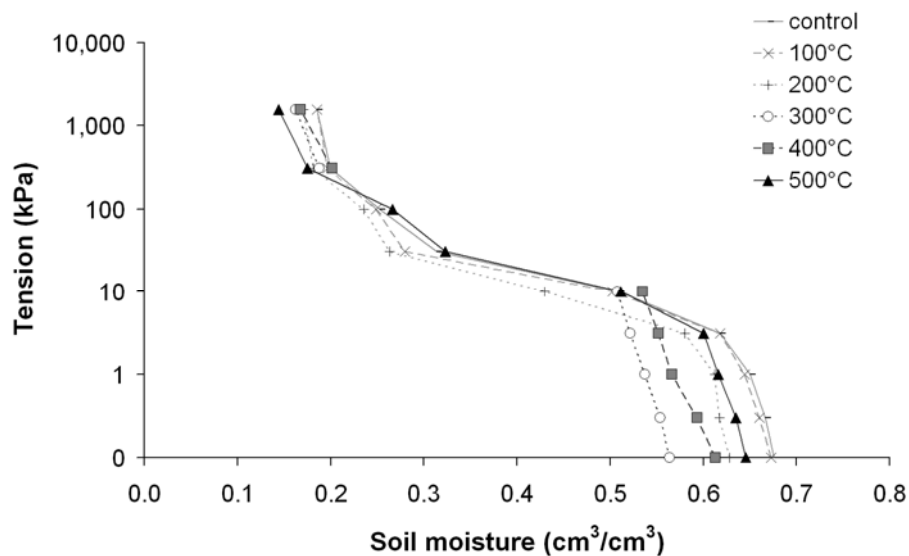
Figure 2.5 Water retention characteristics of samples heated in a muffle furnace at 100, 200, 300, 400 and 500°C, including unburned control. Values are averages over the replicates of the treatments (n=5), and straight lines are drawn to facilitate interpretation of the graph. Note that moisture values for the 300°C and 400°C treatments are missing for the 31 and 100 kPa tensions because of failure of two pressure plates.

Table 2.4 Significance of heating effects on soil moisture content at the given tensions (n=5). Values not sharing the same letter in each column are statistically different at $p < 0.05$, and n/a stands for not applicable.

| Treatment	Tension (kPa)								
	0	0.3	1	3.1	10	31	100	310	1550
Control	a	a	a	a	a	a	a	a	a
100°C	a	a	a	a	a	ab	a	ab	a
200°C	b	b	a	ab	b	b	a	ab	ab
300°C	c	c	b	c	a	n/a	n/a	ab	ab
400°C	b	b	b	b	a	n/a	n/a	ab	ab
500°C	ab	ab	a	a	a	c	a	b	b

2.3.3 Differences between soil and ash, and effect of degree of combustion

Physical properties of the soil and ash varied widely, and degree of combustion played a role in the differences observed between ash (< 2 mm) and char (2-5 mm). Ash had a slightly lower organic matter content than soil, and contained far more clay and silt

(Table 2.5). Ash on the other hand contained only a quarter of the organic matter present in less-combusted char (Table 2.5).

Table 2.5 Bulk density, organic matter content, particle size distribution and potential water storage of soil, ash and charcoal (char). Potential water storage is given for gravitational (0 to 10 kPa), available (10 to 1550 kPa), unavailable (beyond 1550 kPa), and total water (0 kPa to ∞). Values are averages over the replicates of the treatments, standard deviations are given between parentheses (n=5 for soil and ash, n=1 for char available, unavailable, n=2 for char other). Values not sharing the same letter in each column are statistically different at p<0.05. Although the standard deviation of the total water content for char seems to suggest that total water content exceeded 100 mm in 10 cm, the maximum was 98 mm.

Treat-ment	ρ_d (g/cm^3)	OM (%)	Particle distribution (%)			Potential water storage (mm)			
			clay	silt	sand	gravi-tational	available	un-available	total
Soil	0.87 a (0.01)	16.2 a (0.3)	1.4 a (0.2)	17.9 a (0.9)	80.7 a (1.1)	16.6 a (1.6)	32.4 a (1.6)	18.5 a (1.0)	67.6 a (1.5)
Ash	0.37 b (0.01)	11.4 a (0.8)	4.2 b (1.2)	43.4 b (6.5)	52.4 b (7.6)	32.3 b (1.4)	52.6 b (2.0)	11.3 b (0.5)	96.2 b (3.2)
Char	0.21 c (0.03)	48.2 b (10.6)	-	-	-	53.6 c (11.1)	24.6 c	10.7 b	88.9 b (14.1)
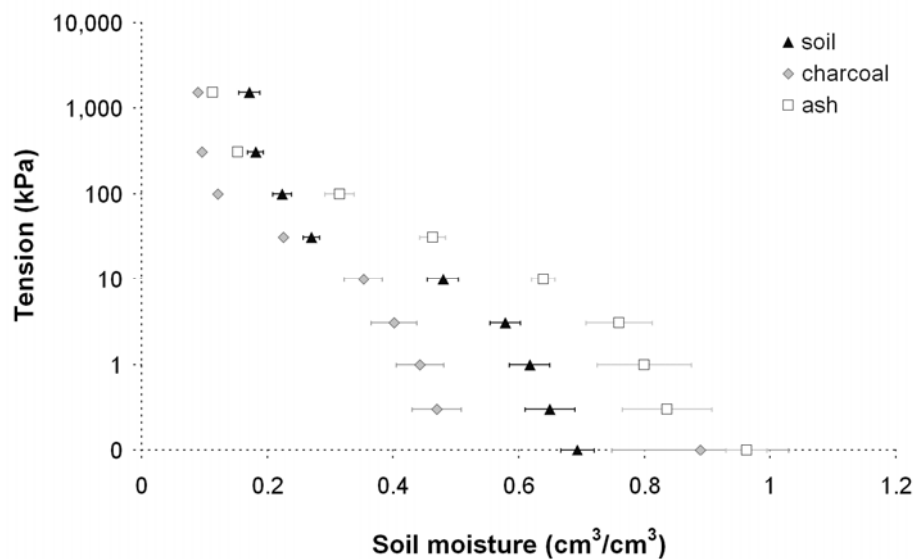
Figure 2.6 Water retention of charcoal, soil and ash. Values are averages over the replicates of the treatments (n=5 for soil and ash, n=2 for char), with error bars representing one standard deviation.

There was a surprisingly large effect of the degree of combustion on the water retention properties of ash and char (Table 2.5, Figure 2.6). The partly combusted char held significantly less water from 0.3 to 310 kPa tension than the fully combusted ash, and contained only half the amount of available water. It also held significantly less water

than the Valtorto soil except at saturation. The ash on the other hand, retained significantly more water than the soil for tensions up to 100 kPa. At tensions of 310 and 1550 kPa, however, ash retained significantly less water than the investigated soil. Saturated water content of char and ash, and therefore the total amount of water that can be stored, by far exceeded that of the soil and reached up to 89 and 96% by volume, respectively. The large drop in moisture content of ash and char between 0 and 0.3 kPa tension reflect the very loose packing of these porous materials. At saturation, much water was held between the ash and particularly between the relatively large char particles. This water was quickly released when a negative pressure was applied using the sandbox. In the case of ash, the majority of the total water potentially stored was available for plant growth, while in the case of char, most of this water was easily lost by gravity (Table 2.5). Plant available water of ash exceeded that of soil and char (Table 2.5).

2.3.4 Effect of ash treatments: incorporation

Dry soil bulk density in the incorporation treatment did not increase, despite the addition of 6 g ash to the soil. This can be explained by the fact that the volume of ash-amended samples increased by swelling (volume increase of 2.0%) whereas the volume of the control samples decreased because of settling (volume decrease of 7.5%, determined at saturation). This resulted in a similar bulk density for both treatments (Table 2.6). Because ash had a lower organic matter content than soil, it added relatively more mineral matter to the soil. Addition of ash therefore decreased the organic matter content by weight (Table 2.6). Despite the large textural differences between ash and soil (Table 2.5), ash incorporation did not significantly alter particle size distribution (Table 2.6).

Table 2.6 Bulk density, organic matter content, particle size distribution and potential water storage of samples in the ash incorporation experiment. Potential water storage is given for gravitational (0 to 10 kPa), available (10 to 1550 kPa), unavailable (beyond 1550 kPa), and total water (0 kPa to ∞). Values are averages over the replicates of the treatments (n=3)), standard deviations are given between parentheses. Values not sharing the same letter in each column are statistically different at p<0.05.

Treatment	ρ_d (g/cm³)	OM (%)	Particle distribution (%)			Potential water storage (mm)			
			clay	silt	sand	gravi-tational	available	un-available	total
Control soil	0.80 a (0.03)	16.1 a (0.3)	2.1 a (0.8)	21.4 a (5.6)	76.5 a (6.4)	21.4 a (0.3)	30.8 a (2.2)	17.1 a (1.7)	69.4 a (1.6)
Soil + ash incorporated	0.79 a (0.02)	12.8 b (0.3)	2.1 a (1.1)	22.0 a (3.3)	75.9 a (4.2)	8.9 b (0.6)	48.5 b (0.8)	17.0 a (0.6)	74.4 a (1.6)
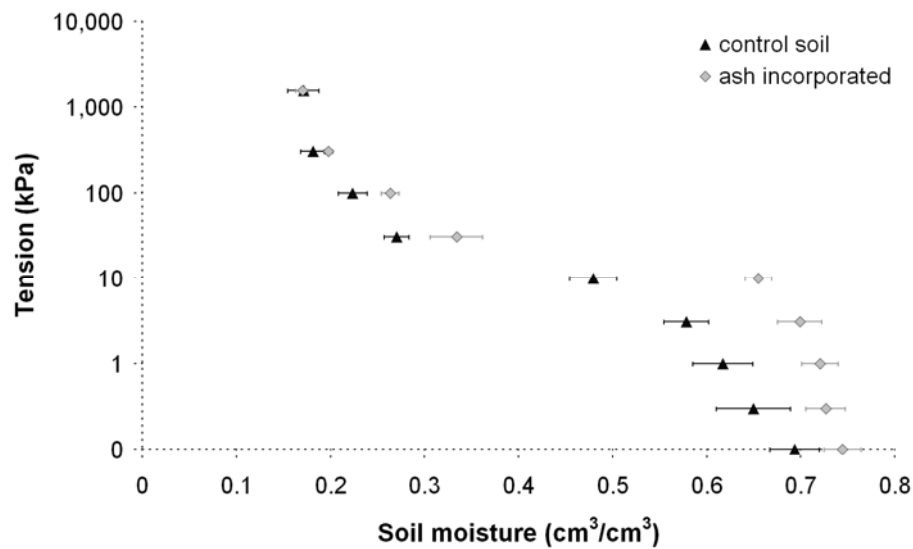
Figure 2.7 Water retention characteristics of soil with ash manually incorporated and control soil. Values are averages over the replicates of the treatments (n=3), with error bars representing one standard deviation.

As expected, the large water retention capacity of ash caused a main effect of tension and ash incorporation on soil moisture content (F=29.94, p=0.000). Ash incorporation increased soil moisture content at all tensions (Figure 2.7); and was significant at tensions from 3.1 to 31 kPa, increasing the amount of plant available water significantly (Table 2.6). Again, the significant interaction between tension and ash incorporation (F=22.65, p=0.000) shows that the magnitude of the ash effect was not the same for all tensions considered.

### 2.3.5 Effect of ash treatments: infiltration

Ash addition by infiltration caused a minor increase in bulk density and, for the same reason as in the incorporation experiment, a significant decrease in the weight fraction of organic matter. It furthermore increased silt content and decreased sand content (Table 2.7).

Despite the thick layer of ash left on top of the soil after the infiltration experiment and the lack of any visible signs of ash infiltration, we found a main effect of ash addition by infiltration on soil moisture content (F=31.63, p=0.000). As in the previous treatment, the magnitude of this effect was found to vary over the range of tensions, and is indicated by the significant interaction between tension and ash infiltration (F=31.41, p=0.000). Figure 2.8 shows that ash addition by infiltration slightly increased soil moisture content at all tensions. This increase is significant at saturation and field

capacity, which suggests that soil porosity also significantly increased by the infiltration experiment. Accordingly, the amount of plant available water significantly increased.

Table 2.7 Bulk density, organic matter content, particle size distribution and potential water storage of samples in the ash infiltration experiment. Potential water storage is given for gravitational (0 to 10 kPa), available (10 to 1550 kPa), unavailable (beyond 1550 kPa), and total water (0 kPa to ∞). Values are averages over the replicates of the treatments (n=4), standard deviations are given between parentheses. Values not sharing the same letter in each column are statistically different at p<0.05.

Treatment	ρ_d (g/cm^3)	OM (%)	Particle distribution (%)			Potential water storage (mm)			
			clay	silt	sand	gravi-tational	available	un-available	total
Control soil	0.87 a (0.01)	16.2 a (0.3)	1.4 a (0.2)	17.9 a (0.9)	80.7 a (1.1)	16.6 a (1.6)	32.4 a (1.6)	18.5 a (1.0)	67.6 a (1.5)
Soil + ash infiltrated	0.88 a (0.04)	14.8 b (1.0)	1.4 a (0.5)	14.6 b (3.0)	84.0 a (3.4)	14.6 a (2.1)	38.6 b (1.7)	19.3 a (1.3)	72.6 b (3.2)
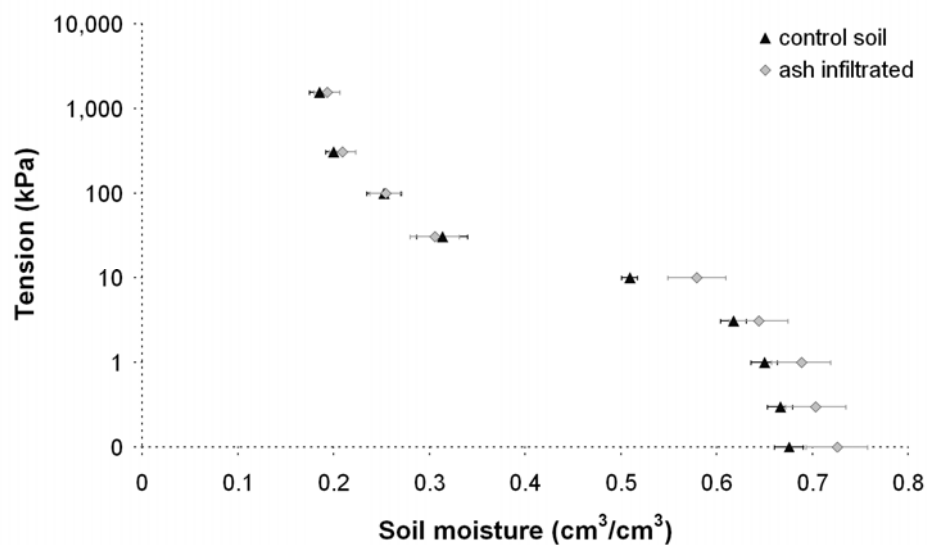
Figure 2.8 Water retention characteristics of soil after the ash infiltration experiment and control soil. Values are averages over the replicates of the treatments (n=4), with error bars representing one standard deviation.

2.4   Discussion

2.4.1 Effect of burning and heating

The effect of burning and heating on organic matter confirms reports elsewhere in the literature, both in the laboratory and in the field (Alauzis et al., 2004; Badía and Martí,

2003; García-Corona et al., 2004; Kitzberger et al., 2005; Nørnberg et al., 2004; Terefe et al., 2008). Organic matter content decreased upon burning, and heating at 300°C and above had a similar effect. Heating at lower temperatures had no effect on organic matter content, which was also observed by Badía and Martí (2003), García-Corona et al. (2004) and Fernández et al. (1997).

The same 300°C threshold was observed regarding soil texture. While other authors reported no changes in soil texture (Greene et al., 1990), or explained increased sand content by the aggregation of clay particles into sand-sized particles (Badía and Martí, 2003; Terefe et al., 2008; Ulery and Graham, 1993), the current experiments show the contrary for soils heated to 300°C and higher. Clay (< 2 µm) and silt content (2-50 µm) increased upon burning and heating, while sand content (50-2000 µm) decreased. Since soils in the present paper were broken up using a rubber pestle and a porcelain mortar, the particle size was analyzed rather than the aggregate size. The soil used in the experiments originated from schist, a rock type often derived from clay. The observed shift in particle size distribution after heating and burning can possibly be explained by physical weathering of the sand-sized particles into silt and clay sized particles. This type of physical weathering has for instance been observed in fire-consumed log burnout openings (Rhoades et al., 2004), as well as in a study on magnetic minerals, grains that are one or two orders of magnitude smaller than the largest clay particles (Oldfield et al., 2009). Oldfield and Crowther (2007) reported fire-generated magnetic minerals to have a significantly finer grain size than those arising from regular weathering and soil formation alone.

Several authors have reported that burned soil retains less water than unburned soil at similar tensions (Alauzis et al., 2004; Boix Fayos, 1997; Kitzberger et al., 2005; Silva et al., 2006). The present laboratory study confirms these field studies as well as two laboratory studies (Badía and Martí, 2003; García-Corona et al., 2004): fire changes the shape of the water retention curve. It also shows that there is a threshold of 200°C at and above which these changes occur. Burning and heating mostly affects the wet range of the water retention curve, between saturation and field capacity. At these tensions, soil water retention characteristics are much affected by soil organic matter (Rawls et al., 2003; Wesseling et al., 2009b). Since burning and heating significantly decreased organic matter content, water retention likewise decreased in the wet range. The decrease in water retention at the tensions considered was however far from linear with the decrease in organic matter. Whereas organic matter content decreased with increasing temperature, soil water retention in the wet range decreased up to 300°C and subsequently partly recovered at 400 and 500°C. A similar pattern was observed by Badía and Martí (2003), who found a decrease in moisture content at field capacity for

heating to 250°C, but a recovery for heating to 500°C. Since water retention increases with decreasing particle size (Wesseling et al., 2009b), the partial recovery for heating to 500°C can be partly attributed to an increase in clay and silt content.

Another explanation might lie in the degree of combustion, that determines the composition of ash (Khanna et al., 1994) and organic matter (Fernández et al., 1997; González-Pérez et al., 2004). Figure 2.6 showed that partially combusted char retains considerably less water than soil, whereas fully combusted ash retains considerably more water than soil. With increasing heating temperature, the degree of combustion, and thus the amount of ash, increases. At temperatures up to 300°C, incomplete combustion of soil organic matter will produce char-like material that retains very little water (Figure 2.6). At higher temperatures however, complete combustion of soil organic matter takes place, and ash is produced. The ash produced has a positive effect on soil water retention (Figures 7 and 8), and therefore partially offsets the decrease in water retention caused by the heating-induced loss in organic matter. This theory is supported by reports of soil pH changes after burning and heating. Because ash generally has a very high pH (Khanna et al., 1994), increased combustion, and thus more ash, is reflected in an increased pH. Badía and Martí (2003) found a pH decrease for soils heated to 250°C, but a consequent increase when heated to 500°C. Similar pH increases have been found after heating organic matter rich soil in the laboratory (Terefe et al., 2008), and after fire in the field (Alauzis et al., 2004; Nørnberg et al., 2004).

Because the effects of burning and heating varied by treatment and tension, the effect on plant available water was also variable. Literature reports on the effect of fire on plant available water also vary widely, ranging from a decrease (Boix Fayos, 1997; Boyer and Miller, 1994; Kitzberger et al., 2005), to no effect (Are et al., 2009; Badía and Martí, 2003; González-Pelayo et al., 2006; Rab, 1996), to an increase (Badía and Martí, 2003; Boix Fayos, 1997; García-Corona et al., 2004; González-Pelayo et al., 2006; Mallik et al., 1984). This depended, among other things, on the tension range considered and the parent material. The present study suggests that the effect of fire on plant available water depends on heating temperature. Although they found different temperature thresholds, Badía and Martí (2003) and García-Corona et al. (2004) observed a similar temperature effect on plant available water. The variable responses reported in the literature may therefore be partly explained by variation in fire intensity or heating temperature. In the present study, plant available water is not affected or decreases at low temperatures (100 and 200°C, respectively), while at higher temperatures it increases (Table 2.3). Burning (Table 2.2) had a similar effect to high-intensity heating. However, care should be taken in drawing conclusions too quickly about the beneficial effects of fire on water retention. Although the experiments suggest that high intensity

fire can be beneficial in increasing plant available water, the fate of burned areas will depend on the impact of a fire on the entire soil system. High temperatures severely affect rhizome and seed survival (Granström and Schimmel, 1993; Williams et al., 2003), and by inducing soil water repellency and changing soil structural parameters can lead to increased vulnerability for runoff and erosion (Shakesby and Doerr, 2006). In prescribed fires, we therefore recommend to keep soil heating to a minimum, despite the favorable effects that high intensity heating can have on plant available water.

As mentioned earlier, heating does not fully simulate the conditions during a fire, because it fails to account for direct effects of flames. Therefore we included the burning treatment using a propane burner to simulate the effects of the flames. Regarding soil water retention, soil heating to 300°C and above had similar effects to burning. They both decreased soil moisture content at most tensions. Under conditions similar to those studied, it is suggested that heating to 300°C and above can therefore be a good substitute for burning to study changes in soil water retention.

Effects of fire in the field will however not only depend on fire temperature, but also on heating duration. Flame contact and fire residence time will therefore play a large role in determining fire effects, and so will soil moisture content, because of its profound impacts on soil heating during fire (Beadle, 1940, Chapter 3). Another difference between the present laboratory study and the more complex field situation is soil structure and pore size distribution, which is changed when undisturbed soil is sieved and repacked. Pore-size distribution and particularly large pores considerably affect the near-saturated part of the water retention characteristic (Ahuja et al., 1998). Because of the fire-induced collapse of soil structure (García-Corona et al., 2004), fire can therefore possibly have a larger effect on soil water retention than reported for the repacked soil columns in the present study. Fire effects on water retention characteristics may furthermore vary with soil organic matter content, bulk density and texture. The presented experiments showed that fire can have major impact on soil water retention characteristics of an organic matter rich sandy loam that is commonly found in a region that is much affected by forest fires. The considerable organic matter loss upon burning and heating (27% and up to 51% of initial OM, respectively) can partly be attributed to the soil's high organic matter content before burning (16.2%). Extrapolation of these findings to soils with low organic matter contents should therefore be done with care: effects may well be less pronounced because of a lower loss in organic matter and a consequently smaller production of ash. The simple methodology presented in this paper can be used as a standard to evaluate and compare the effect of fire on different soils.

2.4.2 Effects of ash

The increase in water retention and plant available water due to ash that was observed in the present study confirms results and suggestions reported by others (Adriano and Weber, 2001; Campbell et al., 1983; Chang et al., 1977; Ghodrati et al., 1995; Mallik et al., 1984). Also the increase in moisture content at saturation has been reported in other studies (Ghodrati et al., 1995; Pathan et al., 2003). These findings seem to contradict mineralogical studies in which thin sections showed soil pores to be filled by ash particles, consequently decreasing soil porosity (Balfour and Woods, 2007; Woods and Balfour, 2008a). The explanation might lie in the swelling nature of ash: for a soil containing ash, the volume of water stored at saturation does not only account for water stored in pores (i.e. soil porosity) but also for the volume of water absorbed by the ash particles. The saturated water content may therefore have increased because of water absorption by ash, despite the fact that ash may fill soil pores and thus decrease soil porosity.

A number of authors have reported that the effect of ash on soil water retention increased with increased ash addition (Adriano and Weber, 2001; Campbell et al., 1983; Chang et al., 1977). The results of the incorporation and infiltration experiments reported here are in agreement with this: incorporation of only part of the ash during the infiltration experiments caused a less pronounced effect than direct incorporation of the ash into the soil. One large difference however is the effect on particle size distribution. While ash incorporation did not significantly change soil texture, ash infiltration decreased the proportion of silt-sized particles (2 to 50 µm) and increased the proportion of sand-sized particles (50 to 2000 µm). An increased amount of aggregates may have played a role, because the ash infiltration samples all developed a hard crust after oven drying. This crust was absent in all other treatments, and may have been formed because ash or ash leachates aggregated the soil particles at the soil surface after the infiltration experiment.

The effect of ash infiltration on soil water retention was surprising, given the fact that a thick layer of ash remained on the surface after the infiltration experiment. Apparently, only a small amount of ash is needed for a considerable increase of soil water retention. We hypothesize that the finest ash particles infiltrated with the water leaving the coarser material on top of the sample. A possible explanation for the large amount of un-infiltrated ash is swelling of the ash particles, causing them to become too large to wash into most of the soil pores, and resulting in only the smaller particles infiltrating into the underlying soil. During a (simulated) rain event, ash absorbs water and because of a textural interface (Baker and Hillel, 1990) the ash will generally only release its water to the underlying soil when it is almost saturated. The infiltration experiment showed that

part of the ash indeed washed into the soil in a 5-mm rain event in 5 min. In the field, such processes will depend on site characteristics and weather conditions, since for instance high intensity or prolonged rainfall can easily wash the ash down slope (Cerdà and Doerr, 2008).

The fate of ash during the first rains primarily depends on rainfall characteristics such as timing, duration and intensity (Cerdà and Doerr, 2008; Woods and Balfour, 2008b), but will also depend on ash characteristics (size, shape, composition and amount), soil physical and chemical characteristics (pore size distribution and geometry, soil structure, bulk density, wettability, infiltration capacity, and alkalinity), and slope. In the present study, only one soil and ash type were considered to explore the effect of ash on soil water retention. The infiltration experiment shows that ash particles and/or leachates can indeed wash into the soil, a finding which is supported by Balfour and Woods (2007) and Woods and Balfour (2008a), who found reductions in soil porosity that appeared to be associated with pore clogging by ash. The current study did not reveal similar pore clogging effects. This is an area that requires further study for understanding the physical processes and consequences of ash infiltration.

2.5   Conclusions

- Heating soils in a muffle furnace to 300°C and above for 30 min can result in soil physical effects similar to burning the soil surface for 5 min using a propane burner.
- Burning and heating can increase dry bulk density and clay and silt content, and decrease organic matter and sand content. Changes only occurred for soils heated to 300°C and above, but the effects did not always increase with increasing temperature.
- Burning and heating considerably decreased soil moisture content at most tensions – this effect seemed most pronounced for soils heated between 300°C and 500°C and in this study was largest for soils heated to 300°C.
- Effects of burning and heating were most pronounced at low tensions, between saturation (0 kPa) and field capacity (10 kPa).
- The effect of fire on plant available water appeared to depend on heating temperature. At low temperatures, plant available water was not affected (100°C) or decreased (200°C), while at higher temperatures it increased. Burning had a similar effect as high-intensity heating.
- The volume of water stored by ash exceeded that of soil at nearly all tensions considered. Ash addition therefore favored soil water retention and available water not only when it was incorporated into the soil, but also as a result of the influx of ash and/or ash leachates during simulated rain.

- Degree of combustion affected water retention characteristics of burned woody material. Water retention of fully combusted ash by far exceeded that of partially combusted char.

Appendix 2.1 Van Genuchten parameters

In the following tables, θ_r is the residual water content, θ_s is the saturated water content, α is approximately the inverse of the air entry value, n and m are shape parameters, and R^2 gives the coefficient of determination of each fit.

Table A.2.1.1 Van Genuchten parameters burning experiment

Treatment	θ_r (cm³/cm³)	θ_s (cm³/cm³)	α (cm⁻¹)	n (-)	m (-)	R^2
Control	0.170	0.668	0.0083	1.42	0.73	0.973
Burned	0.161	0.574	0.0006	1.01	2.83	0.996

Table A.2.1.2 Van Genuchten parameters heating experiment

Treatment	θ_r (cm³/cm³)	θ_s (cm³/cm³)	α (cm⁻¹)	n (-)	m (-)	R^2
Control	0.170	0.668	0.0083	1.42	0.73	0.973
100°C	0.195	0.659	0.0097	1.88	0.67	0.992
200°C	0.171	0.620	0.0183	2.25	0.36	0.994
300°C	0.162	0.552	0.0005	1.01	2.94	0.991
400°C	0.163	0.592	0.0011	1.01	1.65	0.987
500°C	0.123	0.634	0.0119	1.72	0.35	0.975

Table A.2.1.3 Van Genuchten parameters pure soil, ash and charcoal

Treatment	θ_r (cm³/cm³)	θ_s (cm³/cm³)	α (cm⁻¹)	n (-)	m (-)	R^2
Soil	0.170	0.668	0.0083	1.42	0.73	0.973
Ash	0.013	0.889	0.0128	1.01	0.43	0.969
Charcoal †	0.087	0.462	0.0022	1.01	1.91	0.975

† Because RETC was not able to fit the macropore behavior around saturation, Van Genuchten parameters were fitted to the data between 0.3 and 1550 kPa only. The parameters are therefore only valid for this tension range, and should not be used near saturation.

Table A.2.1.4 Van Genuchten parameters ash incorporation experiment

Treatment	θ_r (cm³/cm³)	θ_s (cm³/cm³)	α (cm⁻¹)	n (-)	m (-)	R^2
Control soil	0.179	0.670	0.0031	1.01	2.17	0.983
Ash incorporated	0.176	0.723	0.0117	34.28	0.03	0.992

Table A.2.1.5 Van Genuchten parameters ash infiltration experiment

Treatment	θ_r (cm³/cm³)	θ_s (cm³/cm³)	α (cm⁻¹)	n (-)	m (-)	R^2
Control soil	0.170	0.668	0.0083	1.42	0.73	0.973
Ash infiltrated	0.211	0.700	0.0052	1.74	1.22	0.981

Appendix 2.2 Standard deviations heating experiment

Table A.2.2.1 Heating experiment, standard deviation of soil moisture content

Tension (kPa)	Standard deviation of soil moisture content (cm³/cm³)								
	0	0.3	1	3.1	10	31	100	310	1550
Control	0.02	0.01	0.01	0.01	0.01	0.03	0.02	0.01	0.01
100°C	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01
200°C	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.00	0.01
300°C	0.02	0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.02
400°C	0.01	0.01	0.02	0.02	0.02	0.01	0.02	0.02	0.02
500°C	0.04	0.04	0.04	0.04	0.03	0.02	0.03	0.02	0.02
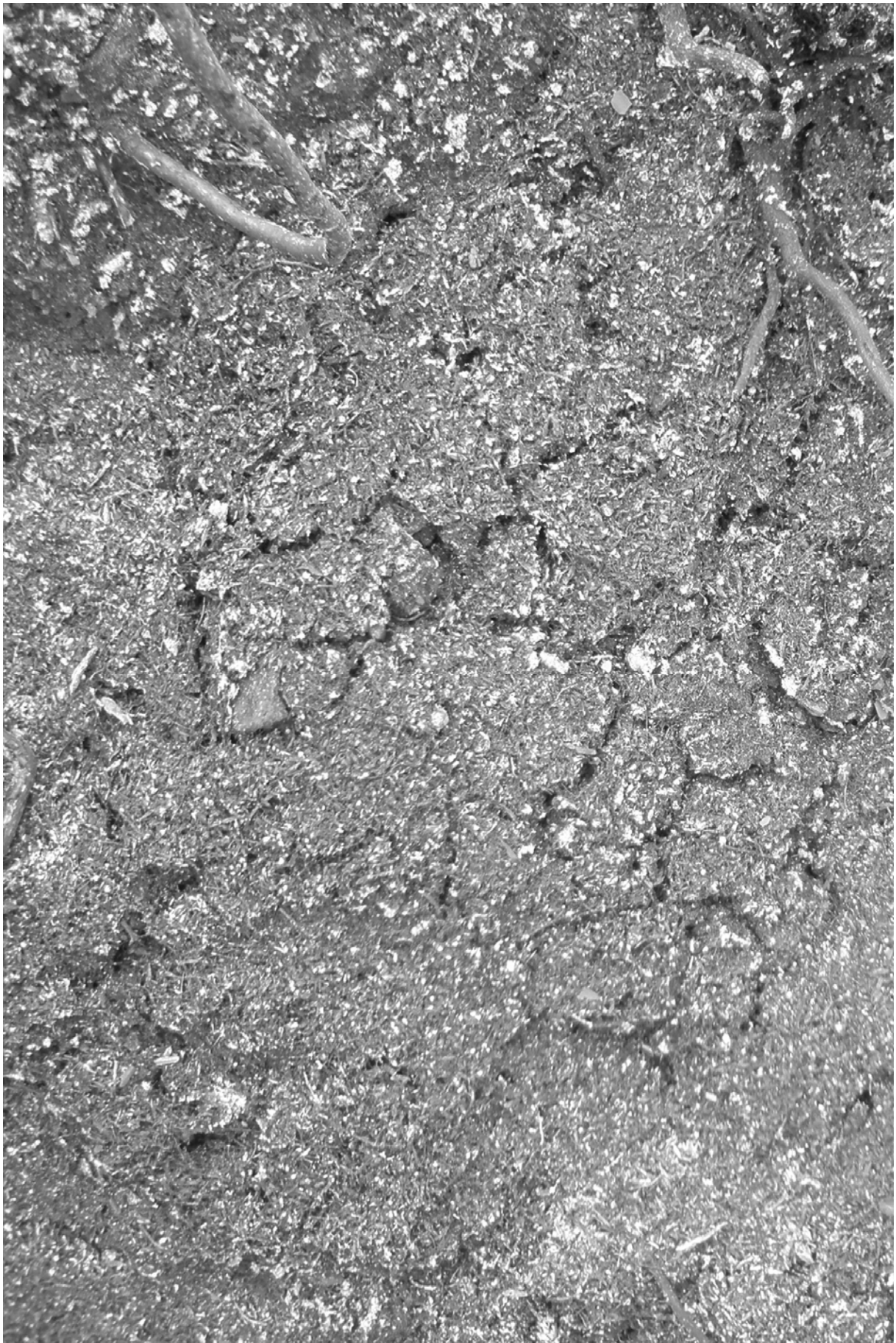
3   Soil heating:
role of rock fragments
and soil moisture

Abstract

Soil heating during forest fires can considerably impact the soil system, with effects ranging from seed and microbe mortality to nutrient losses and structural degradation. Since soil heating is related to soil moisture and composition, fire impact may also depend on the presence of rock fragments in and on the soil. In laboratory burning experiments, the effect of rock fragments on soil heating was evaluated using factorial combinations of soil moisture, rock fragment cover and rock fragment content. Soil moisture significantly reduced maximum temperatures, as well as the depth and duration of sustained temperatures (duration of heating) above 60 and 175°C. Effects declined with depth. A rock fragment cover similarly protected the soil from high maximum temperatures, especially in dry soil. While it decreased the depth of lethal heating (60°C) from 3 to 2 cm, it increased the duration of heating at the soil surface. Incorporated rock fragments had no significant effect on maximum temperature or depth of lethal heating, and effects on heating duration were limited to dry and/or bare soil. The data suggest that by changing the degree of soil heating, rock fragments may reduce the risk of fire-induced biological, chemical and physical degradation, but increase the biological impact of fire at the soil surface. These findings highlight the importance of soil moisture and rock fragments as key factors regulating potential damage to the belowground ecosystem, and have implications for controlled fire decision making in rocky areas where soil heating is desired or should be avoided.

3.1 Introduction

Fires can considerably affect belowground ecosystem functioning. The degree of changes is largely determined by the soil temperatures reached and the time that high temperatures are sustained (Cerdà and Robichaud, 2009; Neary et al., 1999). Despite the fact that fires often occur in rocky areas, there is a surprising lack of literature concerning the effect of rock fragments on soil temperatures during fire. Because rock fragments have pronounced effects on diurnal soil temperature fluctuation (Childs and Flint, 1990; Mehuys et al., 1975), it is very possible that they also affect soil temperatures during fire and thus the impact of fires on the soil system.

Soil surface temperatures during fire typically range between 200 and 700°C (DeBano et al., 1998), although surface temperatures as high as 1150°C have been reported (Cerdà and Robichaud, 2009). High soil temperatures can significantly affect belowground processes, with physical and chemical processes being affected at higher temperatures than biological processes. A temperature of 60°C can for instance be lethal for rhizomes, certain fungi and bacteria and heat-sensitive seeds (Dunn et al., 1985; Granström and Schimmel, 1993; Grasso et al., 1996; Tozer and Auld, 2006). Fire-adapted seeds however actually break seed dormancy or increase germination after heating at 60°C and are only killed at temperatures between 100 and 120°C (Beadle, 1940; Tozer and Auld, 2006; Williams et al., 2003). Physical and chemical processes are affected from 175°C upwards. Soil water repellency, a phenomenon that impedes the infiltration of water, is induced around this temperature (DeBano, 1981). At 200°C, nitrogen volatilization and organic matter distillation start, while the volatilization of other nutrients and the complete combustion of organic matter occur at higher temperatures (García-Corona et al., 2004; Gray and Dighton, 2006; Neary et al., 1999). Associated with the loss in organic matter is soil structural degradation (García-Corona et al., 2004) and a change in soil water retention (Chapter 2). Both biological and physical changes are known to be related to the time that high temperatures are sustained (the 'heating duration'). This is for instance the case for seed mortality and seedling growth (Gleadow and Narayan, 2007), post-fire tree stress (Morgan Varner et al., 2009), the elimination of soil water repellency (Doerr, 2004) and soil color changes (Ketterings and Bigham, 2000).

It is clear therefore that the various impacts of fire on the soil system are highly dependent on both the degree and the duration of soil heating. This in turn is largely determined by the characteristics of the fire (heat release, temperature, duration, degree of contact with the soil) and the thermal properties of the soil, that depend on the soil's composition (Van Wijk, 1963), its structure (Massman et al., 2008) and its bulk density and moisture content (Abu-Hamdeh and Reeder, 2000). By increasing thermal

conductivity and heat capacity, soil moisture has profound effects on soil heating during fires. It considerably reduces soil temperature rise and slows heat propagation (Campbell et al., 1995; Valette et al., 1994). As a result, maximum soil temperatures during fire are generally much higher in dry soils than in moist soils (Beadle, 1940; Busse et al., 2010; Busse et al., 2005). Rock fragments in and on the soil likewise affect soil thermal properties, changing heat flow propagation into and through the soil. The presence of rock fragments may therefore change soil temperatures during fire and consequently affect fire impact, especially in mountain areas where fires occur on stony soils.

Stony soils are widespread and common where wildfires occur. The very shallow and often stony Leptosols (less than 25 cm deep) are the most common soil type in the world, covering roughly 11% of the earth's land surface. Most of these soils are covered with forest and can be found in mountainous regions where they are generally less than 10 cm deep (IUSS Working Group WRB, 2006). Analysis of the ISRIC-WISE Database (Batjes, 2005) furthermore reveals that 55% of the world's soils have a rock fragment (particles sized > 2 mm) content greater than 0.05 cm^3/cm^3, and 20% of soils contain more than 0.20 cm^3/cm^3 rock fragments. Fires often occur on shallow or stony soils. Combining the European Soil Database (European Commission and European Soil Bureau Network, 2004) with wildfire perimeters (GAUF, 2009) shows, for instance, that in Portugal 37% of the fires between 1990 and 2008 occurred on soils with ≥ 0.15 cm^3/cm^3 rock fragments, corresponding to 21% of the total area burned in this period. 51% of the fires between 1990 and 2008 occurred on shallow soils (< 40 cm deep), corresponding to 67% of the total area burned.

Little is known about the relation between fire-induced soil degradation and the presence of rock fragments. The impact of rock fragments on soil heating during fire has not been studied. A growing body of literature has however reported on the profound effect that rock fragments can have on soil heat and water regimes. Rock fragments can change soil thermal properties and insulation (Childs and Flint, 1990), and affect soil water (re)distribution and percolation in both hydrophobic and non-hydrophobic soils (Mehuys et al., 1975; Urbanek and Shakesby, 2009). Moreover, there are various reports of decreased soil evaporation, increased soil water availability and reduced land degradation where there are rocks (e.g. Cerdà, 2001; Katra et al., 2008; Li, 2003; Poesen and Lavee, 1994).

Surface rock covers have been found to affect daily soil temperature fluctuations by keeping the soil cool during the heating period, and by keeping the soil warm during the cooling period (Li, 2003; Mehuys et al., 1975). The degree of impact often depends on the thickness of the rocks (Huey et al., 1989). Ecological implications of surface rock

covers are already known to range from prevention of frost damage to plants in cold regions as suggested by Li (2003), to in certain conditions causing heat stress to burrowing animals during daytime (Huey et al., 1989). It is therefore reasonable to hypothesize that surface rock covers would also impact the effects of wildfires on the soil system.

While rock fragments on the surface mainly affect the rate and amount of energy reaching the soil, rock fragments incorporated into the soil matrix also change overall soil thermal properties. Childs and Flint (1990) therefore concluded that, because of differences in heat capacity and thermal conductivity, soils containing rock fragments have a higher total heat flux into the soil and a deeper penetration of the daily heating cycle. Mehuys et al. (1975) accordingly suggested that, in dry regions, temperature gradients around buried stones may cause a considerable water flux towards rock fragments in the early morning. Various authors have suggested that the resulting water accumulation underneath rocks, affected by rock content, creates favorable microhabitats for soil flora and fauna (e.g. Jaeger, 1980; Nobel et al., 1992).

Despite the considerable effect of rock fragments on soil heat flow and the profound effect of soil heating on the belowground impacts of fire, there is a surprising lack of literature concerning the effect of rock fragments on soil heating during fire. We believe this is the first study to evaluate the role of surface rock cover and rock content on soil heating during fire. The objective of this study was to evaluate the role that rock fragments and soil moisture play during fire, which may have important implications for the impact of prescribed fires performed in rocky regions. To minimize spatial variability of fire intensity and soil properties, laboratory burning experiments were performed in which soil temperatures were monitored using factorial combinations of soil moisture, rock fragment content and cover. Our hypothesis was that rock fragments and especially a rock cover would absorb heat and protect the soil from severe heating, but at the same time would prevent the soil from cooling, thereby increasing the duration of lethal temperatures. Based on previous studies (Busse et al., 2005; Valette et al., 1994), we further hypothesized that soil moisture would considerably decrease both maximum temperatures as well as the duration of lethal heating.

3.2 Methods

3.2.1 Experimental design

Controlled laboratory burning experiments were performed to evaluate the effect of rock fragments and soil moisture on soil heating during fire. A burning time of 5 min was used

as representative of shrub understory fires (Chandler et al., 1983a; Glass et al., 2008). The surface of soil columns was burned using a propane burner, and soil temperatures were recorded. Three treatments factors were considered: a) soil moisture content (0.022 and 0.193 cm^3/cm^3), b) rock fragment cover (0 and 100%), and c) 'incorporated rock fragments' or rock fragment content (0 and 0.150 cm^3/cm^3, 0.312 g/g) (Figure 3.1). Three replicates were performed per treatment factor combination and, since soil organic matter and texture have been found to only nominally affect the maximum temperature or the duration of heating during burning (Busse et al., 2010), only one soil type was used.
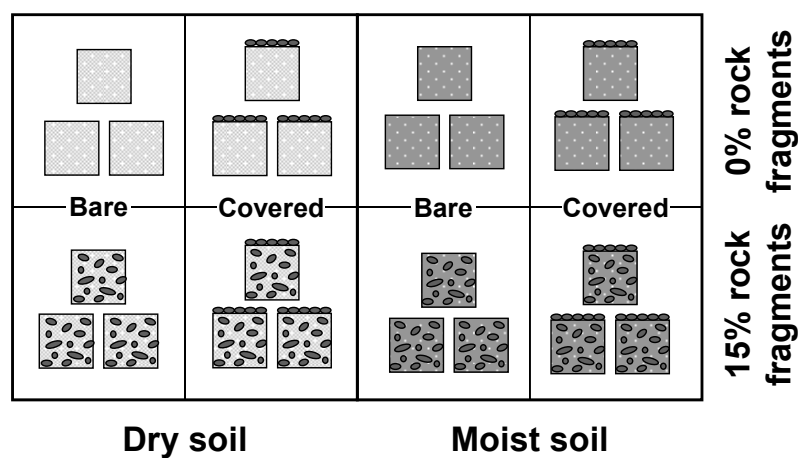
Figure 3.1 Experimental design using factorial combinations of 1) soil moisture (dry vs. moist), 2) surface rock fragment cover (bare vs. cover), and 3) incorporated rock fragments (0 vs. 0.15 cm^3/cm^3 rock content). The number of squares shows the number of replicates per treatment (n=3).

3.2.2 Sample construction

The soil used in these experiments is a soil commonly found in the fire-affected region of north-central Portugal: an organic matter rich topsoil derived from schist. This region has an Atlantic-Mediterranean climate with dry soils and high wildfire risk in summer. In winter (when soils are moist), prescribed fires are often performed to reduce fuel loads and to stimulate biodiversity and improve pastures in mountain areas. The soil and rock fragments originate from the shrub-covered Valtorto catchment in north-central Portugal (40° 06' 21'' N, 8° 07' 03'' W), where a large-scale field investigation of fire effects on soils, hydrology and erosion is currently underway (Shakesby et al., 2010a; this thesis). The catchment is steep and characterized by shallow soils (often < 10 cm deep), which have a mean rock fragment content of 0.170 cm^3/cm^3 (0.401 g/g), while surface rock

cover ranges from 30 to 90%. The soil is classified as a gravelly loamy sand (USDA, 1993) with an organic matter content of 16.3%.

The amount of soil and rock fragments required in the experiments was calculated using a fine earth bulk density and particle density representative of the soil in the Valtorto catchment (0.88 g/cm^3 for particles < 2 mm; 2.36 g/cm^3 for particles 2 to 20 mm). Fine earth bulk density was kept constant with rock fragment content; total bulk density was therefore higher for soils containing rock fragments (1.10 g/cm^3) than for rock free soils (0.88 g/cm^3). Air-dried soil was used for the dry soil treatment (0.022 cm^3/cm^3 moisture), to which a fixed amount of water was added to reach moist soil (0.193 cm^3/cm^3). Soil columns were constructed by manually filling PVC cylinders (103 mm in diameter, 100 mm in height) with the previously mixed soil, rock fragments and water, while trying to ensure uniform density. Where required, a 100% rock cover (1 cm thick, 96 g, particles sized 2-20 mm) was placed on top of the sample (Figure 3.2).

Figure 3.2 Setup of a soil column without (left) and with (right) a rock fragment cover during the burning experiment. Thermocouples were inserted in the soil column at 1-cm increments along a diagonal. The uppermost thermocouple was held in place using a metal bar.

3.2.3 Temperature recording

K-type thermocouples (1.5 mm in diameter, 50 mm in length, TC-direct, The Netherlands) were installed horizontally and connected to data loggers (EL-USB-TC, Lascar Electronics, United Kingdom) to monitor soil temperatures at centimeter intervals from the surface (underneath any rock fragment cover) down to 8 cm (Figure 3.2). A concentrated flame was used, because only the tip of the thermocouple probe measured the temperature and all tips were aligned in the very center of the soil column. This was verified when all

thermocouple probes were excavated the day after the experiments. It was therefore assumed that all readings reflect the temperature directly underneath the flame. Since propagation of the heat wave was relatively slow, it was furthermore assumed that the cooler (unheated) surrounding soil had negligible effects on the temperatures measured in the center of the column.

Soil temperatures were recorded at 1-sec intervals until the data logger storage was full, capturing the burning experiment including a nine-hour cooling period. After burning, samples were packed in rock wool to prevent heat losses through the sides and left to cool overnight. Temperature data was subsequently downloaded from the data loggers. Visual data quality checks showed that unreliable data was gathered for 8 out of 216 thermocouples due to data logger failure. These records were deleted before data analyses.

In addition, two entire columns (moist soil with rock content and cover) had to be removed from analyses because during burning these columns, surface rock fragments split apart. This thermal fragmentation or weathering can be caused by strong thermal gradients in rocks (Waragai, 1998), and partly exposed the soil surface. The very large variation in soil temperature observed in this moist rocky soil treatment with rock cover (482 to 1160°C at the soil surface) was likely caused by the incomplete rock cover rather than by variation in treatment.

3.2.4 Soil thermal properties

To facilitate explanation of treatment effects using soil heat flow theory, the thermal properties of the soil mixtures were determined. Thermal conductivity, λ (W/m·K), was measured using a KD2 thermal property meter (Decagon Devices, USA). Heat capacity, C (J/m^3·K), was calculated following Van Wijk (1963) as the sum of the heat capacity of the soil components:

$$C = \chi_m \, \rho_m \, c_m + \chi_o \, \rho_o \, c_o + \chi_w \, \rho_w \, c_w + \chi_a \, \rho_a \, c_a \tag{3.1}$$

where χ_i is the volume fraction (Table 3.1), ρ_i is the particle density (kg/m^3), and c_i is the specific heat (J/kg·K) of the ith soil component: mineral (m), organic (o), water (w), and air (a). Thermal diffusivity, a (m^2/s), was calculated as λ/C. Rock cover was not taken into account in these calculations but was accounted for by adjusting the mineral fraction (Table 3.1). The specific values used in Eq. (3.1) were: $\rho_m = 2.36 \cdot 10^3$, $\rho_o = 1.3 \cdot 10^3$, $\rho_w = 1.0 \cdot 10^3$, and $\rho_a = 1.2$ kg/m^3; and $c_m = 0.70 \cdot 10^3$, $c_o = 1.9 \cdot 10^3$, $c_w = 4.2 \cdot 10^3$, and $c_a = 1.0 \cdot 10^3$ J/kg·K.

3.2.5 Data analyses

One-way ANOVA's were used to test treatment effects on thermal conductivity, heat capacity and thermal diffusivity. In addition, various parameters were extracted from the temperature time series obtained at each depth: 1) maximum temperature, 2) heating and cooling velocities, determined from start, maximum and final temperature (after nine hours), and the time at which this occurred at each depth, and 3) the depth and duration of sustained temperatures above threshold temperatures of 60 and 175°C ('duration of heating'). The threshold values of 60°C and 175°C were chosen as indicators of possible biological changes (lethal heating) and the onset of physical and chemical changes, respectively (see Section 3.1).

Two approaches were used to analyze the different types of response variables. Maximum temperature and heating and cooling velocity were continuous and were log-transformed to achieve normality before applying a 4-way factorial model that was fitted using residual maximum likelihood. Since depth was not randomized, the correlation between observations within each soil column was accounted for in the models. This was achieved by analyzing the data in a similar way as a repeated measures experiment, though one in which measurements were taken repeatedly with depth rather than with time. The optimal model in terms of the correlation model and the variance structure was found using a similar approach as described by Webster and Payne (2002).

The depth and duration of heating above threshold temperatures was analyzed using a different approach. Because the heating duration had many zero values, particularly at depth, a mixture model was fitted. This involved fitting 1) a binary logistic model based on indicator coding (0 = did not reach threshold, 1 = reached threshold), and 2) a continuous model for the time values greater than 0, which in effect was a 3-way ANOVA. Each depth of measurement was analyzed separately. All analyses were performed in R (R Development Core Team, 2010), and the nlme package (Pinheiro et al., 2009) was used to fit the 4-way factorial models.

3.3 Results

3.3.1 Thermal properties

Thermal conductivity was fairly low, ranging from only 0.08 to 0.22 W/m·K, which is typical for soils with high porosity (~50-60% in this case). Thermal conductivity significantly increased with water content, but was not significantly affected by rock fragment content (Table 3.1). In contrast, heat capacity significantly increased with water content and with rock fragments (Table 3.1). Thermal diffusivity likewise increased

with water content, while the effect of rock fragment content was less clear and less pronounced. This is consistent with the observed lack of changes in thermal conductivity with rock fragment addition.

Table 3.1 Bulk soil thermal properties: volume fractions of the different soil components, measured soil thermal conductivity λ, and calculated heat capacity C and thermal diffusivity a. Rock fragment content is accounted for in the mineral fraction. Values are averages over the replicates (n=6), grouping treatments with different rock fragment cover. Values not sharing the same letter in each column are significantly different at p<0.05.

| Sample	Rock content	Volume fraction (cm³/cm³)				λ (W/m·K)	C (J/m³·K)	a (m²/s)
		mineral	organic	water	air			
Dry soil	0%	0.312	0.110	0.022	0.556	0.082 a	$0.9 \cdot 10^6$ a	$0.9 \cdot 10^{-7}$ ab
	15%	0.416	0.093	0.022	0.469	0.083 a	$1.0 \cdot 10^6$ b	$0.8 \cdot 10^{-7}$ a
Moist soil	0%	0.312	0.110	0.193	0.385	0.192 b	$1.6 \cdot 10^6$ c	$1.2 \cdot 10^{-7}$ ab
	15%	0.416	0.093	0.193	0.298	0.223 b	$1.8 \cdot 10^6$ d	$1.3 \cdot 10^{-7}$ b

3.3.2 Maximum temperature

Examination of the treatment factors; rock cover, rock content, soil moisture and depth below the soil surface revealed no significant 4-way or 3-way interactions, but did reveal four significant 2-way interactions (Figure 3.3), namely moisture : cover (p=0.0170), rock content : cover (p<0.0001), moisture : depth (p<0.0001), and cover : depth (p<0.0001). Rock cover, rock content and soil moisture all decreased maximum temperatures, but their effects were interrelated and in the case of moisture and cover also depth-dependent.

Increased soil moisture reduced the overall mean maximum temperature, irrespective of rock fragment cover (Figure 3.3a) or content (Figure 3.3b). Rock cover had a similar effect, which was however only significant in dry soil (Figure 3.3a) and in rock-free soil (Figure 3.3c). There was a sharp contrast between the effect of rock fragment content on temperatures in bare soil or covered soil: incorporated rock fragments decreased overall maximum temperature in bare soil, however they increased temperatures in covered soil (Figure 3.3c). Rock fragment content had no overall effect in either dry or moist soil (Figure 3.3b).

Maximum temperatures were highest at the soil surface, and dropped quickly with depth (Figure 3.3). While the effect of rock fragment content was constant with depth (Figure 3.3f), the insulating effect of soil moisture and rock fragment cover were depth-

dependent (Figure 3.3d-e). The increase in soil moisture from 2.2 to 19.3 vol% significantly decreased maximum temperature from 1 to 5 cm depth, and had no effects below. The effect of rock cover decreased with depth but was only significant at the very surface of the soil.
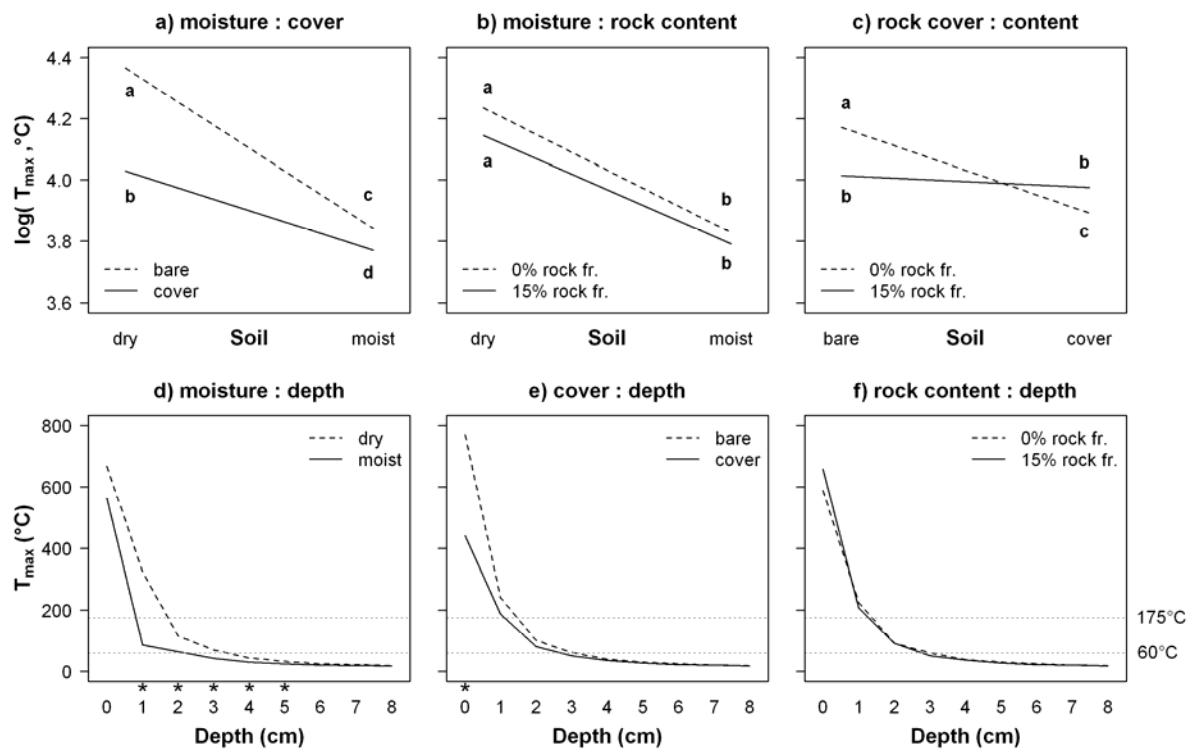

Figure 3.3 Two-way interaction plots of maximum temperature (T_{max}), note that only the interactions given in figures a, c, d and e are significant. Values are averages over the treatments (n=12). In figures a-c, different lower case letters within one plot indicate significant differences (at p<0.05). Likewise in figures d-e, asterisks indicate significant differences between the treatments at the given depth below the soil surface.

3.3.3 Heating and cooling process

Heating as well as cooling velocities were positively correlated to maximum temperature (r = 0.98 and 0.97, respectively). Soil temperatures responded very slowly to the heat of the flames, especially at greater depths. While soil heating at 1 cm started, at most, 1 min later than at the surface, at 8 cm this took between 15 and 22 min, depending on moisture, rock cover and rock content. An example is given in Figure 3.4. Heating velocity was often not constant over time: it markedly reduced when soil temperatures approached 100°C, which has been associated with the evaporation of water (Hartford and Frandsen, 1992). Heating slowed down when soils reached 67 to 85°C (average 73°C), and accelerated again when soils reached 72 to 99°C (average 86°C)

(Figure 3.4a). This was particularly the case in dry soil; in moist soil, temperatures remained mostly below boiling point. In three cases, moist soil remained at a constant peak temperature between 87 and 93°C for up to 2 minutes before temperatures started to decrease and cooling started (Figure 3.4b).
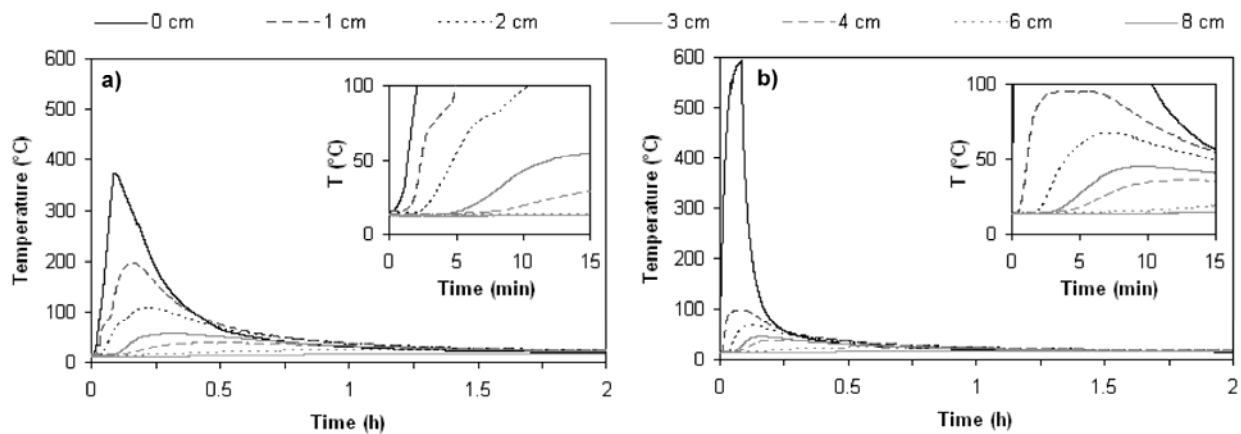

Figure 3.4 Example of temperature time curves for column 11 (a: dry, with 15% rock content and rock cover) and column 18 (b: moist, with 15% rock content but without rock cover), showing the delayed response of temperature with depth, as well as the delay of heating in soil approaching 100°C (insets). Each line represents one depth (given in cm below the soil surface).

In the case of heating velocity, there was no significant 4-way interaction, but there were four significant 3-way interactions (Figure 3.5), namely moisture : rock content : cover (p=0.001), moisture : cover : depth (p<0.001), moisture : rock content : depth (p=0.002), and rock content : cover : depth (p=0.023). Soil moisture and rock cover both slowed heating, but their effects depended on rock content and depth. Moisture slowed heating in bare soil (Figure 3.5a,b, bare) and in covered rocky soil, but had no effect in covered rock-free soil (Figure 3.5a,b, cover). Rock fragment cover likewise only slowed heating in dry soil (Figure 3.5a), and in rocky moist soil (Figure 3.5b). Rock fragment content had contrasting effects: while it slowed heating in bare dry soil and covered moist soil (Figure 3.5a, bare; Figure 3.5b, cover), it increased the heating rate in covered dry soil (Figure 3.5a, cover). Effects of moisture, rock fragment cover and rock fragment content were all depth-dependent. The effects of rock cover were most pronounced near the soil surface (Figure 3.5c-f), in dry soil (Figure 3.5c-d) and in rock-free soil (Figure 3.5e-f). The effect of rock content was however only apparent at the surface of dry soil (Figure 3.5g-h).
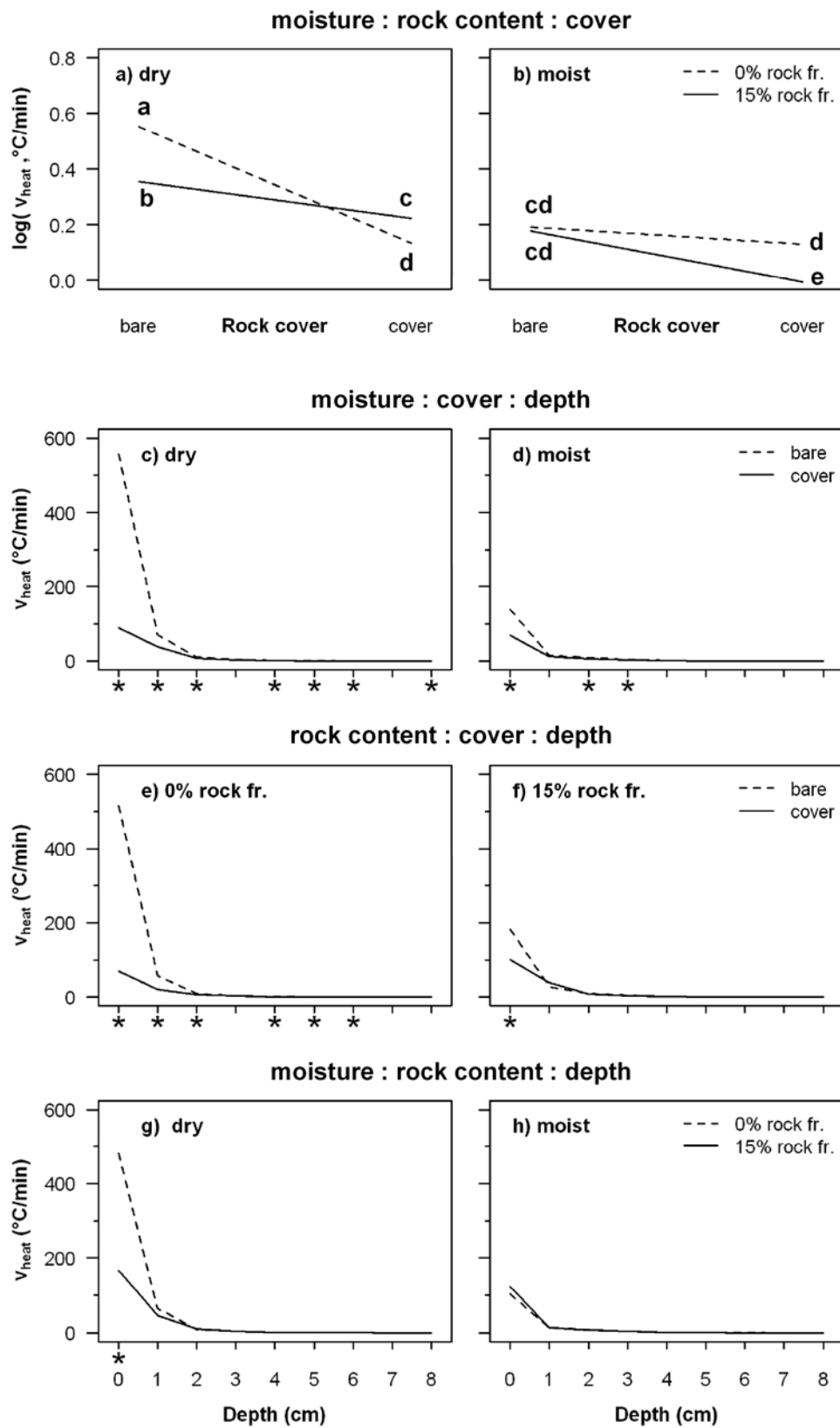
Figure 3.5 Heating velocity (v_{heat}): four 3-way interactions here illustrated using 2-way interaction plots. Values are averages over the treatments (n=12). Different lower case letters within a 3-way interaction indicate significant differences at $p < 0.05$ (in figures a,b), while asterisks indicate significant differences between the treatments at the given depth (in figures c-h).

Examination of the results for cooling velocity revealed a significant 4-way interaction (p=0.001), which showed that effects of soil moisture, rock cover and rock content were interrelated and depth-dependent. Differences in cooling velocity were most pronounced at or near the soil surface (Figure 3.6). A complete rock cover impeded cooling at the very soil surface, regardless of soil moisture or rock content. While it also impeded cooling down to 3 cm deep in moist rocky soil, it had no deeper effects in other treatments. Likewise, soil moisture impeded cooling at the soil surface of bare soil and from 1 to 3 cm deep in moist soil, while rock fragment content only impeded cooling at the surface of dry bare soil.
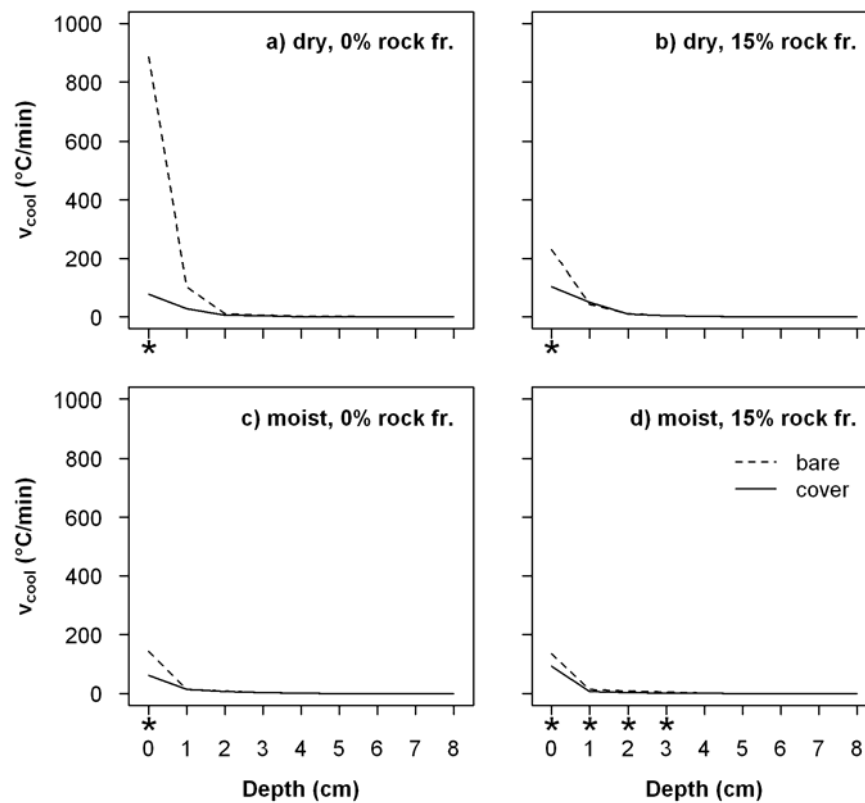
Figure 3.6 Cooling velocity (v_{cool}): four-way interaction (soil moisture : rock cover : rock content : depth) illustrated as the interaction of rock fragment cover with each combination of soil moisture and rock fragment content. Values are averages over the treatments (n=12). Asterisks indicate significant differences (at p<0.05) between the treatments at the given depth.

3.3.4 Duration of heating above threshold temperatures

Soil temperatures during this 5-min burn exceeded 60°C at various depths. Nearly all treatments exceeded this lethal threshold from 0 to 2 cm, and soil temperature did not reach 60°C at depths below 4 cm. Effects of soil moisture and rock cover were significant

at 3 cm depth, where the probability of exceeding the threshold was significantly higher for dry or bare soil than for moist or rock-covered soil (Table 3.2). In contrast, rock fragment content had no significant effects.

175°C was only exceeded at shallow depths: at the very soil surface, all treatments exceeded this threshold, and at 1 and 2 cm depth only some did. Significant effects were only visible for soil moisture at 1 cm depth: only dry soil reached this threshold whereas moist soil did not.

Table 3.2 Heating above threshold temperatures: probability of and treatment effects on exceeding the given threshold temperature T. Asterisks indicate significant differences between treatments at p < 0.05.

Depth (cm)	Exceedance probability (%)	
	T>60°C	T>175°C
0	100	100
1	100	41*†
2	90	5
3	30*†‡	0
4	10	0
5 to 8	0	0

† Exceedance probability dry > moist soil (only dry soil reached threshold); ‡ Exceedance probability bare > rock covered soil.

Treatment effects on the duration of heating were also more pronounced for the 60°C than the 175°C threshold (Figure 3.7). For 60°C, soil moisture significantly reduced the duration of lethal temperatures from the soil surface down to 2 cm, in contrast to rock fragment cover that significantly increased the duration of lethal temperatures at the soil surface. Rock fragment content on the other hand significantly decreased heating durations at 1 to 2 cm depths, but only in dry soil and bare dry soil, respectively. For the duration of heating above 175°C, only soil moisture had significant effects: at the soil surface, dry soil exceeded this temperature significantly longer than moist soil.
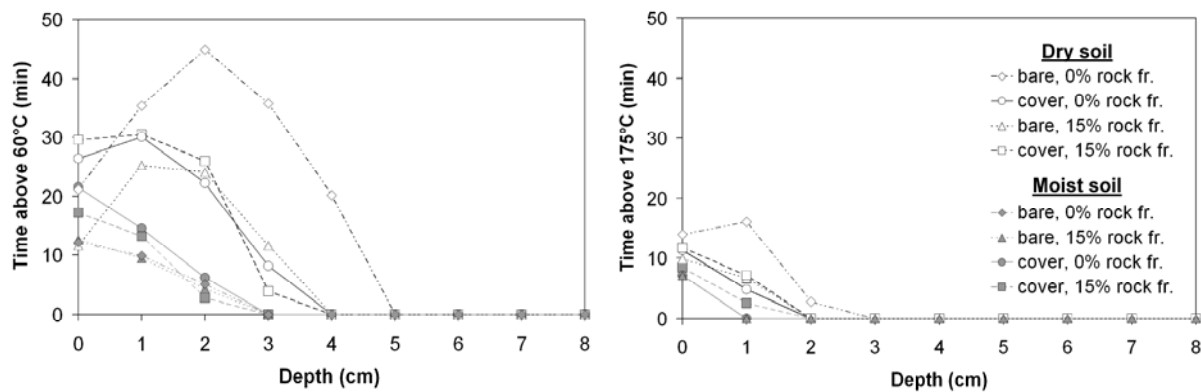
Figure 3.7 Duration of heating above 60°C (left) and 175°C (right). Bold lines show values for dry soil, dashed lines for moist soil.

3.4 Discussion

3.4.1 Effect of moisture

Soil water content greatly influenced soil heating during burning. Heating rate in soils approaching 100°C first decreased, likely due to water evaporation. The following increase in heating rate may be explained by the subsequent drying of the soil (Campbell et al., 1995). Despite the lower thermal diffusivity of dry soil (Table 3.1), dry soil heated up faster than moist soil. This could be due to the fact that moist soil quickly transports heat downwards, and that water evaporation will not allow moist soil to exceed 95°C, causing moist soils to rarely exceed 100°C (Campbell et al., 1995).

The lower maximum temperature with higher soil moisture (Figure 3.3) may be explained by the higher heat capacity of moist soil (Table 3.1), which has also been observed by others (Beadle, 1940; Busse et al., 2010; Busse et al., 2005; Mehuys et al., 1975; Valette et al., 1994). The corresponding decreased depth and duration of moderate heating (60°C), also reported by Busse et al. (2010), and intense heating (175°C) imply that associated risks of physical, chemical and biological degradation due to fire are lower in moist soil and highest when the soil is dry. Because of the steep temperature gradients with depth, these risks decrease sharply with depth. In dry soil however, the duration of moderate soil heating (< 60°C) was highest slightly below the surface (Figure 3.7), which may be explained by the high cooling velocity at the surface (Figure 3.6). This does however not necessarily mean that overall fire effects at the surface are also reduced, because the duration of intense heating in dry soil remains highest at the surface, and fire-induced changes in belowground ecosystem functioning are likely the result of an interaction of physical, chemical and biological changes.

3.4.2 Effect of surface rock cover

During the short burning period, surface rock fragments acted as a heat sink, reducing heating velocity and peak temperatures of especially the surface soil. During the long cooling phase however, the rock fragments acted as a heat source, preventing surface soil from cooling (Figure 3.6), thereby prolonging the duration of lethal temperatures at the surface (Table 3.2, Figure 3.7). Huey et al. (1989) observed a similar heat source/sink effect of surface rock fragments in a desert climate, and found this effect to be larger for thicker rock fragments. The reduction in heating rate and maximum temperatures corresponds with a study by Mehuys et al. (1975), who found a similar decrease in soil heating during the first hours of a prolonged heating period.

The effect of a rock cover was much more pronounced in dry than in moist soil (Figure 3.3a, 3.4c-d), which may be explained by the amount of heat rock fragments can store and release to the soil during burning. Surface temperatures underneath a rock cover were lower in moist soil than in dry soil (data not shown). However, we also found that rock-covered moist soil cooled down more slowly than rock-covered dry soil (Figure 3.6a vs. 3.6c and 3.6b vs. 3.6d), which may be explained by the rock cover overlying moist soil retaining more heat. The thermal gradient in the rock cover was consequently steepest when overlying moist soil. Because of this, exposure of the soil surface by thermal fragmentation of rock fragments such as observed during burning of two columns (see Section 3.2.3) may be most common for wetter soils. In the field however, this will likely also depend on factors like rock fragment size and fire characteristics, such as flame temperature, duration, and residence time.

The data suggest that by reducing soil heating (Figure 3.3), a rock fragment cover may prevent physical and chemical degradation, which can be beneficial for the resilience of rocky soils to fire. This is an important point, especially given the already degraded nature of many of these soils. Rock cover effects on biological degradation may however be depth-dependent. By decreasing the depth of lethal temperatures (Table 3.2), a rock cover may prevent biological degradation below the soil surface, but by preventing the soil from cooling and therefore increasing the duration of lethal heating, it may on the contrary increase biological degradation at the soil surface. Despite the role that rock fragments can play in preventing fire-induced physical and chemical degradation (this study) and frost damage (Li, 2003), thermal impacts of rock fragment cover may therefore not always be positive for the very shallow soil biological system.

3.4.3 Effect of rock fragments incorporated into the soil

The change in soil thermal properties with incorporated rock fragments observed in this study corresponds with findings reported by Childs and Flint (1990). Overall, incorporated rock fragments only slightly increased thermal conductivity, but because total water content remained the same (and fine earth water content therefore increased from 0.193 to 0.227 cm^3/cm^3), they increased heat capacity (Table 3.1). Thermal properties of soils containing rock fragments are however very heterogeneous.

In dry soil, rock fragments may create pockets of high conductivity and heat capacity within a matrix of lower conductivity and heat capacity, whereas in moist soil, the opposite is true. Thermal propagation in rocky soil is therefore highly dependent on soil moisture, and may be considerably influenced by the spatial distribution of rock fragments in the soil matrix, as well as by the depth and size of the rock fragments. This may explain the contradictory effects of rock content on soil heating that were found in the present and other studies.

The observed reduction in soil heating or lack of effects of rock fragments corresponds with studies by Childs and Flint (1990) and Mehuys et al (1975). Saini and MacLean (1967), however, found increased soil heating with rock fragments. In the present study, rock fragments reduced peak temperatures in bare soil, and reduced the duration of heating above 60°C in dry and/or bare soil. Results imply that fire impact on soils containing rock fragments may be highly dependent on soil moisture and the presence of surface rock fragments, and suggest that rock fragments can reduce fire impact in dry soil without a rock cover.

In these laboratory experiments, soil heating was far more affected by soil moisture than by rock fragment cover or content. The effect of rock fragments however may be considerably more pronounced in the field, because of the interaction between rock fragments and fine earth soil water content and distribution (Katra et al., 2008; Mehuys et al., 1975).

3.4.4 Implications for soil heating in field and model situations

The effect of rock fragments on soil heating during fire is complex, especially when rock fragments are incorporated into the soil. Because rock fragments may act as heat sinks and sources, heat flow in rocky soil cannot be simply regarded as one-dimensional. This has important implications for models of soil heat flow during fire (e.g. Campbell et al., 1995; Choczynska and Johnson, 2009), which currently do not take rock fragments into account. In this study, rock fragments had considerable impact on fire-induced soil temperatures in an organic matter rich sandy loam commonly found in a region that is

much affected by forest fires. Results suggest that the impact of rock fragments is related to their location in the soil profile (incorporated, or on the surface), varies with soil moisture content, and is most pronounced in the topsoil.

Since soil texture and organic matter have been found to only nominally affect the maximum temperature or heat duration during burning (Busse et al., 2010), results may be applicable to a much wider range of soil types. Soil heating during fire is however likely to be affected by the distribution of rock fragments in and on the soil, as well as by their size. Impacts may be more pronounced closer to rock fragments, or near larger rock fragments.

In addition, the effect of surface rock cover is likely to decrease with decreasing cover, or increase with increasing thickness. Variation in the distribution of rock fragments in and on the soil may therefore cause variability in fire effects in and on the soil, in addition to the already existing variability of fire and soil characteristics. Flame contact and fire residence time will play a large role in determining soil heating and thus fire effects. So will pore size distribution, because of its considerable impacts on soil heating during fire (Busse et al., 2010). This highlights the need for further field research on soil heating during fire and its physical, chemical and biological impact in rocky soils.

3.4.5 Implications for belowground fire impact and controlled fire strategy

The findings presented here contribute to a better understanding of the belowground impact of both wildfires (when the soil is generally dry) and controlled fires (when the soil can be either dry or moist, depending on the fire season). Controlled fires are increasingly performed in many regions around the world, as a tool to reduce wildfire hazard, rejuvenate landscapes and/or restore native vegetation (Fernandes and Botelho, 2003; Ferreira et al., 2009; Van Lear and Waldrop, 1991). Because of lower fire intensity, the impact of controlled fires is generally much lower than that of wildfires (Ferreira et al., 2009). This has been attributed to the fact that controlled fires are generally performed when air temperature is lower, relative humidity is higher, and fuel and litter are moister than during wildfires (Collins et al., 2007). Results of the present study are consistent with previous research (Busse et al., 2005; Valette et al., 1994) that suggests that an additional explanation may be that higher soil moisture reduces soil heating. Because of this, dry season fires may also have a larger and deeper impact on the soil system than wet season fires (Table 3.3). The considerable effect of soil moisture on soil heating observed in this study may also provide an explanation for the strongly varying impact of controlled fires reported in the literature, ranging from negligible to substantial effects (Arkle and Pilliod, 2010; Carter and Darwin Foster, 2004).

Our results furthermore highlight the importance of rock fragments in determining fire impact, and suggest that their effect may also vary with soil moisture content (Figure 3.3) and therefore with fire season. The slow response of soil temperatures to soil heating, especially at greater depths, may give soil fauna time to escape a fire by moving deeper into the soil. Moreover, the data suggest that even heat-sensitive organisms may survive a fire when located a few cm below the soil surface (more than 3 to 5 cm under the studied conditions), depending on soil moisture content and the presence of rock fragments (Table 3.2). When minimal fire impact on the soil system is desired, soil heating should be kept to a minimum, and controlled fires are best performed when the soil is moist or in places where rock fragment content is small (Table 3.3).

Table 3.3 Summarized results: effect of soil moisture and rock fragment cover and content on soil temperatures and possible belowground fire impact. Pronounced heating is indicated with an increased number of +, limited heating with increasing number of -

Treatment	Dry soil				Moist soil			
Rock cover (%)	0		100		0		100	
Rock content (%)	0	15	0	15	0	15	0	15
Expected soil heating	++++	+++	+	+	-	-	--	--

In some regions, however, controlled fires are performed with specific intent to break seed dormancy of fire-responsive species (Penman and Towerton, 2008). The goal of these fires is therefore to reach relatively high soil temperatures, despite associated risks for the soil system. The present study suggests that these management burns should ideally be planned in areas with rock-free soils, and be performed when soils are dry. This can for instance be the case in the late dry season or early wet season. When safe burning possibilities are restricted to periods in which soils are moist, soil heating will be considerably less and restricted to the soil surface (Table 3.2, Figure 3.3, 3.7). Currently, neither soil moisture nor rock fragments are key factors in controlled fire decision making (Fernandes and Loureiro, 2010). The current experiments however suggest that they can have significant effects on soil heating, and may therefore considerably influence the outcome of controlled fires in which soil heating is desired or should be avoided.

3.5 Conclusions

- Incorporated rock fragments significantly increased heat capacity but did not affect thermal conductivity. Water had a more pronounced effect, and significantly increased both heat capacity and thermal conductivity.

- A soil moisture increase from 0.022 to 0.193 cm^3/cm^3 significantly reduced maximum soil temperatures, as well as the depth and duration of heating. Effects declined with depth.

- A 100% surface rock fragment cover significantly reduced peak temperatures in dry and moist soil, and in soil without incorporated rock fragments. Effects declined with depth. Rock cover decreased the depth at which 60°C was exceeded, but because it prevented the soil from cooling, it also increased the duration of heating above 60° at the soil surface.

- The effect of incorporated rock fragments on soil heating was highly dependent on soil moisture and rock cover. While they did not significantly alter peak temperatures, incorporated rock fragments did reduce the duration of heating > 60°C below the surface of dry (bare) soil.

- The data suggest that belowground fire impact depends on soil moisture content and the presence of rock fragments in and on the soil.

- Soil moisture and rock fragments should be considered in controlled fire decision making, to achieve defined goals.

4 Catchment scale experimental fire: hot fire, cool soil

Abstract

Worldwide, vegetation fires affect hundreds of millions of hectares annually causing economic and ecological havoc. Soil temperature is a key factor determining fire damage to soils and risk of post-fire degradation. However soil temperature dynamics during fire remain poorly understood. Our study of a 9-ha experimental fire reveals that soils can stay surprisingly cool where fire is hot, and be hot where they are expected to be cooler. This suggests that the greatest fire damage to the soil does not necessarily occur where fuel load and fire intensity are highest, which has important implications for management of fire-prone areas.

4.1   Introduction

Worldwide, vegetation fires burn an average of 3.7 million km^2 annually (Giglio et al., 2010), causing ecological and economical havoc in an area nearly the size of the entire European Union. Although fire responds predictably to vegetation characteristics, topography and weather conditions at the landscape scale (Bowman et al., 2009), effects on soil temperatures remain poorly understood. Fire damage to soil is known to increase with increasing soil temperature (Cerdà and Robichaud, 2009; Chapter 2) and, based on plot experiments, it is currently understood that soil temperatures increase with increasing fuel load and fire intensity (Gimeno-Garcia et al., 2004b; Molina and Llinares, 2001a). However, recent data from the more complex landscape scale do not support this theory. For instance, the extreme 2009 wildfires in Australia (Doerr et al., 2010) had relatively little impact on the soil. Here, we present the results of a catchment-scale experimental fire in which we studied the spatial pattern of soil temperatures in relation to fuel load and fire intensity, in order to reveal the drivers of soil heating at the landscape scale.

4.2   Methods

4.2.1 Study area

In Portugal, a country facing severe problems with fires and post-fire land degradation, we intentionally burned a shrubland catchment (40°06′21″N, 8°07′03″W; Figure 4.1a). The area's climate is Atlantic-Mediterranean with an annual precipitation of 1050 mm, and soils and vegetation are typical for the region. Soils are shallow (Figure 4.1b), developed from schist and quartzite, and covered by dense heathland dominated by *Erica* spp. and *Pterospartum tridentatum* (81±18% cover).

4.2.2 Fuel mapping

We gathered spatially explicit data on fuel (Figure 4.2a): we intensively surveyed the area in 2007 and measured vegetation height (n=266) and soil depth (n=283) using 5 replicates per site. In November 2008, we determined the fuel load of six 1-m^2 plots by harvesting and weighing the vegetation and calculating the dry weight of the whole sample from three oven-dried subsamples (80°C, 24h). Given their strong correlation (r=0.96, Eq. 4.1), we used vegetation height as a proxy for fuel load to create a catchment-scale fuel load map.

FL = 61.3 * h − 3.9   (4.1)

where FL= fuel load (t/ha) and h = vegetation height (m).
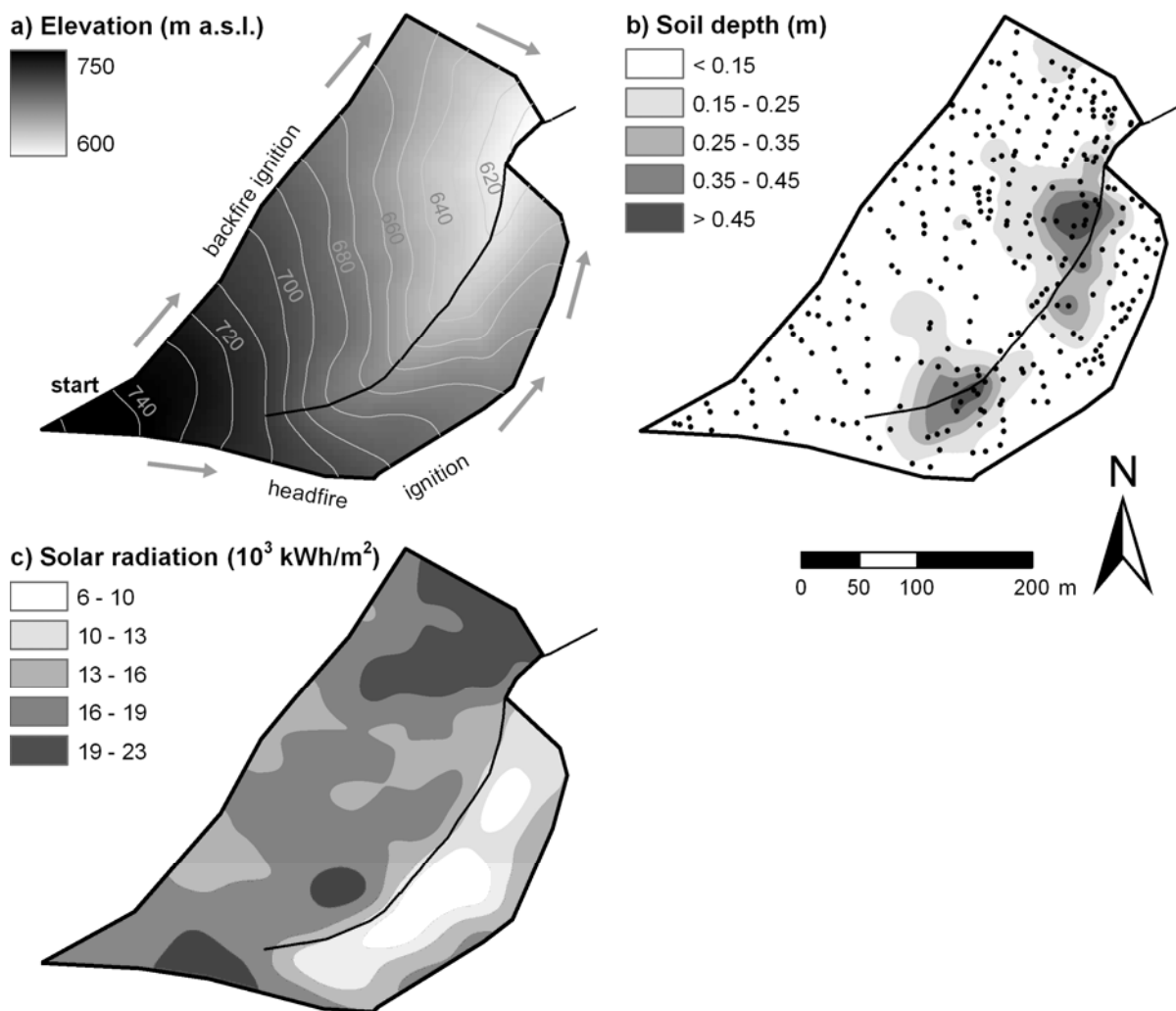
Figure 4.1 Valtorto catchment elevation, fire ignition pattern (a), soil depth (b) and solar radiation (c). Soil depth was defined as the depth of mineral soil to (bed)rock determined using a 0.6-m long probe, and was positively correlated to vegetation height (r = 0.58), indicating that the shallower, more degraded soils were characterized by shorter vegetation and lower fuel loads than the deeper soils. Solar radiation was calculated from geographical position and terrain attributes using ArcGIS.

4.2.3 Experimental fire

We burned the area after a 10-d dry period on the morning of 20 February 2009, when mean air temperature was 14.2°C, relative humidity 33%, wind direction N–NW, and wind speed 6.1 m/s with gusts up to 9.7 m/s. Soil moisture content (0-2.5 cm depth) was 0.28 ± 0.06 cm^3/cm^3, and solar radiation for the 10-d dry period preceding the fire is given in Figure 4.1c. We used a combination of back- and headfiring techniques (Figure 4.1a) to maximize convection and to reach the maximum potential fire intensity under the prevailing weather conditions, which indicated low to moderate fire danger according to the Canadian Fire Weather Index (Van Wagner, 1987).
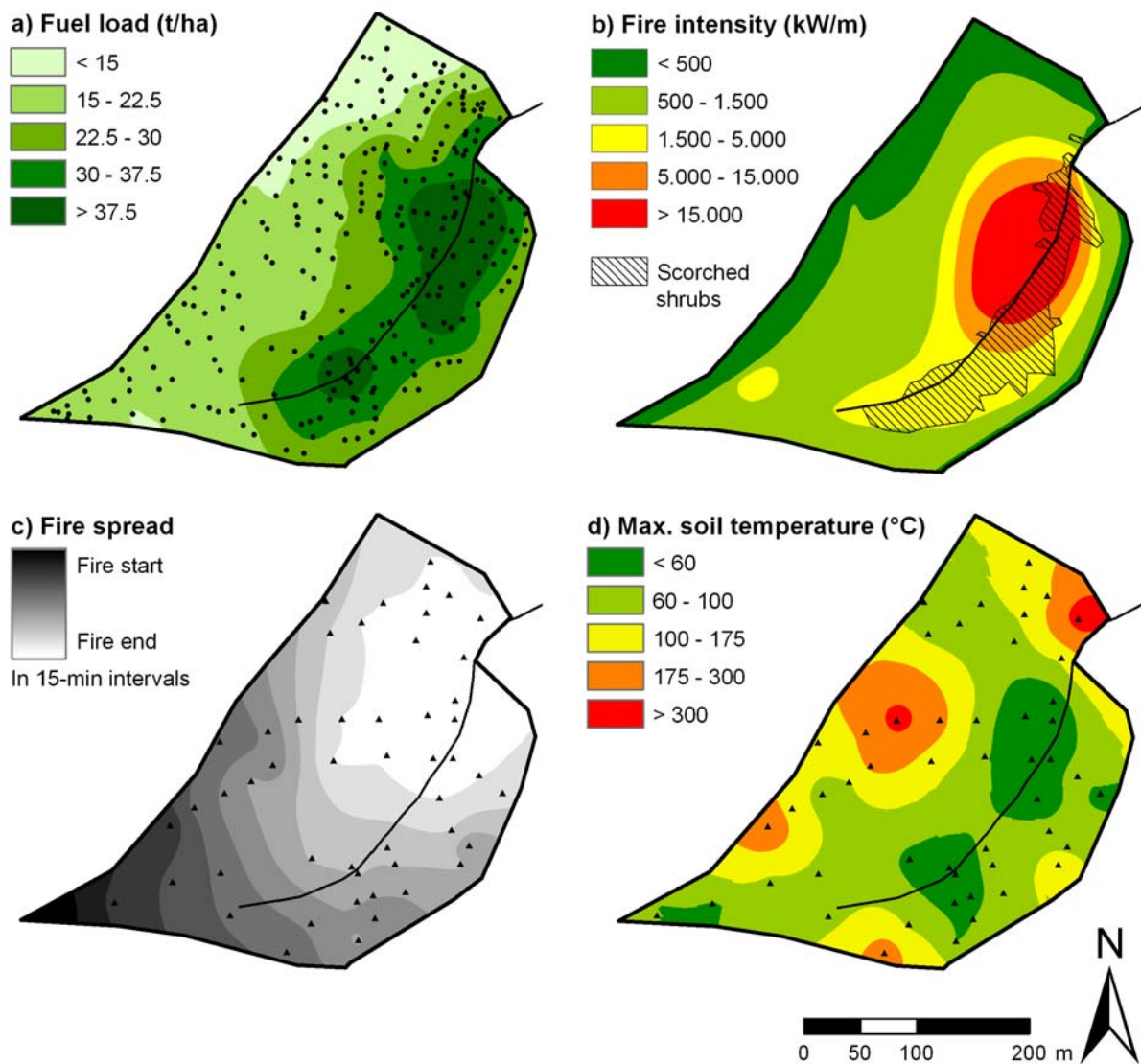
Figure 4.2 Fire and fuel characteristics in the Valtorto catchment. High fuel load (a) and fire intensity (b) were associated with rapid fire spread (c) and cool soils (d). In contrast, hotter soils were associated with low fuel load and fire intensity and slower fire spread.

Figure 4.3 Experimental fire in the top of the catchment (a) and during the high intensity fire at the valley bottom (b). Photo © Diederik van der Laan.

During the early stages of the fire (Figure 4.3a), we measured flame temperatures on the southern flank of the catchment (n=226) using a handheld infrared pyrometer (Omegascope OS534E, Omega Engineering, USA). For safety reasons, flame temperatures were not measured during the final stage of the fire (Figure 4.3b). Furthermore, we measured soil surface temperatures every 2 s at 51 sites using K-type thermocouples (Ø 1.5 mm, TC-direct, The Netherlands) connected to data loggers (EL-USB-TC, Lascar Electronics, UK) installed the day before the fire, and used the timing of maximum temperature to create a map of fire spread. Finally, we estimated fire intensity from flame lengths using an empirical relationship derived for similar vegetation in NW-Spain (Vega et al., 1998), for which we estimated flame lengths in the field and from 20 photo and film snapshots.

4.3   Results and discussion

Flame temperatures were 736 ± 126°C and fire intensity ranged from < 500 (low) to > 15.000 kW/m (extreme) (Figure 4.2b). Fire spread was particularly rapid in the valley bottom (Figure 4.2c), where 25% of the area burned in just 10% of the time. Shrubs were completely consumed except in parts of the valley and northwest-facing slope (Figure 4.2a) because these sites received less solar radiation (Figure 4.1c) and were therefore initially moister. During the fire, maximum soil temperature was locally as high as 800°C while in most of the catchment temperatures remained below 100°C (Figure 4.2d).

Spatial analysis showed that soil temperatures (Figure 4.2d) were inversely related to fuel load and fire intensity. Surprisingly, the highest soil temperatures did not occur where fuel load or fire intensity were highest, but were instead concentrated where fire intensity and fuel load were low. By contrast, where fuel load and fire intensity were highest, soil temperatures were unexpectedly low. Contrary to common findings, this shows that soil temperatures do not necessarily increase with increasing fuel load and fire intensity.

The inverse relationship between soil temperature, fuel load and fire intensity may result from a combination of:

- Reduced downward heat transfer at places with high fire intensity because the large air temperature gradients increased upward heat movement (Figure 4.2b),
- Variation in fire spread rate, causing limited flame residence time in areas where fire spread was rapid and fire intensity was high (Figure 4.2d), and
- Spatial variation in fuel moisture caused by differences in solar radiation (Figure 4.1c) and vegetation characteristics (Figure 4.2a, whereby lush areas with higher fuel loads

were moister and less prone to high soil temperatures than more sparsely vegetated and degraded areas that dried out more quickly. Since spatial variation in fuel moisture can even exist during droughts (Fernandes et al., 2010), this is also relevant in summer.

Our results have important implications for understanding and managing ecosystem resilience of fire-prone areas. Lush areas where soils can stay cool are not necessarily at greatest risk for fire-induced degradation, while more sparsely vegetated areas are at higher risk than previously thought. Therefore, the resulting spatial variation in fire damage and recovery potential can magnify already existing differences in degradation and ecosystem resilience across landscapes. To mitigate ecological and economical damage during and after fires, areas with sparse vegetation should receive specific attention during prescribed burns and wildfire suppression operations – and the same areas should be included in post-fire restoration strategies.

5   Fire-induced soil and surface changes

Abstract

Post-fire land degradation is to a large degree determined by what happens to soil properties and soil cover during and after the fire. To study fire impact in relation to fire intensity and post-fire soil exposure, a small Portuguese shrubland catchment was burned by experimental fire in the 2008/9 winter season. Despite the high fire intensity, soil burn severity was low: topsoil bulk density, organic matter, porosity, saturated conductivity and moisture did not significantly change. The occurrence of soil water repellency however increased, even though soil temperature stayed low at most sampled sites (median 60°C). Soil surface characteristics also changed: Manning's n and random roughness both decreased, increasing the risk and erosivity of overland flow. Results indicate that a high-intensity winter burn does not necessarily lead to severe soil changes. Nevertheless, the development of soil water repellency as well as soil surface changes during and after fire may increase runoff and erosion risk in these areas.

5.1   Introduction

In areas burned by wildfire, erosion and flooding events can pose a great threat to human lives and property. These events can lead to severe degradation of the burned hill slopes with further negative impact on natural resources, including short- to long-term threats to water quality and drinking water supply downstream of the areas affected by the fire (Shakesby and Doerr, 2006). Post-fire land degradation risk is to a large degree determined by what happens to soil properties and soil cover during and after the fire. However, since fire impact on the soil is not easily predicted, better understanding of the relation between fire intensity, soil changes and post-fire soil exposure can improve assessment of degradation risk after wildfires and contribute to evaluating the sustainability of prescribed fires.

Fire changes a landscape's vulnerability to runoff and erosion by changing soil properties governing water flow and soil stability, and by removing ground cover. The direct effects of fire on soils are caused by the heat of the fire that changes soil properties. These effects range from consumption of soil organic matter and an associated loss of water retention properties (Chapter 2), to increased bulk density, decreased infiltration capacity (Martin and Moody, 2001) and a change in aggregate stability (García-Corona et al., 2004). Another direct effect of fire is the development of soil water repellency (DeBano, 2000a), which hinders infiltration of water into the soil. Indirect fire effects result from both the removal of vegetation and litter cover and the post-fire soil exposure, rather than from soil heating alone. Since soil cover plays an important role in surface storage of rainfall and protects the soil from large raindrop impact, removal of vegetation and litter increases the risk and erodible force of overland flow (Andreu et al., 1998), as well as the soil's vulnerability to rainsplash erosion (Mati, 1994).

The various impacts of fire on the soil system are highly related to the degree and the duration of soil heating (Beadle, 1940; García-Corona et al., 2004; Tozer and Auld, 2006, Chapter 2). This is in turn largely determined by fire and soil characteristics (Abu-Hamdeh and Reeder, 2000; Massman et al., 2008; Van Wijk, 1963; Chapter 3). Fire impact on the soil is however not always easily estimated based on fire behavior alone (Doerr et al., 2010; Hartford and Frandsen, 1992). Better understanding of the relation between fire intensity, soil changes and the processes behind post-fire land degradation can therefore facilitate prediction of erosion risk after wildfires and prescribed fires.

In one of the first studies that assess fire impact at the catchment scale, a Portuguese mountain catchment was burned by experimental fire in the 2008/9 winter season after a detailed survey of soil, surface and vegetation properties. Soil temperatures were

monitored during the fire, impacts on the soil system were determined, and effects on hydrological and erosion processes were assessed. The present paper evaluates the effect of the fire on soil and surface properties, and discusses the importance of soil surface changes when assessing post-fire erosion risk.
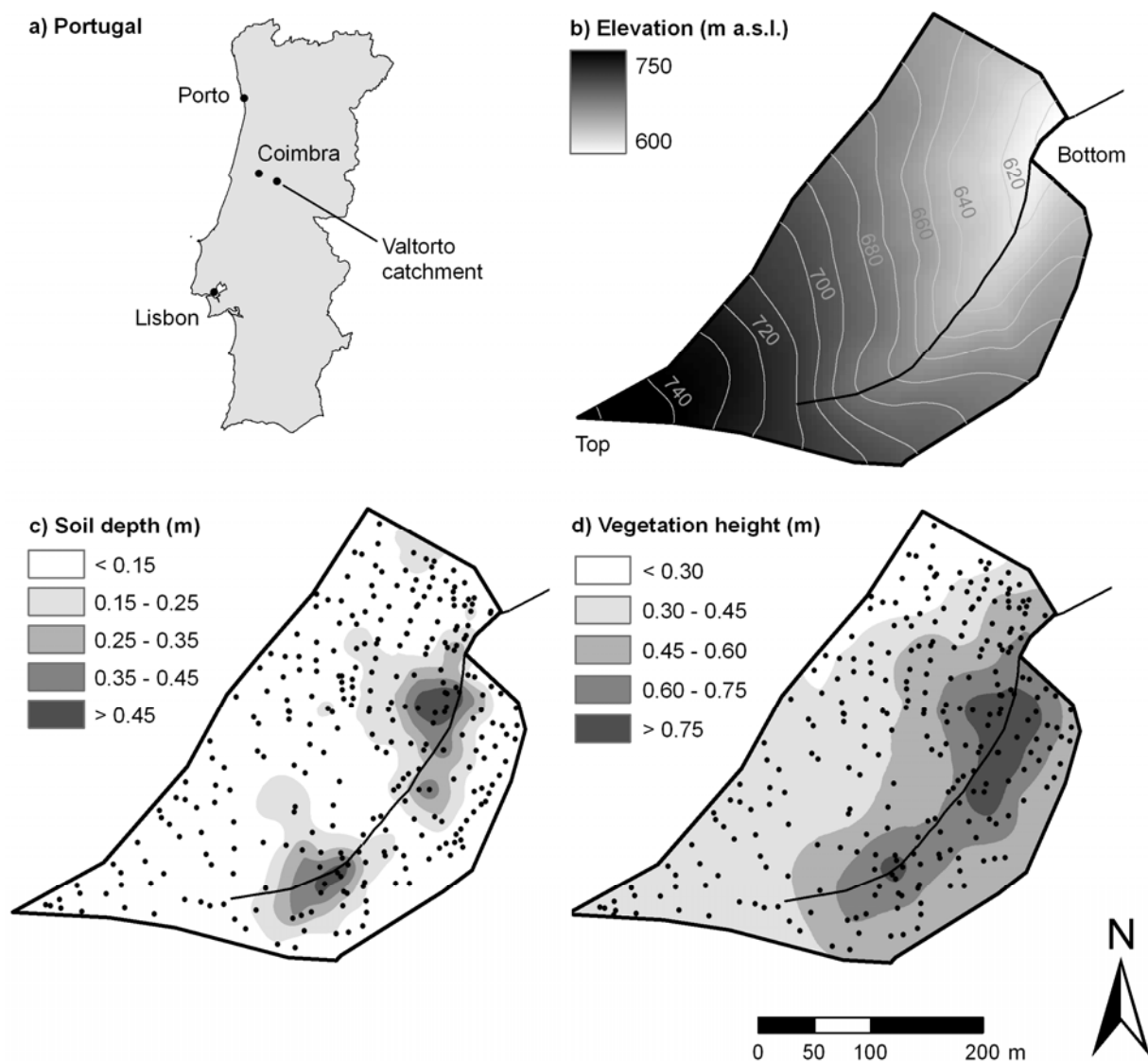
Figure 5.1 Valtorto catchment: a) map of Portugal showing its location, approximately 50 km southeast of Coimbra, b) elevation map with 10-m contour lines, c) soil depth and d) vegetation height as mapped in 2007. In figures c and d, sampling locations are indicated by black dots, and the black line dissecting the catchment represents the ephemeral stream.

5.2 Methods

5.2.1 Study area

The research area is the Valtorto catchment in north-central Portugal (Figure 5.1, Table 5.1) located near the village of Vale Torto (Góis, Coimbra). The climate in the region is Atlantic-Mediterranean, characterized by wet winters and dry summers with high wildfire risk. Soils and vegetation in the catchment (Figure 5.1, Table 5.1) are typical for the region. Soils are shallow, stony, rich in organic matter and developed from schist and quartzite. Prior to the fire, the vegetation consisted of dense shrubs regenerated after a prescribed fire in April 1996. It was dominated by heaths and heathers (Ericacea) such as *Erica umbellata, E. cinerea* and *Calluna vulgaris*, and several legumes (Leguminosae) such as gorse (*Ulex* sp.), "carqueja" (*Pterospartum tridentatum*) and broom (*Genista triacanthus*). In addition, grasses dominated by Poaceae such as *Brachypodium* sp., *Agrostis* sp. and *Dactylis* sp. were found in places where the shrub cover was less dense, a few small pine trees (*Pinus pinaster*) were found on the slopes, and bracken (*Pteridium aquilinum*) was found in the valley bottom.

Table 5.1 Valtorto catchment characteristics

Parameter	Value
Location	40°06′21″ N, 8°07′03″ W
Mean annual precipitation (mm)	1050
Mean monthly temperature (°C)	7.8 (Dec); 20 (Aug)
Elevation (m a.s.l.)	650-700
Size of burn (ha)	9
Slope (%)	38 ± 16
Soil depth (m)	0.16 ± 0.14
Soil texture †‡	gravelly loamy sand
Soil organic matter (weight%) †	21.0 ± 5.2
Rock fragment content (cm^3/cm^3) §	0.16 ± 0.06
Rock fragment cover (%)	56 ± 26
Pre-fire litter depth (cm)	0.5 – 5.0
Pre-fire fuel load (t/ha)	12.9 - 59.0
Pre-fire vegetation height (m)	0.50 ± 0.26
Pre-fire vegetation cover (%)	81 ± 18
1yr-post-fire vegetation cover (%) ¶	30

† 0 to 2.5 cm depth; ‡ according to USDA classification (USDA, 1993); § 0.44 ± 0.12 g/g by weight; ¶ Shakesby et al. (2010)

Table 5.2 (Hydro)meteorological conditions in the catchment and Canadian Fire Weather Index (FWI) codes for the day of the fire. FWI codes are given for the nearest weather stations Lousã (~11 km W) and Pampilhosa da Serra (~15 km SE); the difference in fire danger class was largely caused by differences in wind speed

Parameter	Value	
Air temperature (°C)	9.7 – 18.7	
Relative humidity (%)	31 – 34	
Wind speed (m/s)	4.7 – 7.5, gusts up to 9.7	
Wind direction	N – NW	
Moisture content of dead fine fuel (%) †	13	
Soil moisture (cm^3/cm^3)	0.28 ± 0.06	
FWI code ‡	**Lousã**	**Pampilhosa da Serra**
Fine Fuel Moisture Code (FFMC)	84.1	88.6
Duff Moisture Code (DMC)	8.6	11.2
Drought Code (DC)	20.1	20.8
Initial Spread Index (ISI)	2.2	8.7
Buildup Index (BUI)	8.5	11
Fire Weather Index (FWI)	1.7	9.5
Fire danger class	Low	Moderate

† Estimated following Fernandes et al. (2002); ‡ Van Wagner (1987)

Figure 5.2 Experimental fire in the top of the catchment (a) and during the high intensity fire at the valley bottom (b). Photo © Diederik van der Laan.

5.2.2 Experimental fire and effects on soil erosion

The area was burned ten days after the last rainfall on the morning of 20 February 2009 (Figure 5.2, Table 5.2). The aim was to simulate a wildfire as closely as possible, within safety constraints. Consequently, this experimental fire was different from the low-intensity prescribed fires commonly performed in this region. Ring ignition was used to

maximize convection and to reach the maximum potential fire intensity under the prevailing weather conditions, which indicated low to moderate fire danger (Table 5.2). No post-frontal flaming combustion was observed, which indicated that flame residence time was low.

The fire varied spatially in intensity: it was similar in nature to a prescribed fire on the mid- to upper slopes of the catchment (fireline intensity < 1.500 kW/m) but reached a much higher intensity on the valley bottom (> 15.000 kW/m). Surprisingly, soil surface temperatures did not increase with fire intensity, and remained below 100°C in most of the catchment (Chapter 4). This was partly due to fuels and soils still being relatively moist. However, soil temperature was locally as high as 840°C. Soil heating was shallow and confined to the very surface: below 0.5 cm, soil temperatures all remained below 60°C and the vast majority (98%) remained below 30°C (Figure 5.3).

Pre- and post-fire monitoring of 'silt fences' or sediment traps showed that the fire markedly increased soil erosion rates during the first post-fire year. Though not as severe as after wildfire, the experimental fire increased soil erosion by 1-2 orders of magnitude from < 0.028 t/ha before the fire to 0.04 - 0.39 t/ha in the year after (Shakesby et al., 2010b)
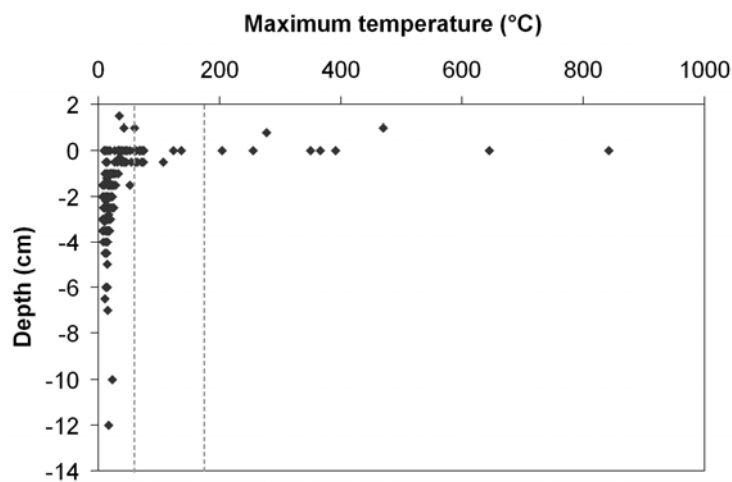
Figure 5.3 Maximum soil temperatures by depth, in which depth is given with respect to the soil surface (0 cm). Negative values are belowground, positive aboveground.

5.2.3 Assessment of soil burn severity and direct hydrological impact

Soil burn severity (e.g. Keeley, 2009) was determined based on the degree of direct changes to belowground soil properties, in particular those important for infiltration and water retention processes: soil bulk density (ρ_d), organic matter content (OM), saturated conductivity (K_{sat}) and porosity (φ) (García-Corona et al., 2004; Martin and Moody, 2001,

Chapter 2). Bulk density and OM were determined on 50 cm^3 soil cores taken at three depths, and K$_{sat}$ and φ were determined on 333 cm^3 topsoil cores according to Table 5.3.

Furthermore, the direct soil hydrological impact of the fire was assessed by evaluating changes in soil moisture and water repellency directly following the fire. At each site, 10 small bulk soil samples were taken (± 50 g), sealed in plastic bags, broken up, and analyzed the following day. After determining the field-moist weight, the occurrence of soil water repellency and the gravimetric soil moisture content were determined (Table 5.3). In all cases, sampling locations corresponded to the sites where soil temperature was monitored during the fire (Chapter 4, Figure 5.3).

Table 5.3 Overview of soil and surface properties analyzed and methods used

Depth	Parameter	Number of sites	Method
		Soil properties	
0-2.5, 3-5.5 6-8.5 cm †	Dry bulk density	42	Determined after oven drying ‡
	Organic matter content	42	Determined by Loss on Ignition (4 h, 550°C)
0-4 cm †	K$_{sat}$	42	Constant head method (Stolte, 1997) ¶
	Soil porosity	42	Calculated from soil volume and saturated and oven dry weight ‡
0-2.5 cm	Soil moisture content	10	Determined by oven drying ‡; 10 replicates per site
	Soil water repellency	10	Measured with the Water Drop Penetration Time (WDPT) test (Letey, 1969); 10 replicates per site
		Surface properties	
Surface	Manning's n	6	Determined following Hessel et al. (2003) on 2.5 m × 0.4 m plots with slope of 34.5 ± 4.1%, vegetation cover before 85% and after fire 0%, litter cover before 100% and after fire 95%. Infiltration was 83% and not affected by fire, and soil erosion was not observed, although the outflow of the burned plots was black because of char and ash. Three replicates per plot.
Surface	Random roughness	42	Measured using a pin-meter (Cremers et al., 1996) and analyzed with Pmpproj.exe (J. Kilpelainen, Finland)
0-3 cm	Soil shear strength	42	Measured using a torvane (Inspection Vane Tester H60, Eijkelkamp BV, The Netherlands)

† Undisturbed soil cores; ‡ 24 h at 105°C; ¶ To be able to start the measurements with saturated soil, all samples were treated with 96% ethanol to overcome any soil water repellency, washed with water five times (following Chapter 2), slowly saturated with water from below and then percolated with water for 45 min before analyses. Measurements were performed in a climate-controlled laboratory with air temperature between 16 and 17°C and relative humidity between 65 and 70%.

5.2.4 Assessment of soil surface changes

Finally, changes in soil surface characteristics were assessed, namely Manning's n for overland flow, random roughness and soil shear strength. These parameters are frequently used in spatially distributed runoff and erosion models (e.g. De Roo et al., 1996) as factors governing overland flow and soil erodibility. As such, they will be used to model runoff and erosion in burned areas.

Manning's n is a flow resistance parameter that is generally taken from the literature instead of measured in the field (e.g. Beeson et al., 2001). To our knowledge, this is therefore the first study to directly evaluate the effects of fire on Manning's n. Measurements were performed on 2.5 m long plots following Hessel et al. (2003) and consisted of determining the discharge, surface velocity and flow width, while water was constantly applied to the top of the plot (Table 5.3).

Random roughness is a measure of soil microrelief, and as such an important factor in determining surface water storage and overland flow (Govers et al., 2000). The temporal change in soil microrelief was evaluated using a pin-meter (Table 5.3) and random roughness was calculated as the standard error of the individual elevations.

The last surface characteristic analyzed, soil shear strength, is a measure for soil erodibility (Léonard and Richard, 2004). Changes in soil shear strength were determined using a handheld torvane (Table 5.3).

5.2.5 Sampling strategy and statistical analyses

Direct fire impact was assessed by revisiting pre-fire sampling sites within a few days after the fire, before the first post-fire rainfall. In cases where sampling was destructive, post-fire samples were taken as close to pre-fire sites as possible. Since soil moisture and soil water repellency are highly variable in time, sampling was done as shortly as possible before (1.5 d) and after (3 h) the fire. There were no reasons to assume that other soil and surface properties would significantly change between pre-fire sampling and the fire itself since this is a natural system where a dense vegetation cover exists throughout the year and grazing was absent before the fire. For practical reasons, pre-fire sampling of bulk density, soil organic matter, random roughness and Manning's n was therefore done a few months before the fire.

Effects of post-fire soil exposure were assessed by revisiting the sampling sites 7 months and/or 1 year after the fire to determine possible (further) changes in soil organic matter, bulk density, random roughness and shear strength. Unfortunately, it was not possible to monitor changes in Manning's n, K_{sat} and soil porosity during the year after the fire

because of the considerable logistics involved. In addition, the temporal variation in soil moisture and water repellency will be discussed in a separate paper.

All results were statistically analyzed using paired t-tests, in which K_{sat} was log-transformed before analysis and effects on soil moisture were evaluated using the mean values per site.

5.3 Results and discussion

5.3.1 Soil burn severity

The experimental fire did not significantly change soil bulk density or organic matter content at any of the depths considered, nor did these properties change significantly in the year after the fire (Table 5.4). Saturated hydraulic conductivity and soil porosity were not affected either (Table 5.4).

Table 5.4 Fire impact on soil properties: dry bulk density (ρ_d), organic matter content (OM), porosity (φ) and saturated hydraulic conductivity (K_{sat}), as measured before the fire (6, 7 Nov 2008), a few days after the fire (22,23 Feb 2009) and one year after the fire (19 Feb 2010). Fire effects or differences in time are not significant at any depth. Values are averages over the treatments (n=42), standard deviations are given between parentheses and 'n.d.' stands for 'not determined'. Note that even though samples were taken at the same locations, measurements of porosity and K_{sat} were performed on different samples than those used for determination of bulk density and organic matter content. Nevertheless, fire effects on bulk density and organic matter content of the K_{sat} and porosity samples were also not significant (data not shown)

| Sampling, depth	0-2.5 cm		3-5.5 cm		6-8.5 cm		0-4 cm	
	ρ_d (g/cm³)	OM (%)	ρ_d (g/cm³)	OM (%)	ρ_d (g/cm³)	OM (%)	φ (%)	K_{sat} (m/d)
Pre-fire	0.80 (0.14)	19.9 (3.8)	0.78 (0.13)	18.9 (3.4)	0.78 (0.12)	17.9 (3.2)	60.2 (4.4)	1.4 (0.7)
Post-fire (d)	0.80 (0.10)	20.6 (4.5)	0.79 (0.14)	19.3 (4.2)	0.80 (0.12)	20.6 (3.2)	59.7 (3.8)	1.9 (1.3)
Post-fire (1 yr)	0.77 (0.11)	20.9 (4.2)	0.79 (0.10)	19.5 (3.6)	0.79 (0.12)	18.5 (3.0)	n.d.	n.d.

Because the fire did not significantly change soil properties, soil burn severity was low. This can be explained by the fact that, despite the high fire intensity, soil temperatures in most of the catchment were not high enough to alter these soil properties. While the absence of fire effects at low temperatures is consistent with both field and laboratory studies (e.g. Badía and Martí, 2003; Hatten et al., 2005; Kutiel et al., 1995, Chapter 2), it is possible that the abovementioned soil properties may have changed locally where soil temperatures were higher in a very thin surface layer. However, the lack of replicates

per site, the thickness of the samples (2.5 and 4 cm) and the considerable small scale variability in soil properties prevented evaluation of these changes.

5.3.2 Direct hydrological impact

The fire significantly increased the occurrence of topsoil water repellency (p<0.001): while only 54% of the samples taken 1.5 d before the fire were water repellent, 97% of the samples taken 3 h after the fire were water repellent (Figure 5.4). This is striking, because soil surface temperatures remained very low at most of the sampled sites (median temperature 60.5°C).
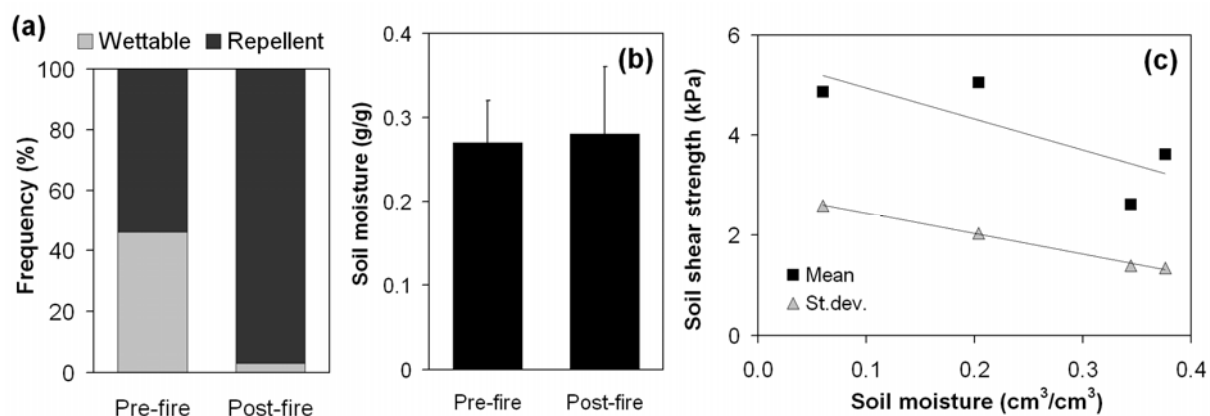
Figure 5.4 Occurrence of soil water repellency (a), soil moisture content (b) and relation between soil shear strength and mean soil moisture (c). Water repellency is given as the proportion of samples that are wettable (Water Drop Penetration Time (WDPT) < 5 s) and water repellent (WDPT > 5 s), surface soil samples (0-2.5 cm deep) were taken 1.5 d before and 3 h after the fire. Soil moisture content of these same soil samples is displayed. Soil shear strength is given as the mean and standard deviation for four sampling dates (Table 5.3), with mean soil moisture having been determined from adjacent soil moisture probes installed at 2.5 cm deep. The mean and standard deviation of shear strength were strongly negatively correlated with mean topsoil moisture content (r = -0.78 and -1.00, respectively).

Although fire-induced soil water repellency is generally thought to develop when soils are exposed to temperatures of 175°C or higher (DeBano, 1981; DeBano, 2000a; Letey, 2001), soil water repellency is also known to increase when soils are oven-dried at much lower temperatures of 65°C (Dekker et al., 1998). It is however debatable to which degree a field fire and oven drying are comparable because oven drying does not account for effects of the burning vegetation. In any case, the fire-induced soil water repellency at these low soil temperatures is surprising, and suggests that soil water repellency in this system is either induced at lower temperatures than previously thought, or by different mechanisms. Because the flames did reach high temperatures (~700°C), the

soil water repellency may for instance have been caused by organic compounds being released from the burning vegetation.

Another reason for the observed increase in soil water repellency may lie in the relation between soil water repellency and soil moisture (Dekker and Ritsema, 1994; Doerr and Thomas, 2000). Although soil moisture content (0-2 cm deep) was not significantly affected by the fire (Figure 5.4), soil water repellency may have been induced when a very thin surface layer dried out during the fire, the layer being too thin to affect bulk soil moisture content. Because only a few repellent particles are needed to make a considerable volume of soil water repellent after mixing (Steenhuis et al., 2005), a small fraction of dry repellent soil would have been sufficient to make the entire sample water repellent, explaining the observed increase in soil water repellence.

The development of soil water repellency, despite the low soil temperatures, increased the risk of overland flow during the first post-fire rains. It should however be noted that the seasonal variation of post-fire soil water repellency lied within the range of natural background levels observed in the study area (Chapter 6), indicating that increased post-fire erosion cannot (solely) be attributed to soil water repellency. This emphasizes the need to know the natural (pre-fire) variation of soil water repellency when assessing the role of soil water repellency as a driving force for land degradation after fire.

5.3.3 Soil surface changes

Soil surface characteristics changed considerably during and after the fire (Table 5.5), which suggests that aboveground processes like vegetation and litter removal may have had a larger effect on soil surface characteristics than the temperatures achieved belowground – this in contrast to fire damage to belowground soil properties, which is very much determined by soil temperature (Cerdà and Robichaud, 2009; Neary et al., 1999; Chapter 2).

Because of the very dense shrub and litter cover before the fire, pre-fire values of Manning's n (0.64 ± 0.18, Table 5.5) were very high compared to other vegetation types (see overview by Hessel et al., 2003). The fire reduced most shrubs to 1 cm-high stumps and consumed part of the litter (Figure 5.5), thereby significantly reducing Manning's n by 56% (p=0.004, Table 5.5). This reduction in flow resistance implies that overland flow velocity is higher for the same unit discharge, increasing the erodible force of the overland flow.

Table 5.5 Fire impact on soil surface properties: Manning's n, random roughness and shear strength as measured before (pre) and after the fire (post). Values are averages over the treatments (n=6 for Manning's n, n=42 for shear strength and random roughness), standard deviations are given between parentheses and 'n.d.' stands for 'not determined'. Values not sharing the same lower case letter within each column are significantly different at p<0.05. Note that no precipitation occurred between the fire and the first post-fire sampling. 366 mm of precipitation was recorded between the first and second post-fire sampling (7 months) and 1229 mm was recorded between the second and third post-fire sampling (1 yr)

Parameter	Manning's n		Random roughness (RR)		Soil shear strength (τ)	
	Sampling date	n (-)	Sampling date	RR (cm)	Sampling date	τ (kPa)
Pre-fire	14 Aug 08	0.64 (0.18) a	28 Jul 08	1.08 (0.44) a	6 Feb 09	3.6 (1.3) a
Post (d)	26,27 Feb 09	0.28 (0.11) b	22,23 Feb 09	0.93 (0.39) ab	22,23 Feb 09	4.9 (2.0) b
Post (7 m)	n.d.	n.d.	2 Oct 09	0.76 (0.27) c	1 Oct 09	4.9 (2.6) b
Post (1 yr)	n.d.	n.d.	2 Mar 10	0.81 (0.25) bc	1 Mar 10	2.6 (1.4) c
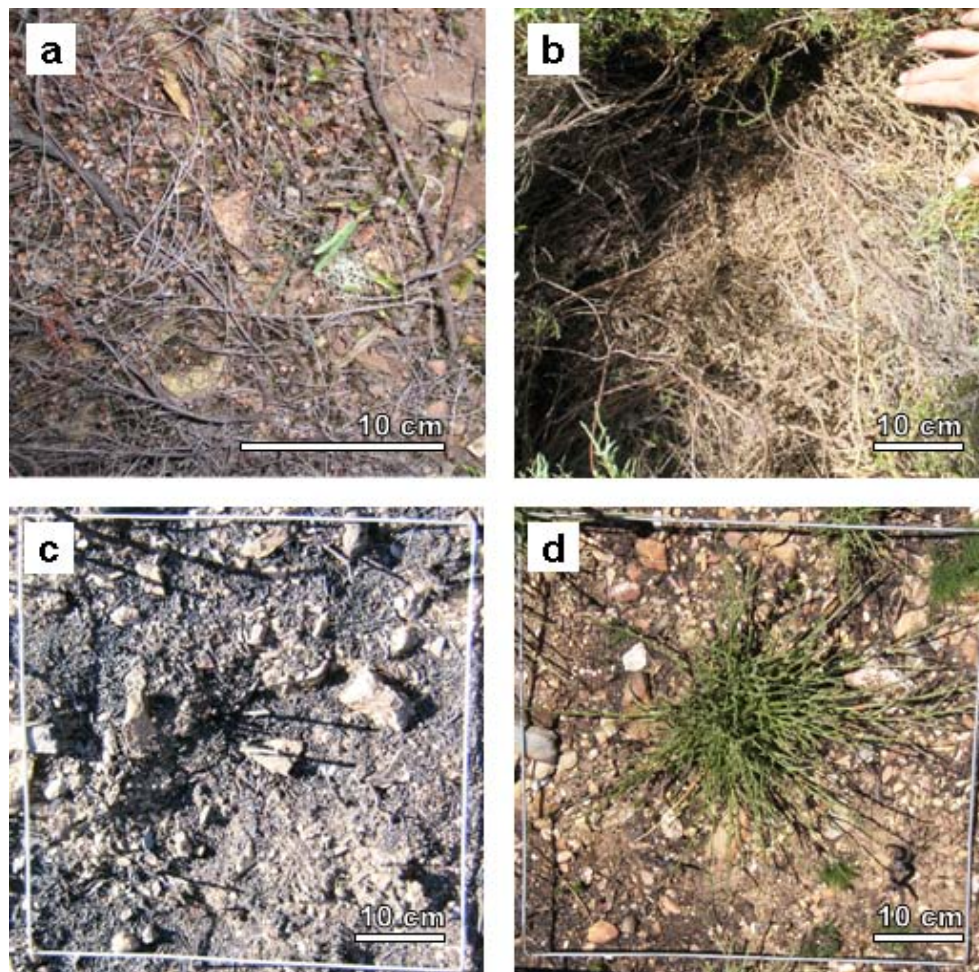
Figure 5.5 Soil surface evolution: examples of the soil surface before the fire (a, b) and 1 day (c) and 4 months after the fire (d). Photo c and d © Carla Ferreira.

While fire is also known to decrease random roughness (Moffet et al., 2007), it did not cause a direct significant decrease in the present study. Reduced roughness was however found when the site was revisited 7 and 12 months after the fire (Table 5.5). Since random roughness and Manning's n are known to be related (Gilley and Finkner, 1991), the delayed decrease in random roughness may have caused a further decrease in flow resistance of the burned soil surface, which implies that the erosivity of overland flow may increase during the first post-fire months. These soil surface changes may not only be caused by litter being washed away, but, as suggested by Zobeck and Onstad (1987), also by soil removal through erosion. This may imply a possible feedback mechanism between soil erosion and the evolution of the burned soil surface (Figure 5.5), in which soil erosion continues or even progressively increases with decreasing surface roughness until surface roughness and protective cover have returned. Fire effects on erosion risk may therefore not be immediately evident and need to be monitored over time.

Soil shear strength changes did not follow the same pattern as changes in Manning's n and random roughness. Rather, it increased after the fire and then decreased to below pre-fire levels one year later (Table 5.5). Soil shear strength was strongly negatively correlated with mean topsoil moisture content (r = -0.78) (Figure 5.4). Given this strong negative relation, also observed by Davies (1985), the observed changes appear to be more related to soil moisture variation than to direct fire effects.

5.3.4 Post-fire erosion: soil vs. surface effects

A soil's susceptibility to erosion after fire is determined by the fire's impact on soil properties and by changes in vegetation and litter cover during and after the fire. Yet, the effect of surface changes may be difficult to separate from soil changes, and vice versa. Fire can cause considerable damage to the soil as well as significant flooding and erosion events (Cerdà and Robichaud, 2009; Neary et al., 1999; Pierson et al., 2002). However, the present fire also increased soil erosion rates (Shakesby et al., 2010b), even despite having no physical damage to the soil. This stresses the importance of soil cover changes in determining post-fire erosion. In addition to the role that decreased canopy storage and increased raindrop impact on the bare soil play in determining post-fire erosion (Andreu et al., 1998; Mati, 1994), the present study suggests that surface roughness parameters caused by fire and post-fire soil exposure can also markedly increase soil erosion. This was previously observed by Kutiel et al. (1995). By reducing flow resistance and surface roughness during and after the fire, the experimental fire increased not only the risk but also the potential erosivity of overland flow during the entire post-fire monitoring period of one year.

Results therefore suggest that post-fire runoff and erosion risk may be underestimated when predictions are only based on direct effect of the fire on soil physical properties. The data show that even when fire has a low impact on soil physical properties, or a low soil burn severity, it can have high impact on the area's vulnerability to runoff and erosion because of the removal of soil cover and the change in soil surface characteristics. This stresses the importance of soil roughness and cover assessment when evaluating erosion risk in burned areas. More accurate assessment of erosion risk can enhance estimation of the degradation potential after wildfires and contribute to evaluating the sustainability of prescribed fires around the world.

5.4   Conclusions

In possibly the first study that assesses fire impact at the catchment scale, a Portuguese shrubland catchment was burned by experimental fire in the 2008/9 winter season. The fire experiment showed that:

- What you see is not always what you get: despite the high fire intensity, soil burn severity was low: topsoil organic matter, bulk density, porosity, saturated hydraulic conductivity and soil moisture content were not significantly affected.

- The occurrence of soil water repellency increased at sites where soil temperature was only ~60°C, suggesting that soil water repellency can respond differently to fire than previously thought, and increasing overland flow risk during the first post-fire rains.

- Surface properties like Mannings' n and random roughness decreased, increasing the risk and erosivity of overland flow.

- Observed soil shear strength changes appeared to be more related to soil moisture changes than to direct fire effects.

- Even when fire has a low impact on soil physical properties, it can have high impact on the area's vulnerability to runoff and erosion. Low soil burn severity therefore does not necessarily imply negligible post-fire degradation risk.

6   Natural and fire-induced soil water repellency

Abstract

Post-fire land degradation is often attributed to fire-induced soil water repellency, despite the fact that soil water repellency is a natural phenomenon in many soils and is therefore not necessarily caused by fire. To improve understanding of the role of soil water repellency in causing fire-induced land degradation, a long-term monitoring study was performed in which the temporal variation of topsoil water repellency (0-2.5 cm depth) was captured in a Portuguese shrubland before and after fire between November 2007 and March 2010. In addition, (dis)similarities between changes following burning and clipping were assessed in a plot experiment. Soil water repellency appeared to be the rule rather than the exception, both before and after fire, and was strongly related to soil moisture and organic matter content. Surprisingly, despite the low soil temperatures during the fire (60°C) and the lack of direct soil moisture changes, fire significantly increased the persistence of soil water repellency (WDPT). Vegetation removal by burning and clipping played a key role in determining post-fire water repellency in litter and at the soil surface, and considerably reduced the time needed to both develop and eliminate water repellency of litter and surface soil. Because pre-fire (or 'natural') soil water repellency was abundant, the increased erosion observed in the catchment after the fire cannot be solely caused by soil water repellency. Nevertheless, fire-induced removal of the protective canopy cover may increase the hydrological significance of soil water repellency in burned landscapes.

6.1   Introduction

Fire-induced soil water repellency has received widespread attention in the scientific literature (DeBano, 2000a; Dekker et al., 2005). By hindering water infiltration into soils, soil water repellency is often regarded as a key driver in post-fire runoff and erosion events (DeBano, 2000a; Doerr et al., 2000). It is however not only caused by fire. Soil water repellency is also very common in long unburned areas, or in areas where fire is absent altogether (DeBano, 2000b; Dekker et al., 2005). To assess the role of soil water repellency as a driving force for post-fire land degradation it is therefore crucial to know the natural variation of soil water repellency before the fire.

Intense soil heating is considered to be the trigger for fire-induced soil water repellency, which is believed to be caused by the volatilization and condensation of organic substances when the soil is exposed to high temperatures during fire (DeBano, 2000a). Soil water repellency has been observed to develop when soils reach 175°C and be eliminated when soil temperatures reach 200 to 350°C (DeBano, 2000a; Dlapa et al., 2008), although these temperature limits vary with heating duration (Dlapa et al., 2008; Doerr, 2004), soil type and texture (Arcenegui et al., 2007; Robichaud and Hungerford, 2000) and vegetation or litter type (Arcenegui et al., 2007). Fire-induced soil water repellency was first recognized in the 1950's and 1960's in the USA, but has since been found in many places throughout the Americas, but also in Europe, Africa and (Austral)asia (DeBano, 2000a; Dekker et al., 2005).

Soil water repellency can considerably affect hydrological processes (Ritsema and Dekker, 1994; Ritsema et al., 1993). By hindering water infiltration into soils, it increases the risk of overland flow generation (Doerr et al., 2003; Ferreira et al., 2000; Woods et al., 2007). As a result, soil water repellency has often been regarded as an important driver not only of the generation of post-fire erosion and flooding events (Doerr et al., 2000; Letey, 2001; Scott and Van Wyk, 1990), but also as a major driver of the generation of destructive debris flows (Capra et al., 2010; Wells, 1987). However, as the full effect of fires on ecosystems is comprised of more than solely the effect of soil water repellency, several authors have highlighted the need to assess the role of soil water repellency as a driving force of post-fire land degradation independently from that of the removal of vegetation, soil roughness and other fire-induced soil changes (Doerr et al., 2000; Kutiel et al., 1995; Larsen et al., 2009; Shakesby and Doerr, 2006).

Assessment of the role of soil water repellency in causing post-fire land degradation is complicated because soil water repellency is not only caused by fire. Unburned soils can also exhibit soil water repellency, because of hydrophobic organic compounds derived from leaves, root exudates, fungi, bacteria or decomposing organic matter (Dekker et al.,

2009; Hallett et al., 2003; Morales et al., 2010). These organic compounds are accumulated on and between soil particles, and although they are hydrophilic when moist, they can turn highly hydrophobic when soils dry out below a critical moisture threshold (Dekker et al., 2009; Hallett, 2007). As such, soil water repellency has also been observed in fire-prone but long unburned areas such as the northwest USA (Doerr et al., 2009b; Woods et al., 2007), Portugal (Doerr et al., 1996; Leighton-Boyce et al., 2005) and Spain (Mataix-Solera and Doerr, 2004; Varela et al., 2005), as well as in countries where fire is typically absent such as Germany (Greiffenhagen et al., 2006) and the Netherlands (Dekker et al., 2000). The widespread existence of soil water repellency in unburned areas suggests that care should be taken in identifying soil water repellency as the primary cause of post-fire erosion and flooding events.

Within the framework of a large project focusing on the drivers of land degradation after fire (Shakesby et al., 2010b; this thesis), a long-term monitoring study was performed to capture the existence and temporal variation of soil water repellency in a Portuguese shrubland before and after fire. Our objectives were to 1) reveal the short- to long-term variation in the persistence of actual soil water repellency in a long unburned system, 2) assess the role of soil moisture as a driving force for the variation in actual soil water repellency, 3) evaluate the effects of fire on the persistence of actual soil water repellency, and 4) determine whether fire-induced changes were the result of changes to the soil system or loss of vegetative cover alone. The present paper evaluates these objectives, and highlights the importance of pre-fire (or 'natural') soil water repellency data when assessing the role of soil water repellency as a driving force for post-fire land degradation.

6.2   Material and Methods

6.2.1 Study area and experimental fire

The study area is the Valtorto catchment in north-central Portugal, a region much affected by forest fires and post-fire land degradation. The climate is Atlantic-Mediterranean, with precipitation concentrated in the winter; summers are dry with high wildfire risk (Table 6.1). Soils and vegetation are typical for the region. Soils are stony and shallow (Table 6.1) developed from schist and quartzite, and covered by dense heathland dominated by heaths and heathers (Ericacea), "carqueja" (*Pterospartum tridentatum*) and broom (*Genista triacanthus*). The area was last burned in April 1996, by prescribed fire (Ceballos et al., 1999), after which the vegetation had regenerated to 81 ± 18% cover when sampling started in 2007.

Table 6.1 Valtorto catchment characteristics

Parameter	Value
Location	40°06'21'' N, 8°07'03'' W
Area burned (ha)	9
Mean annual precipitation (mm)	1050
Mean monthly temperature (°C)	7.8 (Dec); 20 (Aug)
Elevation (m a.s.l.)	650-700
Soil depth (m) †	0.16 ± 0.14
Soil texture ‡§	gravelly loamy sand
Dry bulk density (g/cm^3) ‡	0.82 ± 0.13
Soil organic matter (weight%) ‡	21.0 ± 5.2
Rock fragment content (cm^3/cm^3) ‡¶	0.16 ± 0.06
Surface rock fragment cover (%)	56 ± 26
Pre-fire vegetation height (m)	0.50 ± 0.26
Pre-fire vegetation cover (%)	81 ± 18
1 yr-post-fire vegetation cover (%) #	30

† At the sampled sites, soil depth was always ≥ 7 cm; ‡ 0 to 2.5 cm depth; § according to USDA classification (USDA, 1993); ¶ 0.44 ± 0.12 g/g by weight; # Shakesby et al. (2010)

After a monitoring period of 15 months, the area was burned by experimental fire on the morning of 20 February 2009. The fire was performed after a 10-d dry period, when mean air temperature was 14.2°C and relative humidity was 33%. While flame temperatures exceeded 700°C and fire intensity in some places exceeded 15000 kW/m, shrubs were not completely consumed throughout the catchment and soil temperatures remained relatively low (Chapter 4). Although maximum soil surface temperature was locally as high as 800°C, soils in the majority of the catchment remained below 100°C. As a result, the fire did not significantly change soil properties like organic matter content, dry bulk density, saturated hydraulic conductivity and porosity (Chapter 5).

6.2.2 Soil sampling – transects and plots

Two different sampling schemes were performed, focusing on 1) the occurrence and variation in the persistence of actual soil water repellency before and after fire – analyzed using repeated transect sampling, and 2) the question of whether soil water repellency in burned systems is a direct result of fire or rather simply the effect of vegetation removal contributing to more rapid drying of the soil (Iverson and Hutchinson, 2002; Kasischke and Johnstone, 2005) – analyzed using repeated plot sampling.

6.2.3 Transects

Ten 1-m wide transects were sampled before and after large rain events, capturing the temporal variation in soil moisture content and persistence of actual soil water repellency (water drop penetration time) on 17 occasions before and 6 occasions after the fire. As such, samples were collected year-round between November 2007 and March 2010. The transects covered the range of terrain attributes in the catchment such as slope, aspect, soil depth and vegetation height (Table 6.1). Since sampling was destructive, repeat sampling was always done a few cm upslope of the previous sampling.

At each transect, ten small bulk soil samples were taken (± 50 g, 0-2.5 cm deep), sealed in plastic bags, broken up, and analyzed the following day. After determining the field-moist weight, the persistence of actual soil water repellency was identified using the Water Drop Penetration Test following Dekker et al. (2009) and Dekker and Jungerius (1990) (Table 6.2). The gravimetric soil moisture content was subsequently determined after oven-drying (24h at 105°C). Moreover, for one-third of the pre-fire samples (n=565), soil organic matter content was additionally determined using Loss on Ignition (4h at 550°C).

Table 6.2 Definition of WDPT classes following Dekker and Jungerius (1990) and Dekker et al. (2009)

WDPT class	Infiltration time	Description
0	< 5 s	Non-water repellent, wettable
1	5 – 60 s	Slightly water repellent
2	60 – 600 s	Strongly water repellent
3	60 – 3600 s	Severely water repellent
4	1 – 3 h	Extremely water repellent
5	3 – 6 h	Extremely water repellent
6	> 6 h	Extremely water repellent

6.2.4 Plots

Nine 16-m^2 plots were installed and monitored to capture effects of fire and vegetation cover on soil moisture and persistence of actual water repellency. The plots were located at three sites along the sides of the catchment where burned and adjacent unburned terrain had similar slope, aspect, soil depth and (pre-fire) vegetation cover and type. Installation occurred three months after the fire in June 2009. Each site was comprised of three plots: one undisturbed unburned (UB), one burned (B) and one unburned in which

all vegetation was manually cut and removed and all litter was removed except for a < 0.5 cm thin layer (Clip).

Plots were sampled on 12 occasions shortly before, during and after large rain events in Jun 2009, Oct 2009 and Feb/Mar 2010, often at sub-weekly intervals. In addition, the plots were sampled twice before the vegetation was removed from the clipped plots (3 Jun 2009), to ascertain that pre-clipping differences between unburned and clipped unburned plots were not significant.

At each plot, sampling involved five random readings of topsoil moisture content using a handheld soil moisture meter (TRIME-FM2 with 50-mm P2 probe, IMKO GmbH, Ettlingen, Germany). At the same place, the occurrence of actual soil water repellency was assessed by placing a water drop on the litter, at the mineral soil surface, and at 2 and 5 cm depths. Water repellency was considered to be present when the water drop did not infiltrate within 5 s.

6.2.5 Data analyses

Regarding the transect data, the effect of soil moisture and organic matter content on the persistence of soil water repellency was analyzed using ANOVA. ANOVA was also used to determine possible changes in the upper and lower bounds of the transition zone, the moisture range within which soil was either wettable or water repellent (Leighton-Boyce et al., 2005). For this purpose, upper and lower bounds (soil moisture contents) of the transition zone before and after the fire were calculated as averages of the upper and lower bounds observed for each day that a transition zone was identified. Finally, the direct effect of fire was evaluated from samples taken as shortly before (1.5 d) and after (3 h) the fire as possible. Fire effects on soil moisture content were evaluated using paired t-tests, whereas fire effects on the persistence of soil water repellency (recorded in classes thus classified as ordinal data) were assessed using a Wilcoxon signed rank test. Since the data were clustered, all analyses were performed on the mean values per plot.

Regarding the plot data, the proportion of repellent soil was determined for each depth and plot before further analysis. For this purpose, the number of repellent readings was divided by the total number of readings. Plot treatment effects in time were analyzed by applying factorial models to the aggregated plot means and fitted using residual maximum likelihood for each depth separately. Because sampling sites were revisited in time, the correlation between observations in time was accounted for in the models, and the data was analyzed as a repeated measures experiment. The optimal model was

found using a similar approach to that described by Webster and Payne (2002). All analyses were performed in R (R Development Core Team, 2010).

6.3 Results

6.3.1 Pre- and post-fire levels of soil water repellency

This shrub-covered schist soil exhibits water repellency year-round, both before and after fire (Figure 6.1). Except for a few occasions in winter and spring (24 Apr 08, 21 Jan and 11 Feb 09, and 24 Feb 10), the proportion of repellent soil by far exceeded the proportion of wettable soil in the catchment. Interestingly, there was not only a very high temporal variation, but also considerable spatial variation. Catchment-wide, samples were distributed over 5.5 ± 1.6 WDPT classes on each sampling date, while samples within each transect were on average distributed over 3.1 ± 0.3 WDPT classes. Within-transect variability was therefore on average 57% of the catchment-wide variability, indicating that the majority of the variation between samples was the result of small-scale (1-m) rather than large-scale (< 100 m) variation.
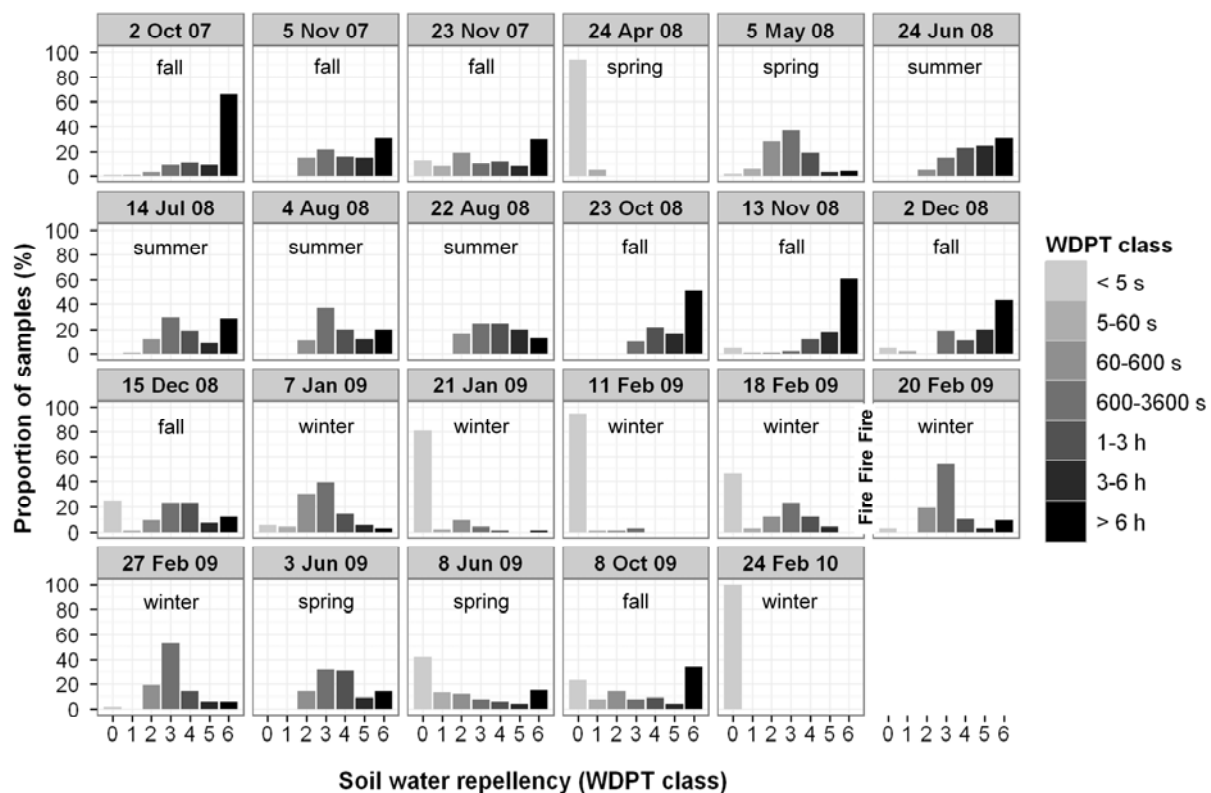
Figure 6.1 Temporal variation of the persistence of actual soil water repellency (WDPT) in the Valtorto catchment, before and after the experimental fire (20 Feb 2009). Bar diagrams in each subplot are based on 100 samples.

6.3.2 Effect of soil moisture, organic matter and rainfall

The considerable variation of topsoil water repellency was strongly affected by changes in soil moisture content: the persistence of repellency significantly increased with decreasing soil moisture ($p<0.001$, Table 6.3), particularly for pre-fire samples. In contrast, the persistence of soil water repellency significantly increased with increasing soil organic matter content ($p<0.001$, Table 6.3), however this effect was only observed for severely to extremely repellent samples (WDPT class ≥ 3). Wettable samples (WDPT class 0) had significantly higher organic matter content than slightly- to severely water repellent samples (WDPT class 1 to 3), which could possibly be explained by the higher moisture content of the wettable samples (Table 6.3) resulting from the organic matter-related increase in water holding capacity (Wesseling et al., 2009b). Nevertheless, the interaction between moisture and organic matter content was not significant ($p=0.178$).

Table 6.3 Effect of soil moisture and organic matter content (OM) on soil water repellency (WDPT). Values are averages over the replicates (n) of the WDPT classes (see Table 6.2 for class definitions), and standard deviations are given between parentheses. Values not sharing the same letter in each column are statistically different at $p<0.05$, and asterisks indicate whether pre- and post-fire moisture contents are significantly different for each respective WDPT class at $p<0.05$. Note that organic matter content was only determined for (part of) the pre-fire samples.

| WDPT class	Soil moisture content (g/g)				OM (%)	n
	Pre-fire	n	Post-fire	n		
0	0.36 (0.11) a *	372	0.41 (0.13) a *	170	23.7 (4.7) b	40
1	0.33 (0.12) b *	35	0.27 (0.05) b *	21	22.2 (6.2) a	8
2	0.22 (0.12) c	172	0.19 (0.08) cd	78	21.6 (4.2) a	74
3	0.20 (0.10) cd	308	0.21 (0.10) cd	155	21.9 (3.8) a	149
4	0.19 (0.09) d *	240	0.15 (0.08) e *	70	23.8 (4.6) b	112
5	0.17 (0.08) d	172	0.16 (0.09) de	26	24.8 (4.2) c	61
6	0.18 (0.06) d	395	0.16 (0.08) de	78	25.7 (5.2) d	121

The strong negative relation between soil moisture content and the persistence of soil water repellency is illustrated in Figure 6.2, in which the time series of the mean soil water repellency is displayed along with the mean soil moisture content. Moreover, this figure gives insight into the time needed for soil water repellency to develop and be eliminated. Even in winter, soil water repellency developed very quickly: for instance on 18 Feb 09 after just seven dry days, ~50% of the samples were water repellent, and in spring 2008, eleven mostly dry days were sufficient to make ~95% of samples water repellent (Figure 6.1). Although before the fire very little time was needed to develop
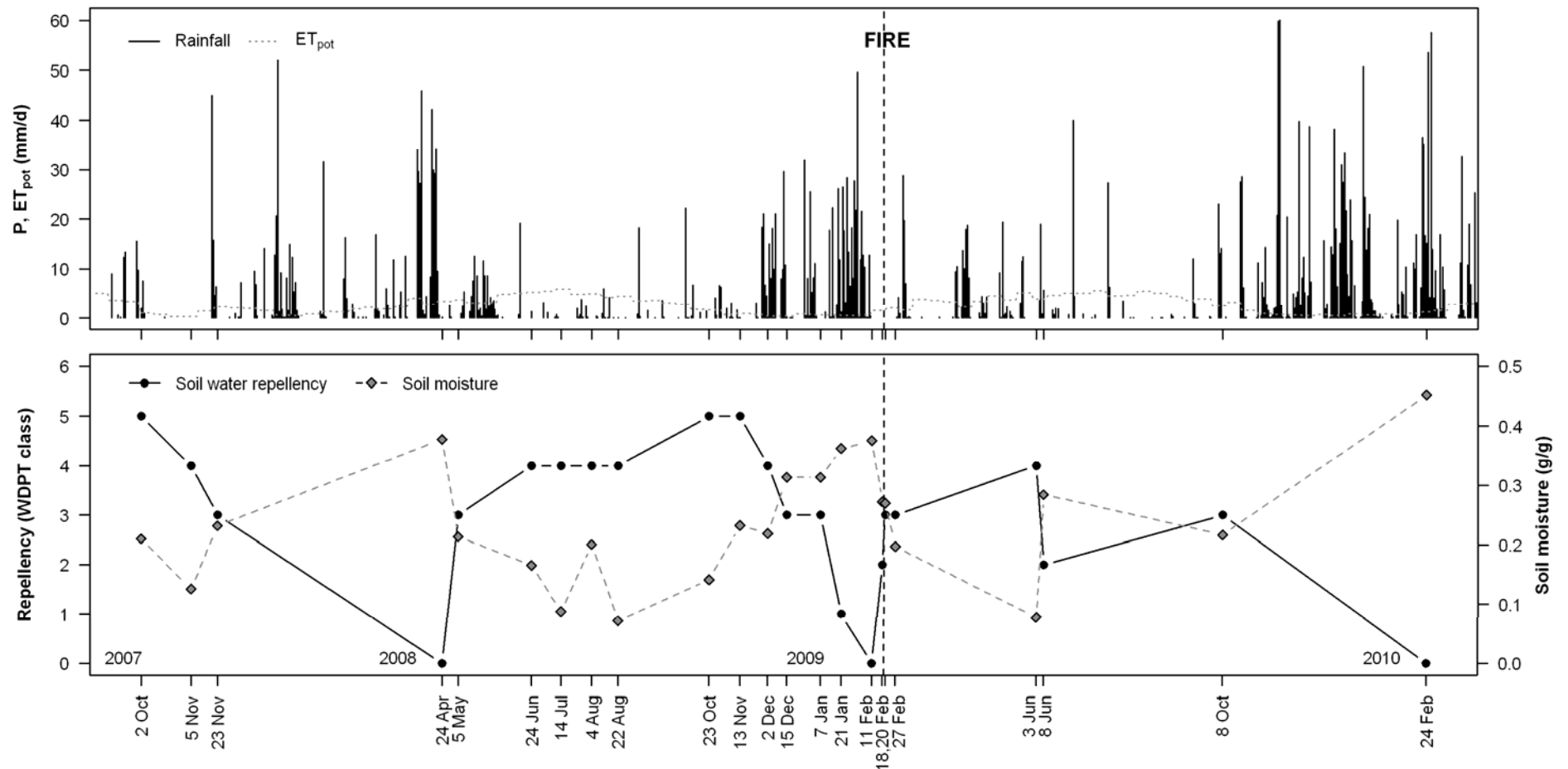
Figure 6.2 Time series of the persistence of actual soil water repellency before and after fire along with soil moisture content, rainfall (P) and potential evaporation (ET_{pot}). To facilitate interpretation of the bottom graph, straight lines are drawn between observations, which are mean values of soil water repellency and soil moisture content (based on the transect data, n=10*10, 0-2.5 cm depth). The experimental fire was performed on 20 Feb 2009, and is indicated by the dashed vertical line.

water repellency, it took a lot of time (and rainfall) for it to be eliminated. For example, in Dec-Jan 08/09 (Figure 6.1, 6.2), 131 mm of rainfall in 13 d only increased the proportion of wettable samples from 5 to 20% (2-15 Dec 08), and despite receiving another 91 mm of rainfall during the 11 d preceding the next sampling 23 d later (7 Jan 09), the proportion of wettable samples dropped again to just 5%. Counter to expectations, soil water repellency of the unburned soil still persisted when the 50-d rainfall sum totaled ~300 mm on 21 Jan 09, and after an additional 292 mm of rainfall in 21 consecutive days on 11 Feb 09 (Figure 6.1).

In contrast to the unburned situation, soil water repellency in the burned system was eliminated fairly rapidly: between 3 and 8 Jun 09, only 29 mm in four consecutive days was sufficient to make 42% of the previously repellent samples wettable.
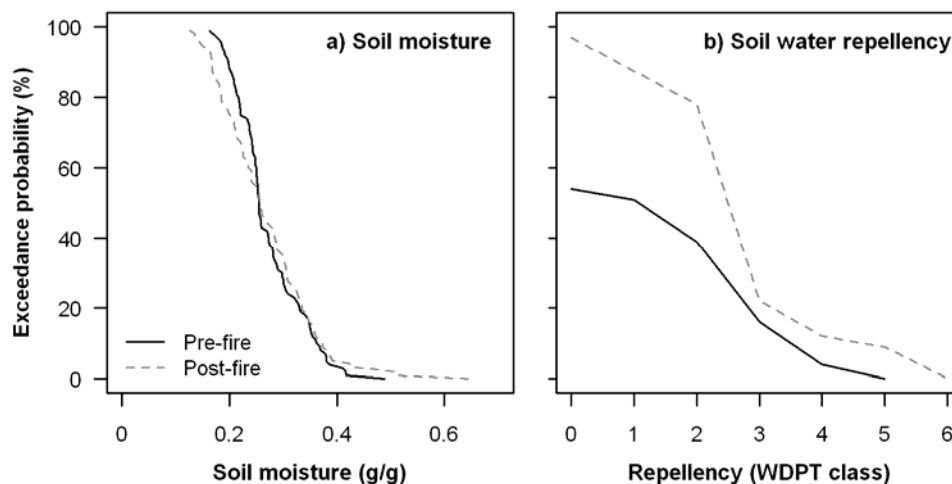
Figure 6.3 Exceedance probability of soil moisture content (a) and the persistence of actual soil water repellency (b) shortly before and after the experimental fire. Pre-fire sampling was done 1.5 d before the fire (18 Feb 09, n=100), while post-fire sampling was done a few hours after the fire (20 Feb 09, n=100). An exceedance probability of 55% for WDPT class 0 (pre-fire, graph b) indicates that the probability of WDPT class > 0 (i.e. repellent soil) was 55%. WDPT classes used are specified in Table 6.2.

6.3.3 Direct fire effects and pre- and post-fire differences

While the fire did not significantly change the mean soil moisture content (p=0.93), it did significantly increase the mean persistence of soil water repellency from strongly to severely repellent (WDPT class 2 to 3, p=0.02). This is illustrated in Figure 6.3, which shows the exceedance probability of soil moisture content and soil water repellency, i.e. the chance that a given soil moisture content or WDPT class is exceeded. Figure 6.3 illustrates that while the fire only slightly changed the exceedance probability of soil

moisture content (a), it considerably increased the persistence of soil water repellency (b). For instance, the probability of water repellent soil (WDPT class > 0) increased from 55 to 98%, whereas the probability of soil exhibiting strong or severe water repellency (WDPT class > 2) increased from 40 to 80%.

Furthermore, the fire slightly shifted the moisture-repellency relationship, by significantly decreasing soil moisture content for slightly and extremely water repellent soil (WDPT class 1 and 4, asterisks in Table 6.3 and Figure 6.4). This change was however not sufficient to significantly alter the upper and lower limits of the transition zone (p=0.22 and p=0.93, respectively), the range of moisture contents in which soil can be both wettable and repellent. Before the fire, a transition zone was observed on 6 out of 17 sampling days, when it ranged from 0.22 ± 0.05 to 0.50 ± 0.10 g/g soil moisture. After the fire, it was observed on 3 out of 6 sampling days and ranged from 0.22 ± 0.04 to 0.41 ± 0.10 g/g. Using the average dry bulk density of the Valtorto catchment soil (0.82 g/cm^3), this corresponds to a pre-fire mean transition zone of 0.18 – 0.41 cm^3/cm^3 and a post-fire mean transition zone of 0.18 – 0.34 cm^3/cm^3.
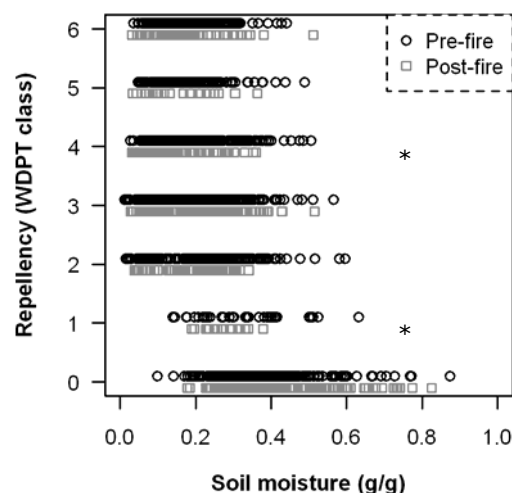
Figure 6.4 Relation between soil moisture content and the persistence of actual of soil water repellency before and after the fire (using pooled data from all pre- and post-fire samplings, n= 1694 and n=600, respectively). WDPT classes used are specified in Table 6.2, and asterisks indicate for which classes pre- and post-fire soil moisture contents were significantly different.

6.3.4 Effect of burning vs. clipping

The occurrence of soil water repellency in the plots was highly variable with both depth and time, and fluctuated more than soil moisture content (Figure 6.5). Nevertheless, some broad patterns arise regarding both the depth profile of soil water repellency and its temporal variation.

The occurrence of soil water repellency was generally highest for the litter layer and at the soil surface, and decreased with depth. On a few occasions however (e.g. 8 Jun and 7, 8 Oct 09), rainfall quickly wet the litter and soil surface, reducing or even eliminating soil water repellency at the surface, while soil water repellency below the surface was still present. Moreover, despite similar moisture contents in June and October 2009, the depth profile of soil water repellency was markedly different during these two monitoring periods. In October 2009, soil water repellency occurrence at 2 and 5 cm depth was considerably higher for all treatments than in June 2009, and treatment effects were less pronounced.

Effects of burning and clipping on soil moisture content and the occurrence of soil water repellency significantly interacted with time (p=0.03 and p=0.002, respectively), indicating that treatment effects were not constant in time. Effects were greater on soil water repellency than on soil moisture, which only varied significantly between treatments on 11 Jun 09, when burned soil was significantly drier than clipped soil (Figure 6.5, soil moisture). While burning and clipping effects on soil water repellency were significant on some occasions in Oct 09 and Feb/March 10, the largest effects occurred in Jun 09 (Figure 6.5, litter – 2 cm).

Summarizing the results of the effects of burning and clipping (Figure 6.5): 1) treatment effects were shallow: although soil water repellency occurrence at 5 cm depth did vary in time, it was not significantly affected by either burning or clipping, 2) burned soil was often, but not always, slightly drier and significantly more water repellent than unburned soil – this was the case for the litter, the soil surface and the topsoil at 2 cm depth, and 3) effects of burning and clipping were different for litter and surface soil than for topsoil at 2 cm depth: while litter and surface repellency of burned and clipped soil were often not significantly different and responded rapidly to rainfall, burned topsoil (at 2 cm depth) exhibited significantly more water repellency than clipped soil, which sometimes appeared to be more similar to unburned soil.

Results from the plot-scale monitoring finally also provided information regarding the time needed for soil water repellency to develop and be eliminated. Although 30 mm of rainfall between 4 and 8 Jun 09 was sufficient to considerably reduce soil surface water repellency in all treatments, other short-interval samplings indicate that repellency fluctuation of burned and clipped soil was more rapid than that of unburned soil. However, water repellency variation of clipped soil did not exactly match that of burned soil. For instance, while less than 50 mm of rainfall in 2-3 d was sufficient to totally eliminate the repellency of the litter and burned surface soil on 8 Oct 09, it only reduced the repellency of unburned and clipped surface soil to 40-60%. Nevertheless, both the burned and
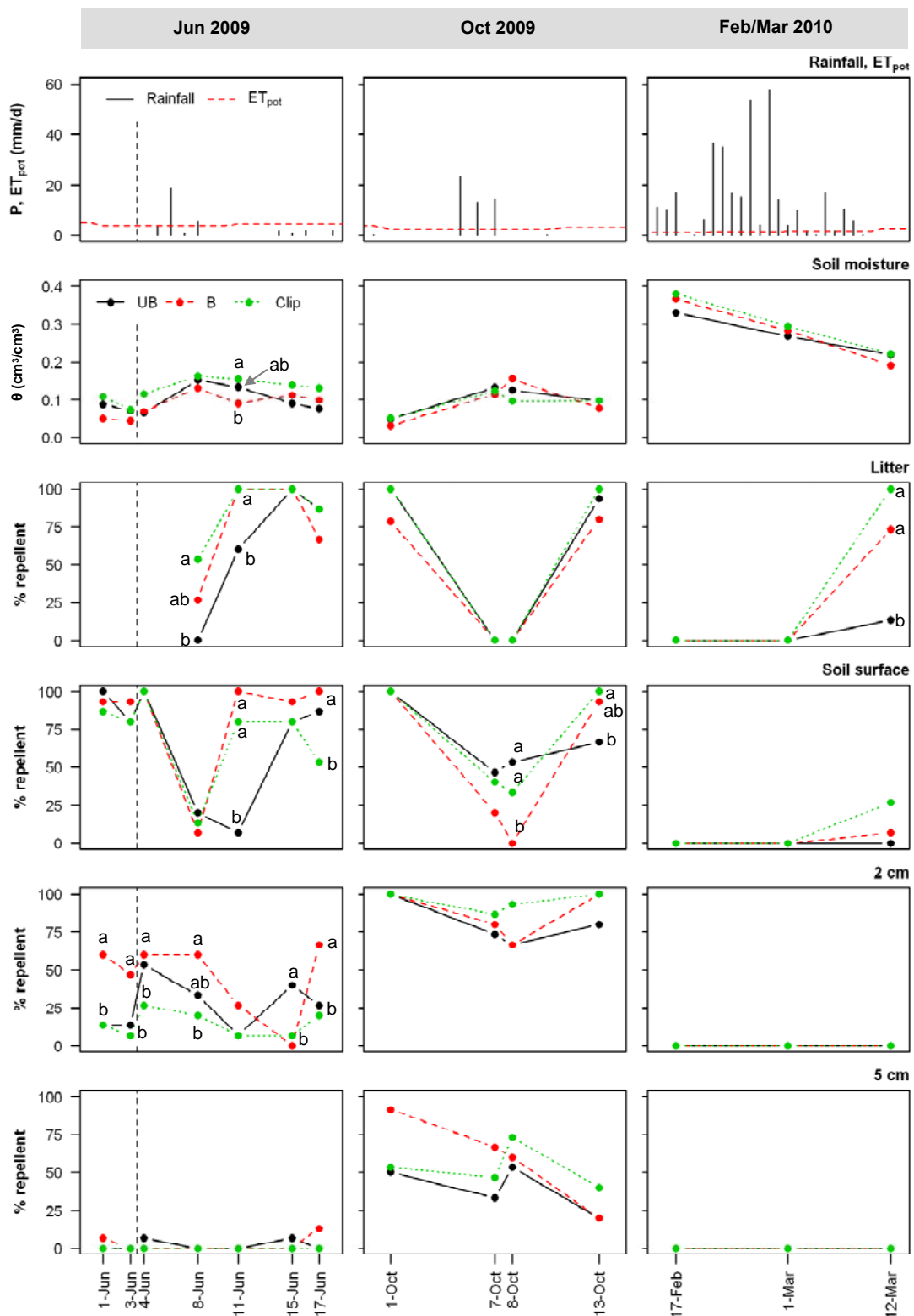
Figure 6.5 Effect of fire vs. (lack of) vegetation cover: soil water repellency and soil moisture (0-5 cm depth) for unburned (UB), burned (B) and unburned and clipped (Clip) plots, along with rainfall (P) and potential evaporation (ET_{pot}). To facilitate interpretation, straight lines are drawn between observations, which are treatment means based on 3 plots with 5 readings per plot. Values not sharing the same letter at a given depth on a given sampling day are statistically different at $p<0.05$. Vegetation was cut and removed from the clipped plots on 3 Jun 09 (dashed vertical line).

clipped surfaces were again nearly completely water repellent 5 dry days later (13 Oct 09), while repellency in the unburned soil had only slightly increased (Figure 6.5). The development of repellency in burned and clipped soil was also rapid in June 2009 and March 2010, when in both cases only two dry days were sufficient to make nearly all burned and clipped litter and/or surface soil water repellent, while unburned litter and especially surface soil remained wettable.

6.4   Discussion

6.4.1 Natural background soil water repellency vs. fire effects

Similar to other fire-prone but long-unburned systems (Doerr et al., 1996; Doerr et al., 2009b; Varela et al., 2005), the natural levels of soil water repellency are often high for this shrub-covered schist soil typical of north-central Portugal. Figures 6.1 and 6.2 show that, like many field soils (Dekker et al., 2005), soil water repellency is therefore the rule rather than the exception. More importantly, soil water repellency in this system is not caused solely by fire.

Soil moisture and organic matter content are known to be important drivers in the occurrence of soil water repellency in the field (Dekker et al., 2001; Huffman et al., 2001; Mataix-Solera and Doerr, 2004). While there is a general sense that the type of organic substances may play a more important role in determining soil water repellency than the total content of organic matter (Doerr et al., 2000; Wallis and Horne, 1992), the positive relationship between soil organic matter content and the degree of soil water repellency in this study is consistent with findings of many working in this field, among others, Mataix-Solera and Doerr (2004) and Varela et al. (2005). Moreover, the key role of soil moisture in determining the temporal variation of soil water repellency (Figure 6.2, Table 6.3) is also consistent with others. Hubbert and Oriol (2005) and Leighton-Boyce et al. (2005), for instance, both reported that soil water repellency followed a moisture-related seasonal cycle, with high occurrence and persistence in dry summer months, and more wettable soils in wet winter seasons. However, while others have found a critical soil moisture content below which all soil was repellent (Dekker et al., 2001), the soil in the Valtorto catchment is better characterized by a transition zone (Leighton-Boyce et al., 2005) within which soil is either repellent or wettable. It should however be noted that the limits of the transition zone were on the high end of values reported in the literature, which range between 0.02 to 0.05 cm^3/cm^3 (Dekker et al., 2001), 0.10 to 0.26 cm^3/cm^3 (MacDonald and Huffman, 2004) and 0.28 cm^3/cm^3 (Doerr and Thomas, 2000) for critical moisture content, or 0.14 to 0.27 cm^3/cm^3 for a transition zone (Leighton-Boyce et al., 2005). The transition zone in the present study was similar to Dekker and Ritsema's

(1996) critical moisture content clayey peat, and lay between 0.18 and 0.41 cm^3/cm^3, possibly because of the high organic matter content of the Valtorto soil (Table 6.3).

Given the fact that soil water repellency is highly affected by soil moisture, it is interesting that the fire decreased the mean moisture content of slightly and severely repellent soil (Table 6.3 and Figure 6.4, WDPT class 1 and 4). This observation could possibly be explained by a reduced input of repellent substances over time because of the highly reduced plant cover (Ceballos et al., 1999; Doerr and Thomas, 2000). In that case, the reduced input of repellent substances affected the persistence of soil water repellency (Table 6.3, Figure 6.4) more than its occurrence (Figure 6.5), since the repellency occurrence did certainly not appear to be lower for burned soil and litter (Figure 6.5). Given the limited number of observations in dry post-fire periods however, we emphasize that these are possible explanations from which, without further study, hard conclusions cannot be drawn.

In addition to changing the relationship between soil moisture and repellency, the fire also had considerable direct effects. The persistence of water repellency in the topsoil (0-2.5 cm deep) increased, even though maximum soil temperatures on nine out of ten sampled sites remained below 60°C, and soil moisture content (0-2.5 cm deep) was not significantly changed. This is surprising, because 60°C is generally considered too low to cause fire-induced soil water repellency (DeBano, 1981; DeBano, 2000a; Letey, 2001). Although the persistence of soil water repellency usually increases with prolonged oven-drying even at low temperatures, such as for instance 3 d at 65°C (Dekker et al., 1998), fire residence times for this study were much shorter (< 5 min). For the same experimental fire as discussed here, Stoof et al. (Chapter 5) previously observed the increased occurrence of soil water repellency, and attributed it to the effects of possible drying of a very thin surface layer during the fire or the possible release of organic compounds from the burning vegetation. Additionally, burning litter may have played a role, since this has been identified as an important factor causing fire-induced repellency (Arcenegui et al., 2007; DeBano et al., 1970; Savage, 1974). A recent study performed by Bodí et al. (2011) added another potential explanation for the increased occurrence (Chapter 5) and persistence (this chapter) of soil water repellence after the fire: the existence of water repellent ash. Although ash is generally regarded as strongly hydrophilic, it can exhibit extreme water repellency, particularly when produced at relatively low temperatures (200-300°C) (Bodí et al., 2011). While the experimental fire did not produce high quantities of ash (< 0.5 cm thick layer), it was sufficient to blacken the soil surface throughout the catchment. Although ash and charred litter were manually removed from the soil surface before sampling, it is possible that a small amount was incorporated when the soil was sampled after the fire. Since a very low proportion of

repellent particles can render a considerable volume of soil water repellent after mixing (Steenhuis et al., 2005), small traces of repellent ash may have been sufficient to cause the observed increase in soil water repellency after the fire.

6.4.2 Time needed for soil water repellency to develop and be eliminated

The time needed for soil water repellency to develop or be eliminated has received little attention in the literature, because monitoring campaigns often focus on spatial variation at a given point in time (Ceballos et al., 1999; Doerr et al., 1998; Woods et al., 2007) and seasonal or annual changes (Hubbert and Oriol, 2005; Leighton-Boyce et al., 2005; Pierson et al., 2008) rather than on short-interval temporal variation. Since sampling intervals in the present study were often less than 1-2 weeks, these data give a more precise assessment of the time it took to develop and eliminate soil water repellency.

It took surprisingly long for soils to wet and overcome water repellency before the fire. Soil water repellency persisted even after two months of heavy and prolonged winter rainfall (~600 mm, Dec-Jan 08/09, Figure 6.1 and 6.2). This may be attributed to the considerable storage capacity of the dense shrub canopy. Canopy interception averaged 48.7 ± 17.8% in the winter season of 08/09 (Chapter 7), and because plant litter can also store significant amounts of water (Gerrits et al., 2010; Marin et al., 2000; Putuhena and Cordery, 1996), only half of the rainfall may have actually reached the soil surface. The dense shrub and litter cover therefore played an important role in reducing the amount of rainfall that the soil was exposed to. In spite of this long-term protection against wetting, the cover's protection against drying appears to have been much shorter: < 7-11 d were sufficient for soil moisture to drop and water repellency to (re)develop. Fire and/or vegetation removal markedly accelerated both the development and elimination of soil water repellency to a matter of days (Figure 6.5), by increasing soil exposure to both rainfall and solar radiation.

Relatively little is known about the longevity of fire-induced soil water repellency, though most studies indicate that increased soil water repellency breaks down to pre-fire levels within a few months to a couple of years (Doerr et al., 2009a; MacDonald and Huffman, 2004). Assessment of the longevity of fire-induced repellency in the Valtorto catchment is however complicated, given the abundance of soil water repellency before the fire and the fact that the exact cause of the fire-induced soil water repellency in the catchment is uncertain. Although Figure 6.1 and 6.2 may seem to imply that soil water repellency persisted until one year after the fire, when soils were all wettable, the strong relation with soil moisture highly suggests that soil water repellency will again return when soil moisture drops.

6.4.3 Depth profile of soil water repellency and effects of vegetation removal

Soil water repellency is generally known to decrease with depth (Dekker et al., 2000; Tessler et al., 2008; Woods et al., 2007). However, the depth profile of soil water repellency for the shrub-covered schist soil in the present study showed considerable temporal variation (Figure 6.5). Both the development and the elimination of soil water repellency appeared to occur from the surface down – creating topsoil-only repellency when soils dry out after winter rainfall, and a wettable surface overlying repellent soil when soils rewet in fall. Moreover, it apparently takes a long dry (summer) period to increase water repellency at 5 cm depth (Figure 6.5) under these conditions and at this location. Finally, given the strong relationship between soil moisture content and persistence of water repellency illustrated in Figure 6.2 and Table 6.3, it is noteworthy to mention that these markedly different depth profiles occurred at similar soil moisture levels, suggesting that, rather than a pooled 0-5 cm depth moisture reading, more detailed information on the moisture distribution in the topsoil is needed to get a good indication of the depth profile of soil water repellency.

While both fire and vegetation removal have often been observed to cause similar effects on soil moisture levels (Hulbert, 1969), effects of burning and clipping on soil moisture were limited in the present study (Figure 6.5), possibly due to the fact that moisture differences were shallower than the 0-5 cm layer that was sampled. In spite of this, burning and clipping did show similar impact as to the occurrence of litter and surface soil water repellency. The clipping experiment showed that vegetation removal played a key role in the occurrence of post-fire water repellency in the litter layer and at the soil surface, suggesting that post-fire water repellency may not only be determined by changes to the soil system. However, the data remain inconclusive as to the effect of vegetation removal on below-surface soil water repellency. At 2 cm, wetting and drying effects were 'processed' less quickly than at the soil surface. Clipped and burned soil therefore behaved quite differently: clipped soil exhibited significantly less water repellency than burned soil – possibly because of the slightly higher moisture content. Although it may be true that burned and clipped soils indeed behave differently below the surface, the differences may also have resulted from the different history of the plots. After all, the fire removed the vegetation from the burned plots about three months before vegetation was removed from the clipped plots, imposing a considerably different wetting and drying history. While the current sampling strategy therefore seemed fit to assess the role of vegetation removal on water repellency in the litter layer and at the soil surface, burning and clipping treatments should be installed at the same time to conclusively assess differences or similarities in treatment effects on below-surface soil water repellency.

6.4.4 Implications for fire management and post-fire runoff and erosion risk

From a fire management point of view, the role of vegetation removal in controlling litter and surface soil water repellency is interesting. Wildfire risk is often managed by reducing the amount and continuity of fuel in landscapes by clearing vegetation to make fire breaks or removing forest understory, either mechanically or by prescribed fire (Fernandes et al., 2000; Fernandes and Botelho, 2003; Liu et al., 2010). However, there is increasing discussion about the sustainability of prescribed fires (Carter and Darwin Foster, 2004; Shakesby, 2011; Shakesby et al., 2010b; Smith et al., 2010; Wanthongchai et al., 2008), partly because of the role of (fire-induced) soil water repellency in post-fire land degradation. Although mechanical treatment will not cause heating-associated soil water repellency, the present study does suggest that mechanically treated sites (clipped) are vulnerable for developing soil water repellency because of the increased soil exposure caused by vegetation removal.

Finally, the present study finally gives insight into the role of soil water repellency in post-fire land degradation in areas where soil water repellency is a phenomenon that exists regardless of fire. Knowledge of the natural (pre-fire) variation of the occurrence and persistence of soil water repellency is therefore crucial when assessing the role of soil water repellency as a driving force for land degradation after fire. Although the experimental fire in the Valtorto catchment did increase the occurrence and persistence of topsoil water repellency, and therefore the risk of overland flow during the first post-fire rains, post-fire soil water repellency was entirely within the pre-fire range (Figure 6.1, 6.2). The increased runoff and erosion observed in the Valtorto catchment after the fire (Shakesby et al., 2010b) can therefore not be caused simply by the existence of repellent soils, but should for a large part be attributed to the lack of protective cover and storage capacity of the shrub canopy and surface roughness changes caused during and after the fire (Chapter 5). However, by removing protective cover and water storage capacity, the fire may have increased the hydrological significance of soil water repellency. Because after fire, rainfall is no longer intercepted by the canopy, the fate of double the amount of water is determined by soil water repellency. This large increase in effective rainfall emphasizes the importance of understanding of the role of soil water repellency in causing fire-induced land degradation.

6.5 Conclusions

- The natural background repellency of this typical Portuguese schist soil is high and shows considerable temporal variation. Soil water repellency is however the rule rather than the exception in this system.

- The persistence of soil water repellency (WDPT) was inversely related to soil moisture content, and, for severely to extremely repellent soil, significantly higher with higher organic matter content.

- Fire increased the persistence of soil water repellency, even though the soil temperature at nine out of ten sampled sites remained below 60°C and soil moisture did not significantly change. However, the range of seasonal variation of post-fire soil water repellency lay within the range of natural background levels observed in the study area.

- Vegetation removal played a key role in determining post-fire litter and surface soil water repellency, suggesting that post-fire water repellency is not only determined by changes to the soil system.

- Fire and/or vegetation removal reduced the time and amount of rainfall needed to eliminate water repellency in litter and surface soil from ~600 mm in two months to a mere 30-50 mm in 4-6 d. Likewise but less drastically, it reduced the time needed to induce soil water repellency from < 7-11 to < 2–5 dry days.

- When soil water repellency exists in long unburned systems, post-fire land degradation may not be solely caused by soil water repellency. Yet, fire-induced removal of protective canopy cover and storage may increase the hydrological significance of soil water repellency in burned landscapes.

7   Hydrological changes and effects of scale

Abstract

Fire can considerably change hydrological processes, increasing the risk of extreme flooding and erosion events. Although hydrological processes are largely affected by scale, catchment-scale studies on the hydrological impact of fire are scarce, and nested approaches are rarely used. Taking a unique approach, we performed a catchment-scale experimental fire to improve insight into the drivers of fire impact on hydrology. In north-central Portugal, rainfall, canopy interception, streamflow and soil moisture were monitored in shrub-covered paired catchments pre- and post-fire. Post-fire runoff coefficients were higher than pre-fire, and fire changed the rainfall-streamflow relationship – although the increase in streamflow was only significant at the subcatchment-scale. Fire also increased the response of topsoil moisture to rainfall, and caused more rapid drying of topsoils after rain events. Since soil physical changes due to fire were not apparent, we suggest that changes resulting from vegetation removal played an important role in increasing streamflow after fire, namely: 1) increased effective rainfall and decreased transpiration – increasing the amount of water available for (sub)surface runoff, 2) more rapid development of soil water repellency and decreased surface water storage – increasing overland flow risk, 3) more rapid breakdown of post-fire soil water repellency – increasing infiltration during extended rain events. Results stress that fire impact on hydrology is largely affected by scale, highlight the hydrological impact of fire on small scales, and emphasize the risk of overestimating fire impact when upscaling plot-scale studies to the catchment-scale. Finally, they increase understanding of the processes contributing to post-fire flooding and erosion events.

7.1 Introduction

Wildfires can increase a landscape's vulnerability to major flooding and erosion events (Shakesby and Doerr, 2006). By removing vegetation cover, changing soil properties and inducing soil water repellency, fire can increase runoff which can lead to floods and erosion (Cerdà and Robichaud, 2009). The impact of fire is however largely affected by scale. Despite this scaling challenge, which is universal across all hydrological problems (Blöschl and Sivapalan, 1995), catchment-scale studies on the hydrological impact of fire are scarce. Even though controlled fire experiments can give valuable insight into the drivers of fire-induced hydrological changes and effects of scale, to date catchment-scale controlled fire experiments have not been performed and particularly nested approaches are rarely used. Taking a unique approach, this paper presents a catchment-scale experimental fire study that assesses fire impact on hydrology using paired catchments and a nested approach.

The impact of fire on hydrological processes is generally attributed to the effects of fire-induced soil changes and vegetation removal (Shakesby and Doerr, 2006). By removing vegetative cover, fire increases raindrop impact on bare soil, and reduces storage of rainfall in the canopy, thus increasing the amount of effective rainfall. Moreover, the removal of vegetation causes a major drop in transpiration, reducing depletion of soil water by plants (Silva et al., 2006) thus creating more favorable conditions for runoff. Since the heat of fire can cause considerable damage to the soil system (Cerdà and Robichaud, 2009; Chapter 2), high soil temperatures during fire can additionally affect post-fire hydrological processes. Of particular importance in post-fire hydrology is reduced infiltration resulting from, for instance: 1) possible pore-clogging by infiltrated ash (Balfour and Woods, 2007; Onda et al., 2008, Chapter 2), 2) development of soil water repellency during fire (DeBano, 2000a), and 3) occurrence of surface sealing due to the increased exposure to raindrop impact (Larsen et al., 2009; Llovet et al., 2008). In addition, pronounced soil heating can reduce soil water retention capacity (Chapter 2) and also contribute to a changed post-fire rainfall runoff response.

Given the abovementioned changes in effective rainfall, transpiration, water infiltration and retention, fire tends to increases the runoff coefficient, or the fraction of rainfall converted to runoff (Onda et al., 2008; Rosso et al., 2007; Rulli et al., 2006; Scott and Van Wyk, 1990). As a result, a number of studies have reported initial increases in overland flow (Beeson et al., 2001; Johansen et al., 2001; Prosser and Williams, 1998) and peakflow volume after fire (Brown, 1972; Gottfried et al., 2003; Scott, 1993; Seibert et al., 2010), explaining the increased vulnerability of burned areas to flooding events. Observed increases in annual and dry season streamflow (Brown, 1972; Hibbert, 1967;

McMichael and Hope, 2007; Meixner and Wohlgemuth, 2003) can furthermore contribute to flooding as a cumulative effect. Since the hydrological impact of fire is related to soil and vegetation changes, the longevity of the hydrological impact is related to the recovery time of soil and vegetation, which varies between ecosystems and can be as rapid as a few years but also as long as many decades (Shakesby and Doerr, 2006).

As mentioned, hydrological processes are highly affected by scale, both in burned and unburned systems (Blöschl and Sivapalan, 1995; Shakesby and Doerr, 2006; Van der Velde et al., 2010). Due to the effects of mixing and filtering (Skøien et al., 2003) and reduced hydrological connectivity at larger scales (Bracken and Croke, 2007; Cammeraat, 2002), changes observed at the plot-scale tend to overestimate changes occurring at the hillslope- or catchment-scale (e.g. Doerr et al., 2003; Prosser and Williams, 1998). For example, increased patchiness and storage at the catchment scale (Ferreira et al., 1997) can facilitate infiltration of runoff downslope, which reduces overland- and streamflow volumes. Because of the pronounced effect of scale on post-fire hydrology, fire effects on flooding risk are best assessed at the catchment scale. Yet, as previously noted, catchment scale hydrological studies assessing fire impact are scarce (Shakesby, 2011; Shakesby and Doerr, 2006).

Although controlled fire experiments are a useful tool for assessment of fire impact in the field, such experiments have to date been restricted mostly to plot and hillslope scales. As a result, catchment-scale fire studies are limited to impact assessment of accidental wildfires in previously or actively monitored watersheds (e.g. Brown, 1972; Meixner and Wohlgemuth, 2003; Scott, 1993), or post-fire assessment of the hydrology of burned catchments (Mayor et al., 2007; Moody and Martin, 2001). In both cases, knowledge of the degree of soil heating during the fire and subsequent impact on soil properties is unknown, thus hindering assessment of all factors contributing to hydrological change. Moreover, despite the high fire occurrence in the European Mediterranean (Moreira et al., 2001; Pausas, 2004), catchment-scale wildfire studies have only been conducted in the USA (Gottfried et al., 2003; Meixner and Wohlgemuth, 2003; Nasseri, 1989; Seibert et al., 2010), South Africa (Scott, 1993; Scott, 1997; Scott and Van Wyk, 1990) and Australia (Brown, 1972; Langford, 1976; Prosser and Williams, 1998), and at just two locations in the European Mediterranean (Lavabre et al., 1993; Mayor et al., 2007). Better understanding of the hydrological impact of fire at the catchment-scale can improve understanding and prediction of the risk of flooding in burned areas.

The purpose of the present study was to evaluate the impact of fire on hydrological processes and the causes of any changes at the catchment scale. A catchment-scale experimental fire was performed in a region of Portugal seriously affected by fires and

post-fire land degradation. This paper focuses on the short-term (≤ 1 yr) effects of fire on (soil) hydrology, and discusses the effects of scale as well as the value of experimental fire research at the catchment scale.

Our main hypothesis follows the reviewed literature and is that fire alters catchment hydrology as a result of reduced canopy interception and an increased occurrence of soil water repellency. Because post-fire streamflow volumes are larger and streamflow response to rainfall events is more rapid, flooding risk is increased. To test this hypothesis and to improve understanding of fire-induced hydrological changes, the effects of fire on streamflow and soil moisture were studied using paired catchments, and the importance of rainfall, canopy interception and soil moisture in streamflow generation was assessed.

7.2   Methods

7.2.1 Research catchments

The study area is located on the eastern slopes of the Serra da Lousã in north-central Portugal (Figure 7.1). Precipitation occurs predominantly in winter, with the summer being a pronounced dry period with high wildfire risk. Both research catchments, Valtorto (burned) and the nearby Espinho (control) are characterized by an ephemeral stream and are similar in size, exposure, geology and vegetation type (Table 7.1, p. 108). Moreover, they lack the man-made terraces often found in (abandoned) valleys in this region, which increase soil water storage potential and thus affect streamflow response.

Soils and vegetation are typical for the region. Soils are formed on schist or quartzite bedrock. They are generally shallow gravelly loamy sands (USDA, 1993), rich in organic matter, with considerable rock fragment content and cover (Table 7.1). The vegetation consists of dense heathland dominated by *Erica* sp*, Ulex* sp., *Pterospartum tridentatum and Genista triacanthos*, regenerated after wildfire burned both catchments in the summer of 1990 and a prescribed fire burned the Valtorto catchment in April 1996. Because of the longer time since the last fire, the vegetation in the Espinho catchment was slightly taller than that in the Valtorto catchment (Table 7.1). Moreover, because of this 1996 prescribed fire, an existing structure of fire breaks confined the burned area in the Valtorto catchment, which closely matched the shape and size of the topographical watershed defined using ArcGIS (Figure 7.1c).
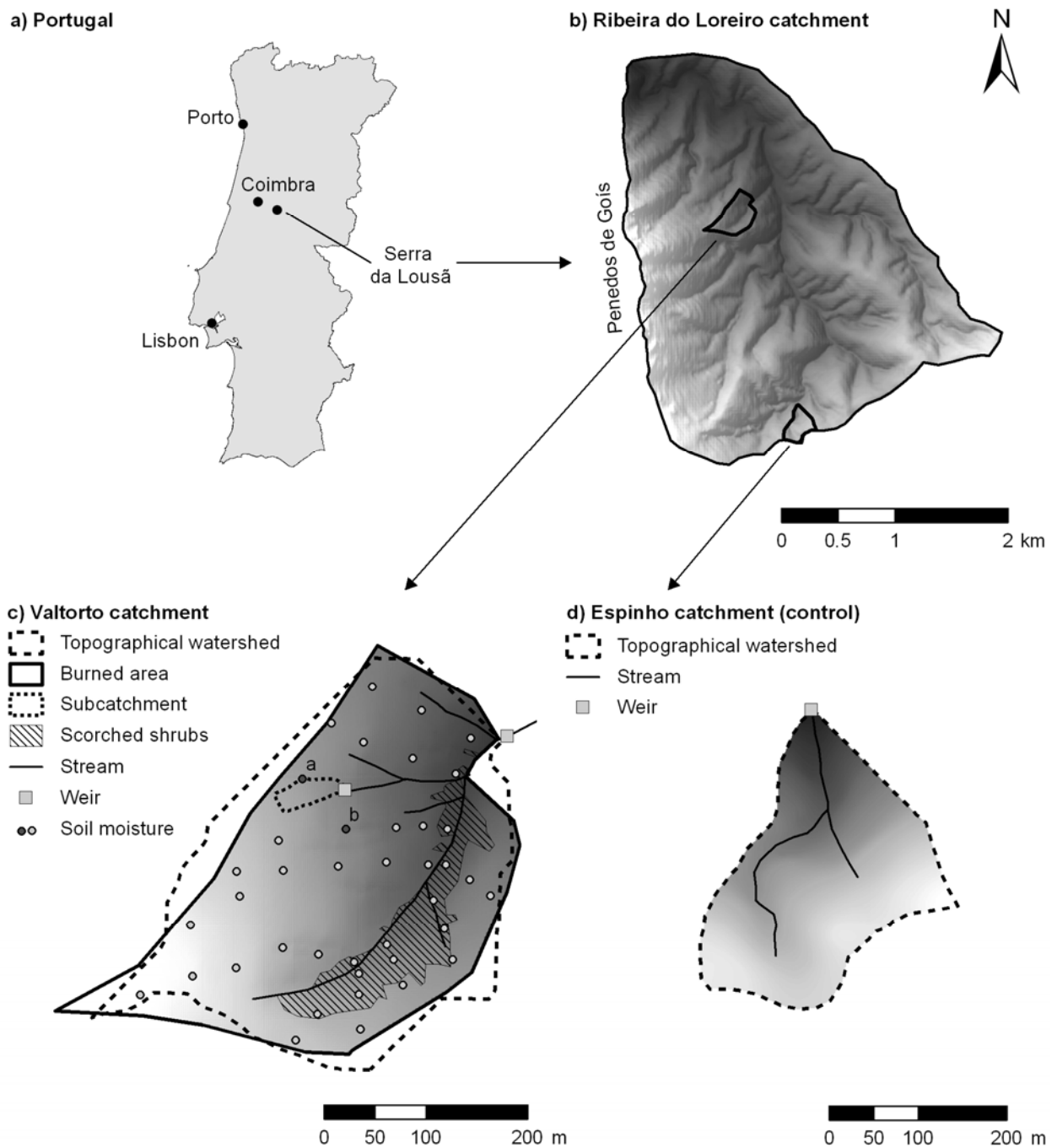
Figure 7.1 Location of the Valtorto and Espinho catchments, showing the sampling design. Letters 'a' and 'b' in graph c indicate the soil moisture locations nearest to the subcatchment (see Figure 7.9). Grey shading in graphs b, c and d represents elevation, enhanced using hillslope shading in ArcGIS.

7.2.2 Experimental fire

The Valtorto catchment was burned by a high-intensity experimental fire on 20 Feb 2009. The aim was to simulate a wildfire to the greatest extent possible within safety

constraints, in order to get a soil hydrological response similar to natural conditions. Details about how the fire was conducted can be found in Chapter 4 and 5. While flame temperatures reached ~700°C and fire intensity in some places exceeded 15.000 kW/m, shrubs were not completely consumed throughout the catchment (Figure 1c) and soil temperatures remained relatively low (Chapter 4). Although maximum soil surface temperature was locally as high as 800°C, soils in the majority of the catchment remained below 100°C. As a result, soil hydrologic properties such as saturated hydraulic conductivity and soil porosity did not change significantly (Chapter 5). However, overland flow resistance and soil surface roughness decreased significantly because of the fire and the post-fire exposure of the soil (Chapter 5).

Table 7.1 Site and soil characteristics of the Valtorto and Espinho catchments, as mapped before the fire. Values are means over the number of observations (n) ± one standard deviation, and 'n.d' stands for 'not determined'.

Parameter	Value			
Annual precipitation (mm)	1050			
Monthly temperature (°C)	7.8 (Dec); 20 (Aug)			
	Valtorto	**n**	**Espinho**	**n**
Treatment	Burned		Control	
Location	40° 06′ 21″ N 8° 07′ 03″ W		40° 05′ 21″ N 8° 06′ 41″ W	
Size (ha) †	9.7; 0.13 ‡		4.9	
Percentage burned (%)	88; 100 ‡		0	
Elevation (m a.s.l.)	600-750		695-800	
DEM slope (%)	38 ± 16		36 ± 18	
Soil depth (m)	0.16 ± 0.13	322	0.18 ± 0.13	46
Soil bulk density (g/cm^3) §	0.82 ± 0.13	265	0.81 ± 0.16	46
Soil organic matter content (weight%) §	21.0 ± 5.2	226	23.0 ± 8.9	46
Soil porosity (%) #	60.2 ± 4.4	42	n.d.	
Saturated hydraulic conductivity (m/d) #	1.4 ± 0.7	42	n.d.	
Rock fragment content (cm^3/cm^3) §¶	0.16 ± 0.06	247	0.18 ± 0.06	46
Surface rock cover (%)	56.0 ± 26.4	252	54.3 ± 30.1	46
(Pre-fire) vegetation height (m)	0.50 ± 0.26	269	0.79 ± 0.41	46
(Pre-fire) vegetation cover (%)	80.9 ± 18.0	246	75.3 ± 18.2	46

† The size of the topographical watershed was defined in ArcGIS, using a digital elevation model of the area and additional expert knowledge. The 10-m DEM was too coarse to determine the size of the Valtorto subcatchment, which was instead determined in the field using a GPS; ‡ Valtorto main catchment and subcatchment, respectively; § 0-2.5 cm depth; # 0-4 cm depth, ¶ Rock fragments are defined as particles > 2 mm, volumetric values given correspond to a gravimetric rock fragment content of 0.407 ± 0.108 and 0.458 ± 0.108 g/g for Valtorto and Espinho, respectively.

7.2.3 Hydrological monitoring

A paired-catchment design was adopted in order to separate hydrological effects of the experimental fire from natural hydrological variability. Pre- and post-fire time series of rainfall and streamflow were collected in the burned catchment (Valtorto) and in the unburned control catchment (Espinho). Details of the methodology are given in the following paragraphs and summarized in Table 7.2. Effects of scale on post-fire hydrological processes were assessed using a nested approach. For this purpose, streamflow in the Valtorto catchment was not only monitored at the outlet of the main catchment, but also at the outlet of the 0.13 ha unbounded subcatchment halfway up the southeast-facing slope (Figure 7.1c). Finally, topsoil moisture content and canopy interception were monitored in the Valtorto catchment only.

Table 7.2 Monitoring equipment used in the Valtorto (burned) and Espinho (control) catchments between 2007 ('07) and 2010 ('10). Since there was no power source available in either catchment, all loggers were stand-alone, had individual batteries, and were downloaded manually.

| Parameter | # Monitoring sites | | Equipment/Probe and data logger | Monitoring interval | Time period |
	Valtorto (burned)	Espinho (control)			
Rainfall	2	1	Tipping bucket rain collector (Davis Instruments, CA, USA) with Odyssey data recorder (Dataflow Systems, New Zealand)	0.2 mm	Aug'07–Feb'10
Canopy throughfall, interception	3	n/a	5-L water jugs (25 cm high, 196.5 cm^2) using five replicates and one cumulative rainfall measurement per site, manual observation †	~weekly	Nov'08–Feb'09
Streamflow	2 ‡	1	Odyssey capacitance water level probe (Dataflow Systems, New Zealand)	5 min	May'08–Feb'10
			MiniDiver along with BaroDiver for air pressure correction (Schlumberger Water Services, UK) §	5 min	Jul'08–Feb'10
Soil moisture	40	n/a	EC-5 sensor (Decagon Devices, WA, USA) with SMR 100 data recorder (MadgeTech, NH, USA)	5 min	Apr'08–Feb'10

† 4 out of 180 records (2%) were deleted because the amount of throughfall exceeded the cumulative rainfall (likely due to stem flow), which made it impossible to estimate the contributing area; ‡ In the Valtorto catchment, streamflow was monitored at the catchment and subcatchment scale; § Given the short distance between the catchments (3 km) and their similar elevation, one BaroDiver was used for both catchments.

Hydrological monitoring started in August 2007 but due to frequent data logger failure, reliable streamflow and soil moisture data was only collected from May 2008 onwards

(10 months before the fire). Replicate rain gauges and water level recorders were installed to ensure continuation of data collection in case of logger failure. In addition, all sensors and data loggers were removed from the catchment the day before the fire to prevent fire damage to the monitoring equipment. All equipment was consequently reinstalled the day after the fire.

7.2.4 Rainfall and potential evapotranspiration

Rainfall was recorded at 0.2 mm intervals using tipping bucket rain gauges (Table 7.2) mounted above the shrub canopy on 1.5 m-high metal stakes. Two rain gauges were installed in Valtorto, and one in Espinho. Because both rain gauges in Valtorto were highly correlated ($r= 0.996$, RSE 0.67 mm), the catchment rainfall was calculated as the hourly or daily average of the two gauges. Since instrument failure never occurred for both rain gauges at the same time, there were no periods of missing data in Valtorto. Missing data in Espinho were filled using the Valtorto bottom gauge, which was slightly better correlated to the Espinho data ($r= 0.975$, RSE 2.1 mm) than the center gauge.

Potential evapotranspiration was not measured in the catchment but is measured by the Portuguese Meteorological Institute in the city of Coimbra, 50 km NW of the research catchments. Data was acquired from ten-day meteorological bulletins published online at www.meteo.pt.

7.2.5 Canopy throughfall and interception

Canopy interception was estimated from cumulative throughfall measurements during the pre-fire winter period, not taking stemflow into account. We cut the tops off of 5-L water jugs (Table 7.2), and placed five replicate jugs beneath shrubs at three locations in the catchment, characterized by medium dense (44 ± 27% cover, ~0.4 m high), dense (67 ± 24% cover, 0.5 to 0.6 m high) and tall vegetation (84 ± 21% cover, 1.5 to 2.0 m high). Care was taken to make sure that the jugs were level. Cumulative rainfall was measured in a natural clearing close to each location using a similar jug, and canopy interception was calculated for each jug based on the measured throughfall and the mean cumulative rainfall for that period. Jugs were installed on 17 Nov 2008 and emptied on 10 occasions until early February 2009. Because air temperatures were low and jugs were emptied during and/or quickly after major rain events, evaporation loss was considered negligible.

7.2.6 Streamflow

Streamflow, also referred to as 'flow', was measured using V-notch weirs at the outlet of the catchments, and water levels were recorded at 5-min intervals in a stilling pond

upstream of each weir. Two different water level probes were used (Diver and Odyssey type, Table 7.2). The stage-discharge relationship of each weir was determined from a set of manually measured water levels and streamflow (discharge) volumes. Subsequently, the stage-discharge relationships for each weir and water level probe were determined by fitting the power function $Q = aH^b + c$ (or $Q = aH^b$ in case the intercept was not significant) to the set of measured Q-H points[1], where Q is the discharge and H is the water level. Diver and Odyssey logger results were highly correlated (r> 0.999 for Valtorto and r> 0.982 for Espinho), and streamflow was therefore calculated as the mean when records of both loggers were available.

The weirs were regularly checked and plant material that could possibly block the flow was removed. In addition, data was deleted when flow was observed to be obstructed – which happened in the Valtorto main weir in early Dec 2009. In all cases, large data gaps were left as is, while small data gaps (< 2 h) were filled in by linear interpolation.

7.2.7 Soil moisture

Soil moisture content was monitored at 5-min intervals at 40 sites in the Valtorto catchment using Madgetech data loggers connected to Decagon EC-5 sensors (Table 7.2) installed at 2.5 cm depth. This chapter discusses the effect of fire on the catchment average soil moisture – spatial differences will be analyzed and discussed in a future paper.

All soil moisture probes were calibrated in the laboratory before installation in the field, and afterwards validated using soil moisture sampling adjacent to the probes in the field. The laboratory calibration was performed using repacked soil columns with known moisture content, using soil from the Valtorto catchment that was sieved (2 mm) and repacked at a dry bulk density typical for the catchment (0.88 g/cm^3). To choose the best calibration curve, different curves (linear or polynomial, fitted to all sensors together or to each sensor individually) were validated with field topsoil moisture contents sampled within 0.5 m of the probe. Validation sampling was performed on five occasions using soil cores (50 cm^3, 0-2.5 cm deep, n=209 for all sampling dates together) that were weighed and oven dried (24 h at 105°C) to determine field moisture content.

The final calibration using a 2nd order polynomial (Eq. 7.1, next page) resulted in an overestimation of 0.034 ± 0.088 cm^3/cm^3 soil moisture content, which may be attributed to probe-to-probe and bulk density variations (Parsons and Bandaranayake, 2009; Rosenbaum et al., 2010), temperature variation (Bogena et al., 2007), small scale

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[1] n=49 and 54 for Valtorto Diver and Odyssey water level recorder (WLR), respectively, n=17 for Valtorto subcatchment Diver, and n=17 and 16 for Espinho Diver and Odyssey WLR, respectively.

variability of soil moisture content in the field (Dekker and Ritsema, 2000), and the presence of rock fragments in the soils in the Valtorto catchment (Table 7.1).

$$\theta = 1.59{\cdot}10^{-6}\ V^2 + 2.15{\cdot}10^{-5}\ V - 0.116 \qquad\qquad\qquad (7.1)$$

where θ = soil moisture content (cm^3/cm^3) and V = logger output voltage (mV). The 2nd order polynomial fitted the lab calibration points (n=150) with an r^2 of 0.97. See Appendix 7.1 for a comparison between the final lab calibration and Decagon and Madgetech factory calibrations.

7.2.8 Data storage and analyses

Rainfall, streamflow and soil moisture data was managed through a MySQL database (MySQL version 5.0.67), and analyses were done in R version 2.11.1 (R Development Core Team, 2010). Since the length of data and the pronounced wet winter seasons made it difficult to distinguish individual storm events, comparisons of treated and untreated catchments before and after the fire were made using hourly, daily and weekly values of rainfall, streamflow and soil moisture rather than on a storm-by-storm basis.

The effects of vegetation cover on canopy throughfall were assessed following a repeated measures experiment, in which the optimal model was selected using a similar approach as described by Webster and Payne (2002), using the nlme package in R (Pinheiro et al., 2009).

Fire-induced hydrological changes were assessed by comparing pre- and post-fire rainfall-runoff coefficients for the entire monitoring period, as well as daily probability distributions (also referred to as flow, rainfall or moisture distributions) and hourly cross-correlations of rainfall, streamflow and soil moisture. Furthermore, fire effects were statistically analyzed using ANCOVA's, analyzing streamflow and soil moisture changes due to fire effects while taking into account autocorrelation and changes in the rainfall distribution. Given the effects of scale on the delay between rainfall and streamflow response, caused by water routing, mixing and storage (Skøien et al., 2003), these ANCOVA analyses were performed at the time scale appropriate for each spatial scale. This meant that the changes in the rainfall-streamflow relationship in the Valtorto subcatchment and the rainfall-soil moisture relationship were analyzed on a daily basis, while the catchment-scale data in Valtorto and Espinho required aggregation to weekly data. Finally, the role of rainfall and soil moisture on streamflow generation was more closely evaluated in the Valtorto subcatchment. Here, the absence of a slow-flow component did allow analysis on a storm-by-storm basis.
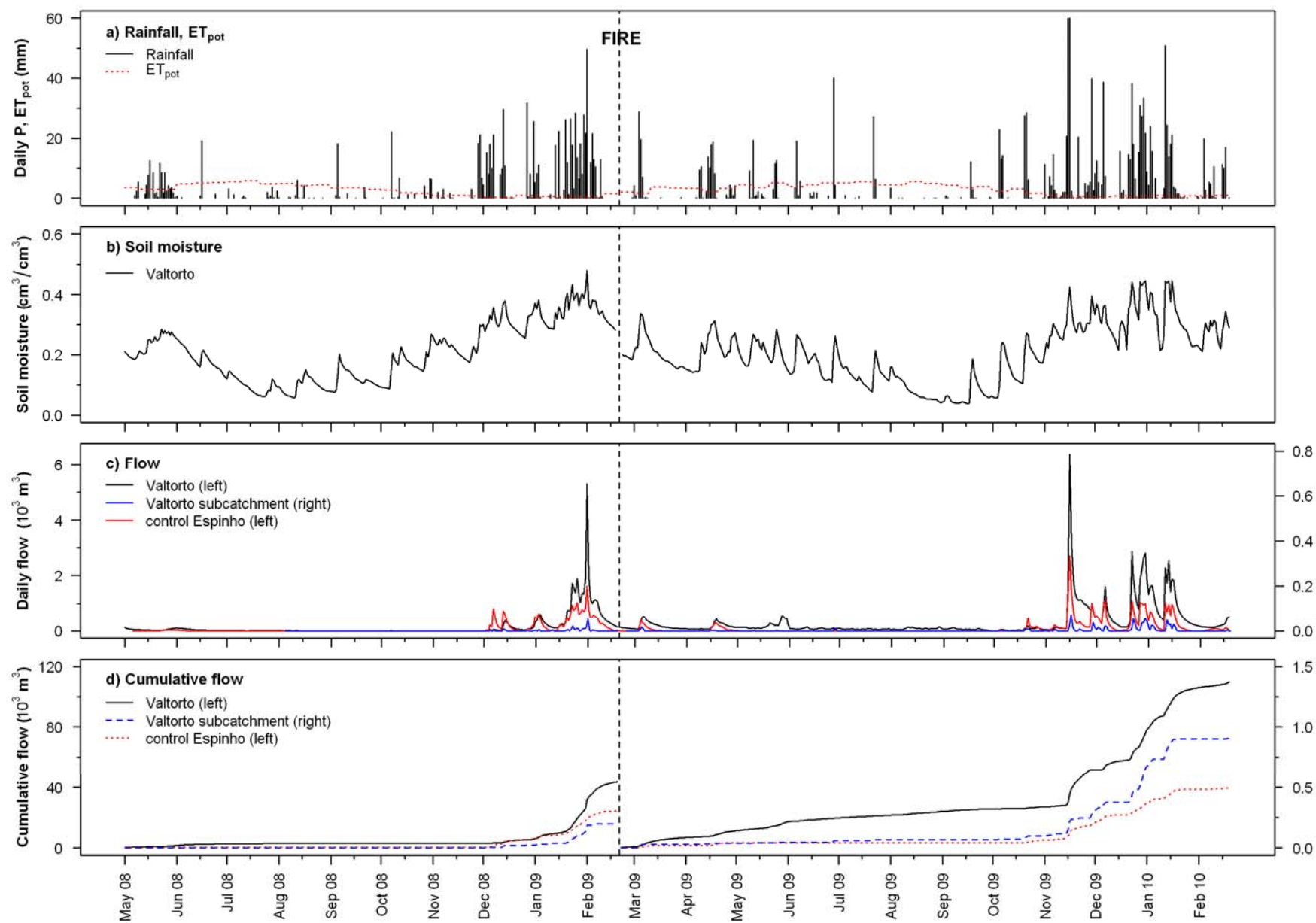
Figure 7.2 (previous page) Time series of daily rainfall (P) and potential evapotranspiration (ET$_{pot}$, a), catchment average soil moisture content (b), streamflow (c) and cumulative streamflow (d) before and after the experimental fire (vertical dashed line). Note that only the Valtorto catchment was burned; Espinho is the unburned control catchment. Also note that in the streamflow graphs (c, d), the values on the primary y-axis (left) apply to the Valtorto and Espinho main catchments, while the values on the secondary y-axis (right) apply to the subcatchment.

Table 7.3 Summary statistics of pre- and post-fire rainfall, potential evapotranspiration (ET$_{pot}$), streamflow (flow) and the catchment average soil moisture, which was calculated by taking the arithmetic mean of the moisture records available for each time step.

| Parameter		Rainfall		ET$_{pot}$	Flow			Soil moisture
		Valtorto	Espinho	(Coimbra)	Valtorto main	Valtorto sub	Espinho (control)	Valtorto
		%	%	%	%	%	%	n/a
Occurrence (% of days)	Pre	45	53	n/a	64	18	33	n/a
	Post	45	51	n/a	99	22	48	n/a
		mm	mm	mm	m^3	m^3	m^3	cm^3/cm^3
Sum †	Pre	878	1069	811	44·10^3	195	24·10^3	n/a
	Post	1352	1568	1068	110·10^3	904	39·10^3	n/a
Daily mean ‡	Pre	3.0	3.6	2.8	148	1.0	84	0.207
	Post	3.7	4.3	2.9	308***	2.5*	108	0.204
Daily median	Pre	0.0	0.2	3.1	11.8	0.0	4.5	0.199
	Post	0.0	0.2	3.4	100.3	0.0	0.0	0.201
Daily min	Pre	0	0	0.4	0	0	0	0.057
	Post	0	0	0.5	0	0	0	0.039
Daily max	Pre	50	43	5.9	5.3·10^3	52	1.6·10^3	0.480
	Post	60	65	5.6	6.4·10^3	71	2.7·10^3	0.447
		%	%	%	%	%	%	%
CV	Pre	228	221	66.4	302	452	251	47
	Post	236	234	58.7	194	344	248	48

† Note that the pre-fire monitoring period for the Valtorto subcatchment (199 d from 5-08-2008 to 20-2-2009) is shorter than the pre-fire monitoring period for all other sites (265 d from 1-05-2008 to 20-2-2009). The post-fire monitoring period is in all cases from 21-2-2009 to 20-2-2010 (365 d); ‡ Daily mean values include days without rainfall or streamflow. Asterisks indicate where pre- and post-fire means are significantly different at $p < 0.05$ (*), and $p < 0.001$ (***).

7.3 Results

7.3.1 Rainfall

Time series of rainfall, potential evapotranspiration (ET_{pot}), streamflow and soil moisture content are displayed in Figure 7.2 and summary statistics are given in Table 7.3.

Pre- and post-fire monitoring periods were both characterized by a moderately wet spring, a fairly dry summer with occasional rain events, and a very wet winter period (Figure 7.2a). The rainfall patterns in Valtorto and Espinho were highly correlated (r= 0.99), despite the fact that total rainfall was considerably higher in Espinho (Table 7.3), likely because of its ridge-side location. Because the post-fire monitoring period was 19% longer than the pre-fire period, total rainfall and ET_{pot} were considerably higher for the post-fire period. However, rainfall occurrence (the fraction of days with rainfall) was similar before and after the fire, and daily mean rainfall and ET_{pot} were not significantly different. In spite of this, the occurrence of large rain events (> 20 mm in one day) was higher after the fire than before (Figure 7.3a).
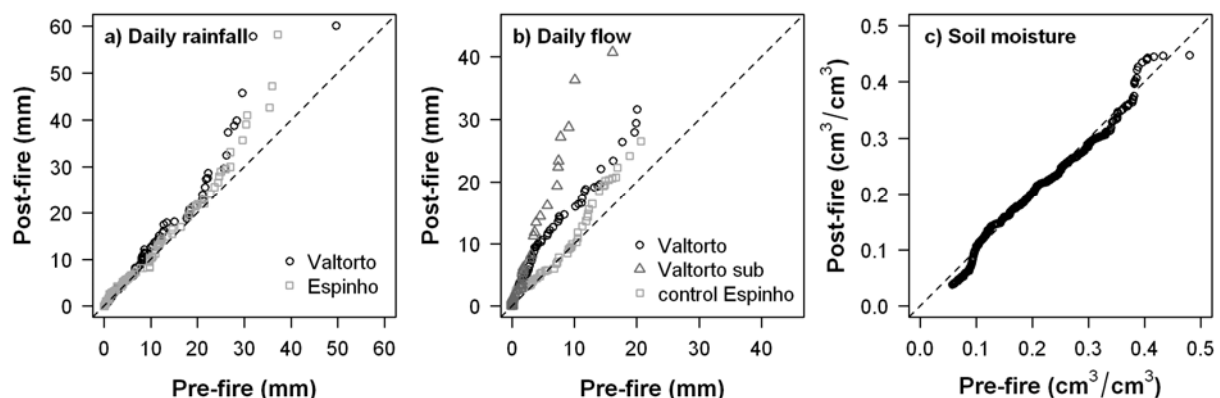
Figure 7.3 QQ-plots of daily rainfall (a), streamflow (b) and soil moisture (c) in the Valtorto (burned) and Espinho (control) catchments, comparing the quantiles of pre- and post-fire distributions relative to the 1:1 line (dashed). To facilitate comparison between the different catchments and scales, flow volumes in graph (b) are given in mm. The graphs show that rainfall (a) and flow distribution (b) changed for all catchments, while the soil moisture distribution (c) remained largely unchanged.

7.3.2 Canopy throughfall and interception

Canopy throughfall of the unburned vegetation in Valtorto was measured in the wet winter period before the fire (Figure 7.4), and averaged 51.3 ± 17.8% of total rainfall, resulting in an estimated canopy interception of 48.7 ± 17.8%. Post-fire canopy interception of the regenerating vegetation was not measured, but was assumed to be
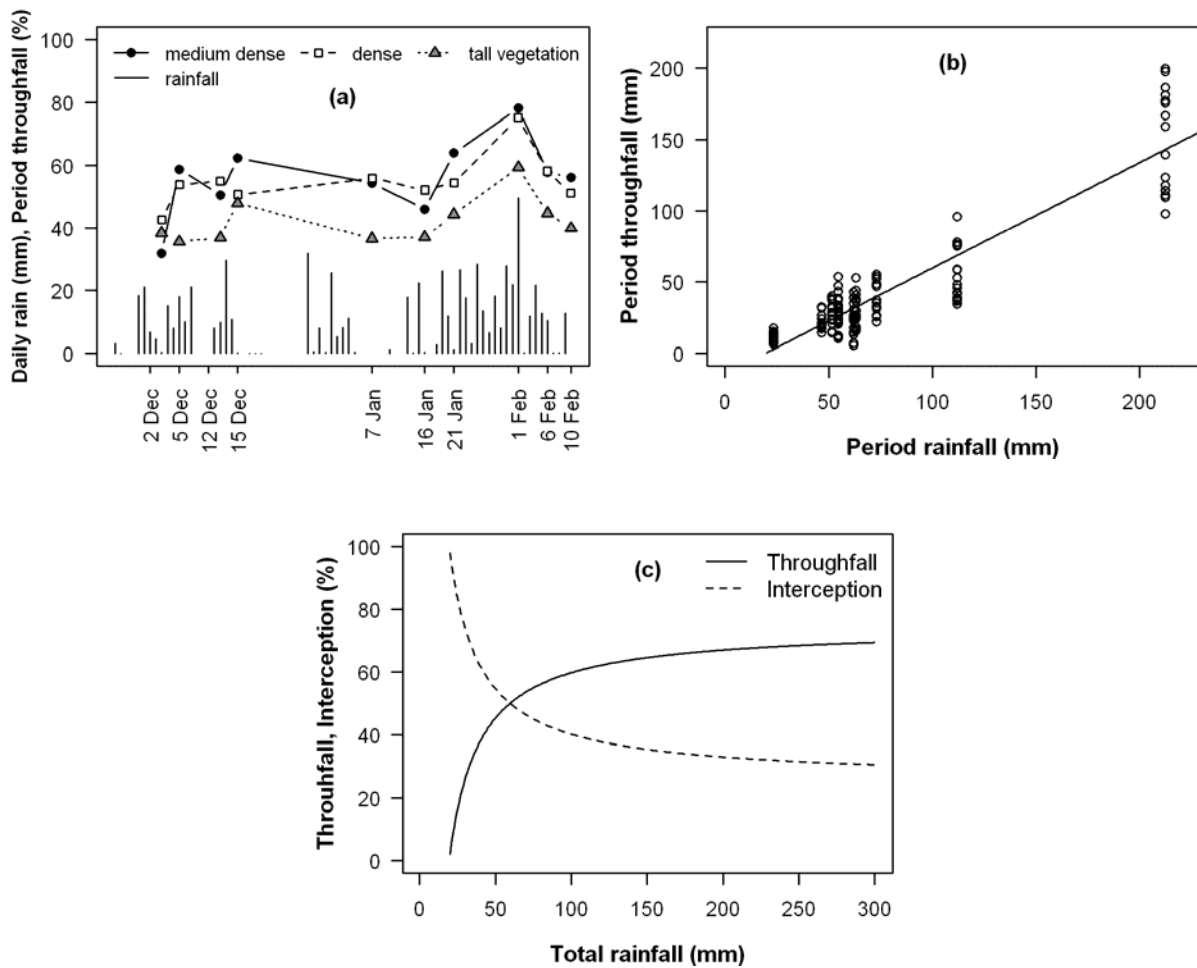
Figure 7.4 December 2008 to February 2009 time series of daily rainfall and period totals of throughfall for different vegetation density and height (a), the relation between throughfall and total rainfall for each measurement period (b), and the throughfall and interception fraction as a function of total rainfall (c). Throughfall fraction was defined as the ratio between the amount of throughfall and total rainfall, and likewise for canopy interception. 'Medium dense' vegetation was ~0.4 m high and had 44 ± 27% canopy cover, 'dense' vegetation was 0.5 to 0.6 m high and had 67 ± 24% canopy cover, and 'tall' vegetation was 1.5 to 2.0 m high and had 84 ± 21% canopy cover.

minimal because of the sparseness of the regenerated vegetation cover, that only reached 30% one year after the fire (Shakesby et al., 2010b).

Pre-fire canopy throughfall was not significantly different between the sites in the Valtorto catchment (p=0.065), although it was slightly less for the tall vegetation than for the lower vegetation ('dense' and 'medium dense', Figure 7.4a). Although throughfall was fairly constant in time, it significantly increased during 15 consecutive rain days mid-January 2009 (p<0.0001, Figure 7.4a), indicating that the throughfall fraction increased with increasing rainfall. Following Gash and Morton (1978), total rainfall was plotted against total throughfall, and a linear regression line (Eq. 7.2, r^2=0.84, n=150) was fitted

through the points (Figure 7.4b). The regression line crosses the x-axis at x=19.5 mm, indicating that roughly the first 19.5 mm of rainfall was intercepted by the canopy. This value should not be confused with the maximum canopy storage, but is rather represents the actual storage and loss over a few days. Because of the offset, the throughfall fraction was not a constant, but increased with rainfall (Figure 7.4c). Likewise, the fraction of canopy interception decreased with rainfall (Figure 7.4c), emphasizing that the relative canopy storage was smaller for larger rain events.

$$TF = 0.742*P - 14.4 \tag{7.2}$$

where TF= throughfall (mm) and P = rainfall (mm)

7.3.3 Streamflow

Similar to the rainfall pattern, streamflow occurred mainly in the winter period, and was highly intermittent at the subcatchment scale. After the fire, the occurrence of streamflow (fraction of days with streamflow > 0) was higher for all three sites (Valtorto and Espinho catchments and Valtorto subcatchment), and resulted in almost year-round streamflow in the main Valtorto catchment after the fire (Table 7.3, Figure 7.2c-d). Because of its larger size, total streamflow in the main Valtorto catchment exceeded that of the control Espinho catchment (Table 7.3, Figure 7.2c-d).

Because of the change in rainfall distribution after the fire (Figure 7.3a), changes in streamflow patterns cannot be simply attributed to the effects of fire alone, particularly because streamflow characteristics also changed in the unburned control catchment. However, for nearly all the measured streamflow parameters, the level of change in the burned catchment relative to the unburned catchment suggests considerable fire effects. Firstly, daily streamflow increased significantly in the burned Valtorto catchment, and did not increase in the control Espinho catchment (Table 7.3). Secondly, the coefficient of variation for daily streamflow decreased in the burned Valtorto catchment, but remained largely unchanged in the unburned Espinho catchment, suggesting that daily flows in Valtorto had become more continuous and less intermittent (Table 7.3). Thirdly, the streamflow distribution showed a distinct shift upward from the 1:1 line in the quantile plot (Figure 7.3b), indicating that streamflow in all catchments was greater post fire than pre fire. However, the upward shift was greater in the burned Valtorto catchment, particularly at the subcatchment scale, than in the unburned Espinho catchment (Figure 7.3b). Fourthly, the overall runoff coefficient, the amount of streamflow per unit rainfall across the entire monitoring period, increased considerably more in the burned catchment (1.7 and 2.5-fold increase at the catchment and subcatchment-scale, respectively) than in the control catchment (1.1-fold increase, Figure 7.5). And finally, while the lag time between streamflow and rainfall decreased and the lag 0 correlation

increased after the fire in both the burned and unburned catchment, the increase in the correlation (and thus the increase in the immediate streamflow response to rainfall events) was most clear in the burned Valtorto catchment, particularly at the sub-catchment scale (Table 7.4).
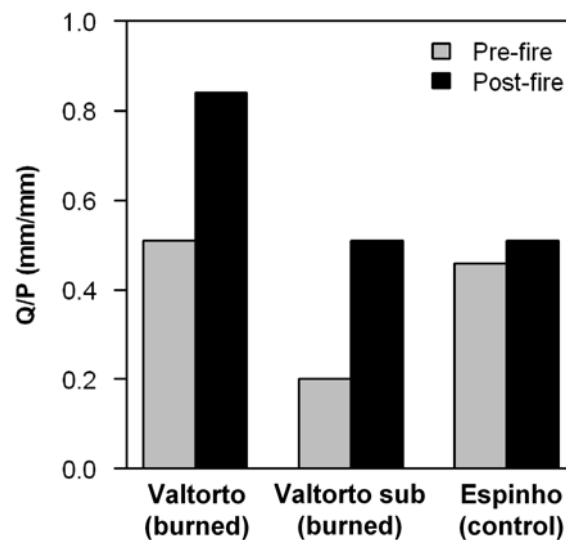

Figure 7.5 Runoff coefficient (Q/P) in the Valtorto catchment, the Valtorto subcatchment (sub) and the Espinho catchment, calculated as the total streamflow divided by the total rainfall, for the entire pre- and post-fire monitoring periods.

Table 7.4 Lagtime of the streamflow and moisture response to rainfall and strength of the correlation between streamflow (flow) and rainfall, and soil moisture and rainfall, derived from cross-correlation analysis of hourly rainfall, streamflow and soil moisture data.

Parameter		Rainfall ~ Flow			Rainfall ~ Soil moisture †
		Valtorto main	Valtorto sub	Espinho (control)	Valtorto
Time to peak (h)	Pre-fire	4	1	3	2.7 ± 1.6
	Post-fire	2	1	1	2.0 ± 1.4 *
Strength of correlation	Pre-fire	0.389	0.514	0.480	0.325 ± 0.048
	Post-fire	0.442	0.636	0.535	0.350 ± 0.055 *
	% increase	14	24	11	8

† Cross-correlation analysis performed on all moisture sites separately for which good quality moisture records were available (n=39), and changes in lagtime and correlation strength were analyzed using ANOVA; significant differences (p<0.05) between pre- and post-fire values are indicated using an asterisk.

More detailed statistical analysis to separate the effects of fire and rainfall variability using ANCOVA indicated (not surprisingly) that rainfall was a highly significant predictor of streamflow (p=0.000 in all catchments). While fire did not appear to change the rainfall-streamflow relationship in the control Espinho catchment (p=0.956, based on weekly data), it did shift the rainfall-streamflow relationship in the burned Valtorto catchment (Figure 7.6). While this shift was not significant at the catchment scale (p=0.323, based on weekly data), it was significant at the subcatchment scale (p=0.048, based on daily data) where the changes were also the greatest (Figure 7.6).
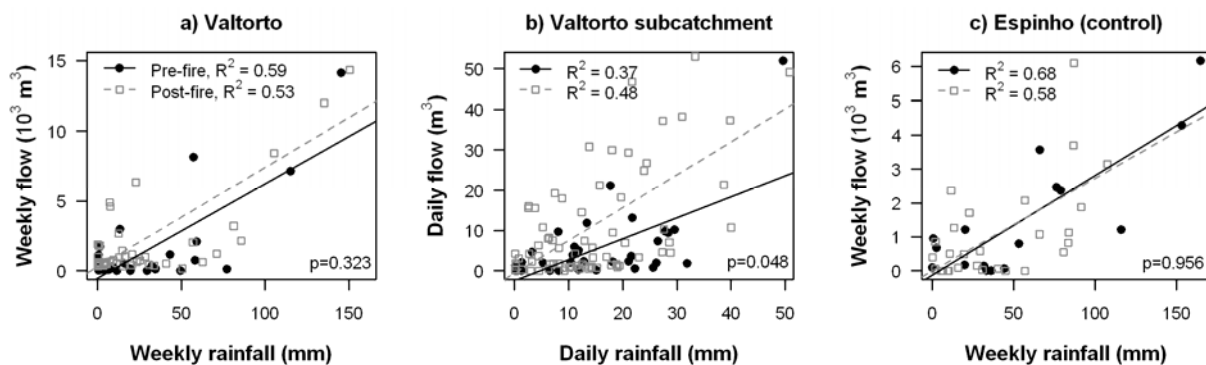
Figure 7.6 Rainfall-streamflow relationships in the burned Valtorto catchment (a, based on weekly data), the Valtorto subcatchment (b, based on daily data) and the Espinho control catchment (c, based on weekly data). R^2 values refer to the goodness of fit of the regression lines, and p-values indicate whether pre- and post-fire regression lines were significantly different.

7.3.4 Soil moisture

Catchment average topsoil moisture fluctuations were strongly related to rainfall occurrence both before and after the fire (Figure 7.2a-b). Although the average topsoil moisture content appeared to drop considerably directly after the fire (Figure 7.2b, near dashed line), the daily catchment mean moisture content for the post-fire period was not significantly different from the pre-fire value (Table 7.3). The distribution of the catchment mean soil moisture content was fairly similar before and after fire (Figure 7.3c), however there was a slight increase in the occurrence of low (< 0.10 cm^3/cm^3) and high moisture contents (0.40 to 0.45 cm^3/cm^3) after the fire.

Analysis of covariance (ANCOVA) of the catchment average soil moisture content indicated that there was a significant interaction between rainfall and fire (interaction p= 0.0002). This indicated that the response of the average soil moisture content to fire varied with rainfall amount, for example, that fire affected the soil moisture content on dry days differently than on rainy days. To illustrate: mean soil moisture content on dry days significantly decreased from 0.171 cm^3/cm^3 before the fire to 0.155 cm^3/cm^3 after

(p=0.03), while the mean soil moisture content on days with rainfall slightly though not significantly increased from 0.251 to 0.263 cm^3/cm^3 (p= 0.256).
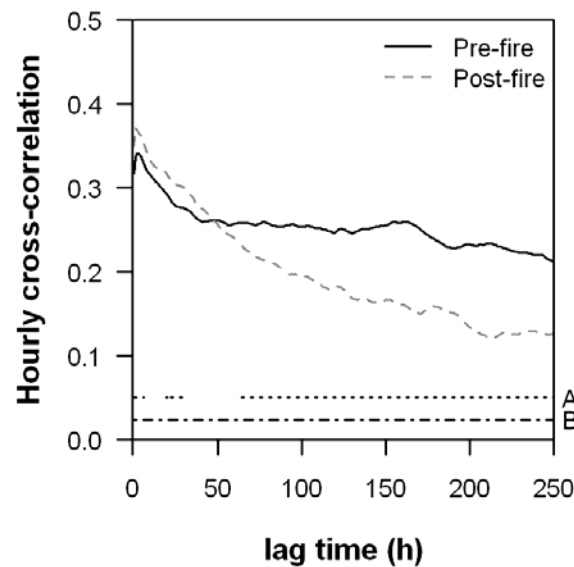

Figure 7.7 Cross-correlation between hourly rainfall and catchment average soil moisture content in Valtorto, indicating the timing and the strength of the soil moisture response to the occurrence of rainfall. The dotted horizontal line (A) indicates for which lag times post-fire cross correlation is significantly different from the pre-fire value (p<0.05), while the dashed horizontal line (B) indicates the confidence interval.

A similar picture emerges from a cross-correlation analysis between rainfall and soil moisture content (Table 7.4). After the fire, soil moisture content was more strongly correlated to rainfall at lag 0 than before the fire, which was indicated by an increase in cross-correlation from 0.325 to 0.350 (Table 7.4) and which suggested a stronger general response of soil moisture to rainfall. In addition, a decrease in the lag to the maximum correlation was observed from 2.7 to 2.0h, suggesting a more rapid response to rainfall after the fire. However, for greater lag times, the correlation between rainfall and soil moisture decreased after the fire for all sites, resulting in a catchment average change depicted in Figure 7.7. The initial increased response of soil moisture to rainfall was therefore followed by a long period of decreased response, suggesting that the burned soil dried out more quickly after rain events.

7.3.5 Effect of rainfall and soil moisture on streamflow generation

As mentioned previously, rainfall was a significant predictor of streamflow in all catchments (Figure 7.6). The role of rainfall and soil moisture on streamflow generation was more closely studied in the Valtorto subcatchment, where the rapid streamflow response and absence of a slow flow component facilitated analysis on a storm-by-storm

basis. Closer analysis of the subcatchment's daily rainfall-streamflow relationship indicated that in addition to an increase in streamflow per unit rainfall (Figure 7.5, 7.6b), the fire also decreased the buffering capacity of the catchment for rainfall, i.e. the amount of rainfall stored in the soil, on the soil surface, and in the (remaining) vegetation before runoff and streamflow were generated. This resulted in a higher proportion of rainfall events generating streamflow, as shown in Figure 7.8a. It furthermore slightly decreased the size of the largest daily rainfall event during which no streamflow was generated, from a pre-fire 22.3 mm to a post-fire 20.7 mm.
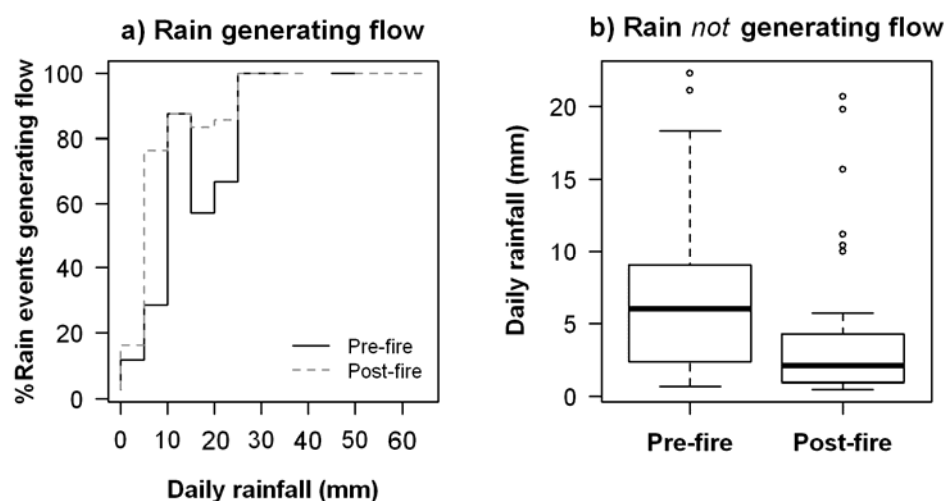
Figure 7.8 Proportion of daily rainfall events generating streamflow (a) and size of daily rainfall events not generating streamflow (b) in the Valtorto subcatchment before and after the fire.

Similarly, the fire significantly decreased the rainfall threshold for runoff generation. While pre-fire 7.2 ± 6.3 mm of daily rainfall was buffered without generating streamflow, this reduced to 3.7 ± 4.5 mm post-fire ($p=0.005$, Figure 7.8b). Since streamflow on days with minor amounts of rainfall (< 0.5 mm) usually resulted from heavy rainfall the day before, this analysis was limited to rainfall events ≥ 0.5 mm.

Antecedent soil moisture condition is an important factor determining the rainfall runoff response of a catchment (Benavides-Solorio and MacDonald, 2001; Castillo et al., 2003). The catchment moisture probes supply some circumstantial evidence that the moisture runoff relationship may have changed. Figure 7.9 shows the relationship between soil moisture content and the daily streamflow of the subcatchment for the two moisture monitoring sites closest to the subcatchment. It is important to note that the rainfall intensity of the events displayed in Figure 7.9 did not change significantly after the fire ($p=0.944$). Figure 7.9 indicates that streamflow was generated from drier topsoils after the fire than before the fire. Two shifts can be observed: 1) fire decreased the threshold

moisture content at which streamflow could be generated (see A, Figure 7.9a,b), and 2) fire decreased the threshold topsoil moisture content at which streamflow was always generated (see B, Figure 7.9a,b).
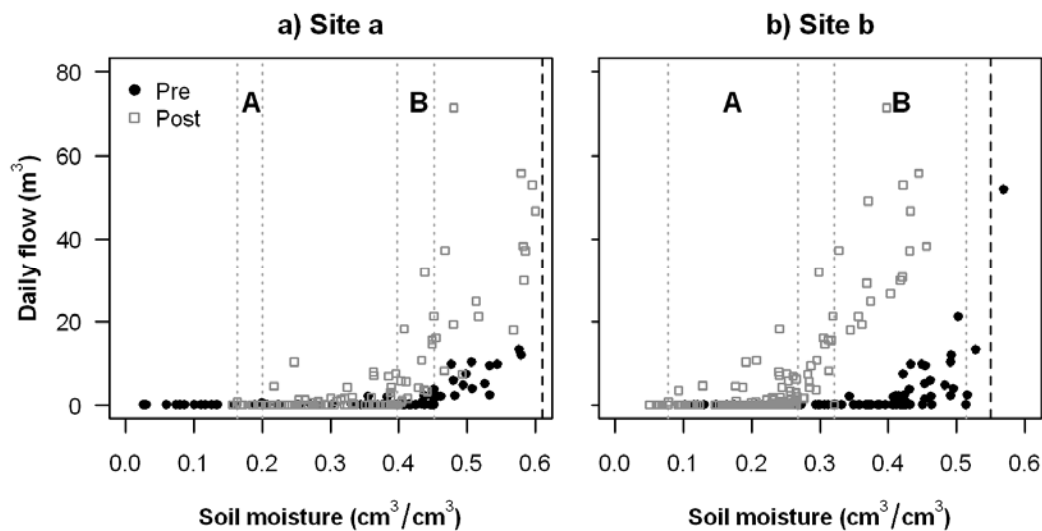
Figure 7.9 Daily average soil moisture content and daily streamflow for the Valtorto subcatchment for days that rainfall occurred pre- and post-fire. Moisture records for the two sites closest to the subcatchment (see Figure 7.1c) are given (with 28 and 17% missing data periods for site a and b, respectively), pre- and post-fire rainfall intensities of the events displayed were not significantly different, the black dashed line indicates total porosity (Chapter 5). After the fire, the subcatchment generated streamflow for lower moisture content; shift A indicates the shift in the threshold moisture content at which streamflow *could be* generated, while shift B indicates the shift in the threshold moisture content at which streamflow *was always* generated.

7.4   Discussion

7.4.1 Fire effects on streamflow generation

Since rainfall distribution and amount have pronounced effects on streamflow patterns (Beven, 2001; Hewlett and Bosch, 1984), attributing observed hydrological changes to the effects of fire must be treated with caution. Because the changes in rainfall distribution and total rainfall amount (Figure 7.3a, Table 7.3) also affected streamflow in the control catchment (Figure 7.3b, Table 7.3, 7.4), it is reasonable to assume that at least part of the observed changes in streamflow in the burned catchment should be attributed to the change in rainfall. However, the streamflow distribution (Figure 7.3b) and runoff coefficient (Figure 7.5) changed more in the burned catchment than in the unburned control, clearly suggesting that fire did have a role in changing streamflow response in the burned catchment. Moreover, separation of rainfall and fire effects using

ANCOVA (Figure 7.6) showed that fire changed the rainfall-streamflow relationship causing an increase in streamflow in the Valtorto subcatchment and possibly in the whole catchment. To explain the observed hydrological responses we present a diagram that summarizes the changes in the hydrological balance due to fire (Figure 7.10, p. 126).

Increases in streamflow after fire have also been observed by others (Lavabre et al., 1993; Scott, 1993; Scott, 1997; Seibert et al., 2010), and are often attributed to decreased canopy interception storage (e.g. Scott and Van Wyk, 1990). Canopy interception in the winter before the fire averaged 48.7% of total rainfall (Figure 7.4a). This value is fairly high compared to the few data available on shrub interception (Dunkerley, 2000), but can likely be attributed to the dense canopy cover (Table 7.1) and the rapid drying of the upper canopy between rain events. Because of the high interception storage, removal of vegetation by fire nearly doubled the effective rainfall (Figure 7.10).

While reduced canopy interception was certainly a factor in this study, additional data suggests that there are more contributing factors. For instance, the reduction in canopy interception does not explain the two shifts in the relation between subcatchment soil moisture content and rainfall (Figure 7.9), i.e. the shift towards streamflow generation on drier soil ('A') and the shift towards decreased rainfall buffering after the fire ('B'). Since the fire did not change soil bulk density, porosity or hydraulic conductivity (Chapter 5), the observed shifts cannot be attributed to a change in these soil properties. Nor can they be explained by changes in rainfall intensity, because the intensity of the rain events generating streamflow in the subcatchment did not change significantly. While these shifts could be attributed to surface sealing (Larsen et al., 2009), which was not assessed in the catchment but neither observed during any of the field visits, there are clear indications that these shifts may be caused by two other processes. We suggest that the shift towards streamflow generation on drier soil may be attributed to soil water repellency, and that the shift towards decreased rainfall buffering may be explained by the combined effects of soil water repellency and the decrease in surface roughness that was observed after the fire (Chapter 5). Soil water repellency is discussed in greater detail in the following section. Surface roughness or microtopography is generally caused by plant litter or surface rock fragments, and has a small but important role in surface water storage (Govers et al., 2000). Because it increases the amount of water ponding on the soil surface (Figure 7.10), surface roughness can delay the initiation and amount of overland flow. Consequently, by reducing ponding capacity, the decrease in surface roughness may have been an additional contributing factor to the more rapid generation of overland flow and reduction in rainfall buffering shown in Figure 7.9.

7.4.2 Role of soil moisture and soil water repellency

The effect of fire on soil moisture variation depends in part on the net effect of the increased effective rainfall and soil evaporation and the decreased plant transpiration (Figure 7.10) (Silva et al., 2006). While burned topsoils are often observed to be drier and warmer than comparable unburned soils (Hart et al., 2005; Hulbert, 1969; Sumrall et al., 1991) and exhibit higher soil evaporation, a review by Silva et al. (2006) shows that the net change in soil moisture is highly dependent on depth: while the increase in soil evaporation can result in a drier topsoil, subsoils can actually get wetter because of the marked reduction in plant transpiration.

In many studies, vegetation cover is identified as an important factor protecting the soil from heating up and drying out (Hulbert, 1969; Sumrall et al., 1991; White and Currie, 1983). Post-fire soil exposure by vegetation removal therefore likely increased soil evaporation, possibly explaining the more rapid drying of the topsoil recorded in this study (Figure 7.7), and the decreased topsoil moisture content on dry days. Since topsoil moisture content was not significantly changed by the fire itself (Chapter 5, 6), post-fire soil exposure may also explain the drop in topsoil moisture content between the fire and the reinstallation of the sensors (Figure 7.2b). In addition to protecting the soil from drying, vegetation cover can also prevent the soil from wetting (Chapter 6). Post-fire soil exposure by vegetation removal therefore also seems to have caused the stronger and faster initial response of soil moisture to rainfall after fire illustrated in Table 7.4 and Figure 7.7. Both observations suggest changes in the development and breakdown of soil water repellency after the fire, as will be discussed in the following paragraphs.

Like many soils worldwide (DeBano, 2000b; Dekker et al., 2005), soils in the Valtorto catchment exhibit water repellency regardless of fire (Chapter 6). While water repellency was prevalent in the catchment before the fire, there was a significant increase in water repellency directly after the fire. There was also a faster development of repellency during dry periods in the burned areas, which was largely attributed to post-fire soil exposure (Chapter 6). Therefore, even though soil water repellency was an important hydrological parameter before the fire, the data suggest that fire may have increased the hydrological impact of soil water repellency in the catchment.

Soil water repellency is often reported to be inversely related to soil moisture content (Dekker et al., 2001; Leighton-Boyce et al., 2005), which is also the case in the Valtorto catchment (Chapter 6). Because of the strong relation between soil moisture and soil water repellency, the lower soil moisture contents resulting from the rapid drying of the topsoil after rainfall (Figure 7.7) likely resulted in faster (re)development of soil water repellency and inhibition of infiltration. In addition, the presence of water repellency

inhibits water uptake by soils – thus creating a vicious cycle in dry periods. The resulting impact on streamflow generation is illustrated in Figure 7.9, with a lower soil moisture threshold for streamflow generation after the fire, as well as a higher fraction of rainfall events generating (overland) flow on dry soil. Since soil properties like porosity and saturated hydraulic conductivity were not significantly affected by the fire (Chapter 5), and rainfall intensity of the events displayed in Figure 7.9 also remained unchanged, the increased streamflow response to rainfall events occurring on dry soil may be attributed to a more prominent role of soil water repellency in the burned landscape, as suggested in Chapter 6. After fire, the faster (re)development of soil water repellency therefore contributed to a higher sensitivity to overland flow (Figure 7.9) – especially for short duration rainfall events. This may explain the increased soil erosion rates observed in the catchment after the fire (Shakesby et al., 2010b).

The impact of the faster development of soil water repellency should not be assessed without considering the effects of its more rapid breakdown resulting from the higher effective rainfall after the fire (Chapter 6). The more rapid breakdown of soil water repellency for burned soil observed in Chapter 6 is consistent with the faster and stronger initial response of soil moisture to rainfall after fire (Table 7.4, Figure 7.7), which suggests that faster disappearance of soil water repellency improves infiltration. As a result, overland flow risk may be reduced during prolonged rainfall events, which, along with the reduced transpiration (Figure 7.10), could increase (sub)soil water storage. In contrast, the increased topsoil evaporation (Figure 7.10) would affect only the top few cm (Wythers et al., 1999). The potential increase in the amount of water stored in the subsoil may explain the increase in dry season flow observed in the present study (Figure 7.2c-d, Table 7.3) as well as in other studies (Berndt, 1971; Hibbert, 1967). Given the fact that (post-fire) plant growth is strongly related to soil water availability (García-Fayos et al., 2000; Kasischke et al., 2007; Ruiz-Sinoga et al., 2011; Yang et al., 2010; Zald et al., 2008; Zeng et al., 2010), the possible increase in subsoil water storage may considerably favor plant recovery in burned areas. Since subsoil moisture content was not measured in this study, no definite conclusion can be drawn; however, it is an interesting topic for further study.

7.4.3 Synopsis of fire impact on hydrology

As pointed out, fire-induced changes to the hydrological balance are summarized in Figure 7.10, which illustrates the impact of fire on soil moisture and water fluxes. After the fire there is a reduced interception capacity (I_{int}) and, consequently, an increase in effective rainfall (P_{eff}). A drop in plant transpiration (T) may cause a further increase in (sub)soil water availability and streamflow (Q_s), while increased soil evaporation (E_{soil})

causes more rapid drying of the topsoil. Topsoil water repellency is therefore more rapidly triggered, resulting in an increased risk of overland flow risk for small rain events. The risk of overland flow (Q_f) is additionally increased through a reduction in surface water storage (S_s) resulting from reduced surface roughness after the fire. This increase in overland flow risk may however be (partly) counterbalanced by the more rapid breakdown of soil water repellency during extended rainfall events, which could enhance subsoil infiltration and water storage and streamflow (Q_s).

Since vegetation and litter cover will return with time after the fire, the net effect of the processes indicated in Figure 7.10 on streamflow will vary with time following fire, and decrease with the reestablishment of the vegetation cover. The net effect will furthermore depend on the type and the age of vegetation, since canopy interception and transpiration vary with vegetation type, stand age, and climate (Bosch and Hewlett, 1982; Murakami et al., 2000; Vertessy et al., 2001).

Pre-fire   **Post-fire**
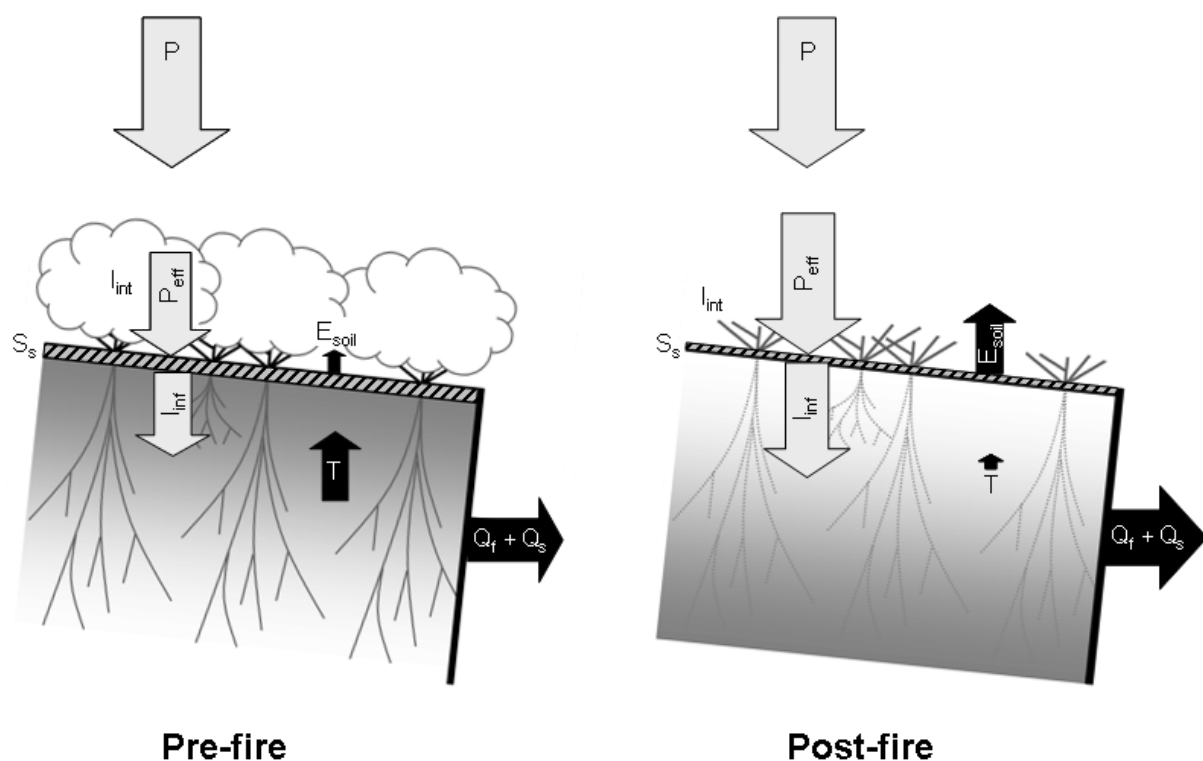
Figure 7.10 Fire impact on hydrology, showing pre- and post-fire water fluxes and rainfall partitioning. Grey arrows indicate water gain, black arrows indicate water loss from the soil profile, in which soil moisture content is indicated using grey shading (darker is wetter). P is rainfall, P_{eff} is effective rainfall (the amount of rainfall reaching the ground surface), I_{inf} is infiltration, I_{int} is canopy interception, S_s is surface water storage, E_{soil} is bare soil evaporation, T is plant transpiration, and Q_f and Q_s is the sum of fastflow (surface runoff) and slowflow (subsurface runoff).

7.4.4 Implications for downstream flooding risk and effects of scale

By showing a changed rainfall-streamflow relationship and increased volume of runoff for a given rain event (Figure 7.6), the data support the commonly reported increased flooding risk after fire (Cannon et al., 2008; Conedera et al., 2003; Jordan and Covert, 2009; Nasseri, 1989; Rulli and Rosso, 2007). Moreover, by increasing streamflow volumes throughout the year, the fire may also have increased the risk of floods as a cumulative effect. Although it is likely that the observed reduction in canopy storage and surface roughness (Chapter 5) also resulted in a stronger and faster response of streamflow after fire, the change in rainfall distribution post-fire (Figure 7.3a) prevented assessment of the exact role of the fire. After all, streamflow response was also stronger and faster in the control catchment – likely because of the increased occurrence of large rain events.

Fire impact was highly affected by scale. In all cases, the subcatchment indicated far greater fire impacts than the main catchment: the increase in streamflow distribution (Figure 7.3b), runoff coefficient (Figure 7.5), and the change in rainfall-streamflow relationship (Figure 7.6a-b) were all greater at the small scale than at the catchment scale. Hence, although the fire may have significantly increased flooding risk inside the catchment, the data suggest that the downstream flooding risk was only slightly increased.

Reduced response at the larger scale is typical for hydrological processes: moving from the subcatchment scale to the catchment scale, the flow paths lengthen, lag time increases and the opportunities for infiltration and storage due to soil heterogeneity increase (Skøien et al., 2003). As a result, catchment rainfall tends to be less correlated with streamflow at a large scale than at a smaller scale. However, this also means that the effects of fire on local overland flow generation and subcatchment runoff (as depicted in Figure 7.10) get diluted due to these catchment filtering processes, resulting in a less pronounced response at the larger scale (Figure 7.6). It is therefore reasonable to expect a decrease in the effects of fire when moving up in scale.

This scale effect is often observed in post-fire hydrology. As summarized in reviews by Shakesby (2011) and Shakesby and Doerr (2006), plot-scale runoff coefficients tend to be higher than hillslope- or catchment scale runoff coefficients. This is generally attributed to increased soil and surface heterogeneity or patchiness at larger scales leading to decreased hydrological connectivity (Doerr et al., 2003; Ferreira et al., 2008; Ferreira et al., 2005). In the Valtorto catchment, the subcatchment was indeed more homogeneous than the catchment itself, for instance in terms of vegetation burn severity or fuel consumption. The main catchment contained a zone where the vegetation was

only scorched (Figure 7.1c), i.e. where vegetation burn severity was low, while fuel consumption in the subcatchment was complete. The subcatchment was therefore much more strongly affected by the fire than the total catchment.

Although it is reasonable to expect a decrease in the effects of fire when moving up in scale because of catchment filtering processes, the catchment-scale hydrological response in Valtorto may have been more pronounced if the vegetation burn severity had been greater, i.e. if fuel consumption had been complete in the entire catchment. More in general, post-fire hydrological changes may be larger when fires occur in systems where the loss in canopy interception and plant transpiration is greater, such as in forests (Bosch and Hewlett, 1982), or in hotter (wild)fires where soil physical changes are more pronounced (García-Corona et al., 2004, Chapter 2).

7.4.5 Lessons for study of fire impact on hydrology

The data presented here contain a number of valuable lessons for study of hydrological effects of fire. Firstly, the markedly different response of the catchment- and subcatchment-scale emphasizes the need to study hydrology at the appropriate scale of interest. Although small-scale studies do provide valuable insight into the processes governing hydrological changes, as demonstrated in Section 3.5, they may considerably overestimate the degree of change occurring at the catchment scale. On the other hand, certain changes may be missed when only analyzing effects at the small scale, for instance the increase in dry season streamflow.

Secondly, the present study shows that it is possible to study fire impact on catchment-scale hydrological processes in a controlled experimental setup. Since studies of wildfire impact on hydrology are hard to plan in advance, this provides a method to purposely study fire effects at the catchment scale. The paired-catchment approach used in the present study and using pre- and post-fire data enabled separation of fire, rainfall variability and site effects through ANCOVA analysis. This is particularly interesting in regions where regular catchment scale hydrological monitoring is not common, and where pre-fire streamflow records are therefore often absent for burned catchments.

Despite their value in scientific research, experimental fires will never mimic summer wildfires. Soil, fuel and weather conditions during experimental fires are highly unlikely to match summer wildfire conditions because of safety concerns, which implies that soil and vegetation burn severity of experimental fires will generally be lower than can be expected for wildfires (Cerdà and Robichaud, 2009). This was also demonstrated in the Valtorto fire: despite its high intensity, soil temperature remained surprisingly low (Chapter 4) and soil physical properties remained unaffected (Chapter 5). Experimental

fire studies can therefore be used to study catchment-scale effects of prescribed fires or low-severity wildfires that occur when soils and vegetation are still fairly moist. Assessment of catchment-scale effects of summer wildfires remains a matter of 'luck'. In all cases, finances and logistics will always limit the number of replicates available in catchment-scale studies. To get a full overview of the general effects of fire on hydrology at the catchment scale, a meta-analysis could be done on all the previous studies worldwide, similar to meta-analyses done to assess the effects of deforestation (Bosch and Hewlett, 1982; Brown et al., 2005).

7.5   Conclusions

Taking the unique approach of a planned catchment-scale fire experiment, this research used pre and post-fire experimental data of paired catchments to assess the hydrological impact of fire. The changed rainfall conditions following the fire highlighted the value of the adopted sampling design, which allowed assessment of fire impact under changed rainfall conditions (because of the availability of pre- and post-fire data) without being hampered by effects of site variability (because of the use of paired catchments). The experiment showed that:

- Vegetation removal markedly increased the amount of effective rainfall, particularly for smaller rain events. The shrub canopy intercepted on average the first 19.5 mm of a rain event before the fire, and canopy interception was on average 48.7% of total rainfall. Since the fire removed nearly all the vegetation and canopy cover was only 30% one year after the fire, post-fire canopy interception was minimal.

- Fire seems to have increased the runoff coefficient, and changed the streamflow distribution as well as the rainfall-streamflow relationship, particularly at the subcatchment scale.

- By significantly increasing the amount of streamflow per unit rainfall at the subcatchment-scale, the fire may have increased the risk of flooding inside the catchment. However, as the increase in streamflow was not significant at the catchment scale, the fire may have only slightly affected downstream flooding risk.

- After the fire, the streamflow response to rainfall events was quicker. However, since the control catchment showed a similar change due to a changed rainfall distribution, the degree to which fire played a role in this could not be assessed.

- After the fire, the moisture content of the 0-2.5 cm soil layer responded more quickly to rainfall than before, and at the same time this layer dried out more quickly after rain events.

Results support existing knowledge that fire impact on hydrology is largely affected by

scale, and emphasize the risk of overestimating hydrological fire impact when upscaling plot- or hillslope scale studies to the catchment scale. This highlights the importance of using the appropriate scale for research design or data use in assessing fire effects.

Finally, results suggest that fire-induced hydrological changes can occur even when soil temperatures during fire remain low. As previous work indicated that soil heating was limited in most of the catchment and soil physical properties remained unchanged, vegetation removal is likely the most significant cause of the observed hydrological changes because of its effects on effective rainfall, soil water repellency fluctuation and surface roughness.

Appendix 7.1 Soil moisture calibration results
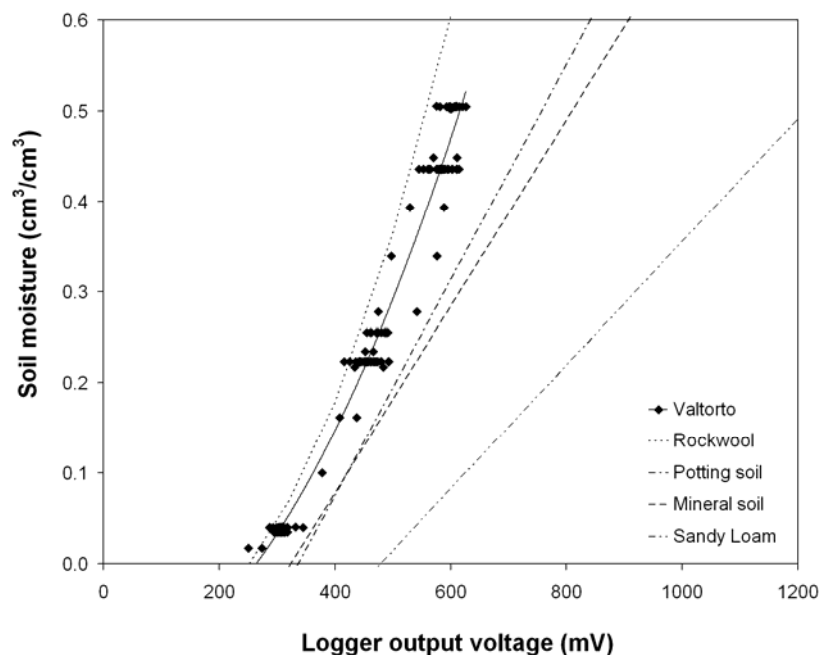
Figure A.7.1.1 Second order polynomial calibration of the Valtorto soil (black dots represent lab calibration results), as compared to standard Decagon (rockwool, potting soil and mineral soil) and Madgetech (sandy loam) calibrations.

8 Synthesis

8.1   General discussion

In order to improve understanding of the role of fire as a driver of land degradation and flooding, this thesis addressed five key questions regarding the impact of fire on soils and hydrology. Here, the previous chapters are summarized and discussed in light of these five research questions, and a synopsis diagram is presented that links the factors and processes involved (Figure 8.1)
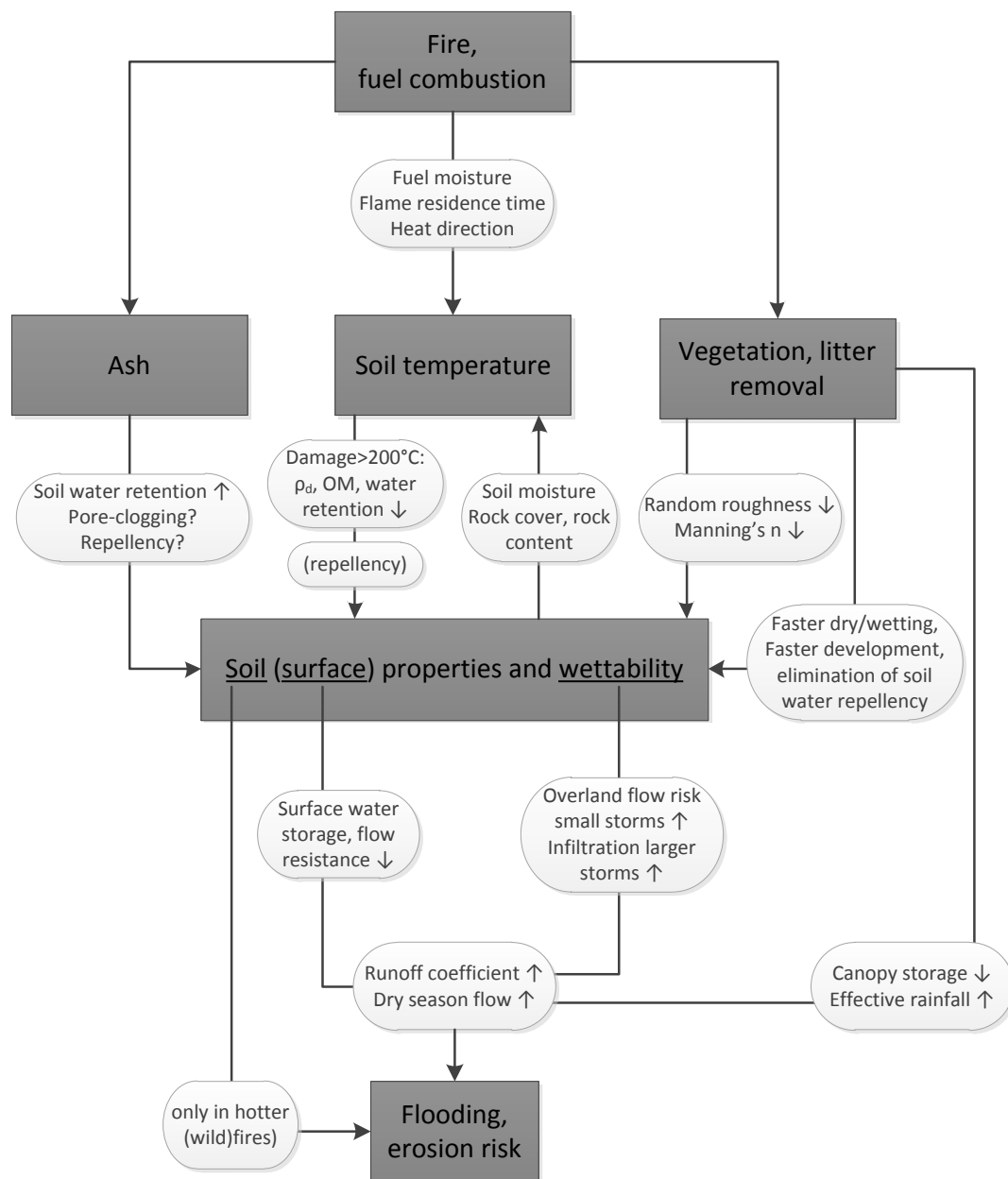
Figure 8.1 Synopsis of the processes regulating fire impact on soil and hydrology. While soil heating did increase soil water repellency in the laboratory study (Chapter 2), it was probably not the cause of fire-induced soil water repellency in the Valtorto catchment (Chapter 5,6).

I.   What are the potential impacts of soil heating and ash on soil physical properties?

The potential effect of fire on soil physical properties is significant (Chapter 2). Pronounced soil heating can result in a decrease in dry bulk density, organic matter content, particle size, and water retention capacity (Figure 8.1). Similar to other studies (e.g. Badía and Martí, 2003; García-Corona et al., 2004), our measurements showed that changes are only significant when soils are heated to above 200°C (for a 30 min heating period). At lower temperatures, changes in soil physical properties were negligible or altogether absent. As organic matter content plays a large role in controlling soil physical properties, the degree of fire-induced soil changes is possibly determined by the soil organic matter content.

The lack of changes for heating at low temperatures explains why soil physical changes during prescribed fires are often limited (Ferreira et al., 2009; Franklin et al., 2003). In four prescribed fires in shrubland and beneath maritime pine in north-central Portugal, soil surface temperatures averaged only 35°C, and soil bulk density and organic matter content remained unchanged (personal observation, winter 2008/2009). Our data however also support observations that the impact of hotter (wild)fires on the soil system can be significant. Soil changes were clearly apparent in two out of five sites burned by wildfire in north-central Portugal in summer 2008 (bulk density and organic matter content, personal observation), which indicated that the soil temperature in these fires likely exceeded 200°C.

Of interest is the non-linear change in water retention with increasing temperature. This is possibly because the loss of organic matter is compensated for by the production of ash, which also favors soil water retention. This is an example of the complexity of the dynamics in burned areas (Ferreira et al., 2008), and emphasizes the importance of looking at the relation between multiple factors in assessing the impact of fires. Furthermore, heating-induced soil water retention changes are most pronounced between saturation (0 kPa) and field capacity (10 kPa), indicating that fire impact on soil water retention is most relevant when soils are wet.

Fire impact on soil hydraulic properties has received little attention in the scientific literature, despite the important role they have in controlling water movement in soils. Soil water retention is an important factor in soil water movement, and so is the (un)saturated hydraulic conductivity of a soil. Both are, among other factors, determined by particle size distribution and organic matter content (Wesseling et al., 2009a). The heating-induced changes in all these physical soil properties suggests that fire can have great implications for the soil water balance, potentially affecting soil evaporation and

infiltration rates and thereby controlling the amount of water available for plant regeneration. An approach similar to Wesseling et al. (2009a), in which the SoWaM model is used to assess the effects of soil hydraulic properties on the water balance, could facilitate further research into the effect of fire-induced soil changes on soil water availability.

Chapter 2 furthermore contains new insights into the role of vegetative ash in post-fire hydrology. The infiltration experiments showed that, even if the majority of the ash remains on the soil surface, ash particles do wash into the soil and can impact soil hydrologic behavior (Figure 8.1). In addition, the data indicate that ash not only affects soil properties after fire (during rainfall events), but also during fire (when soils are heated to above 300°C), by mitigating the decrease in soil water retention caused by the loss of organic matter.
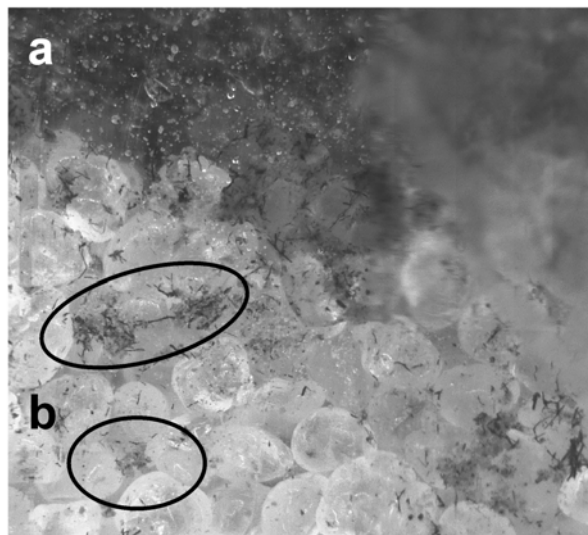
Figure 8.2 Microscope image a layer of ash (black, a) on top of quartz sand sized 0.2-0.4 mm (clear, b) during a steady-state infiltration experiment. Only the smallest ash particles (for instance inside the black circles) moved with the percolating water into the quartz sand.

The increased infiltration of ash during (artificial) rainfall was in Chapter 2 attributed to infiltration of the finest ash particles, leaving the coarser material on top of the soil sample. To confirm this hypothesis, an explorative steady-state infiltration experiment was performed using a setup similar to Crist et al. (2004) and Morales et al. (2009). Pore-scale visualization of the infiltration process showed that fine particles indeed washed into the soil sample, by moving with the percolating water (Figure 8.2). While the results presented in Chapter 2 and Figure 8.2 do provide experimental evidence that ash can wash into soils during (artificial) rainfall, supporting Balfour and Woods (2007)

and Woods and Balfour (2008a), they remain inconclusive as to the hypothesized pore-clogging effect of ash. The pore-scale visualization technique presented in Figure 8.2 does allow assessment of possible pore clogging by ash in greater detail, and is recommended for use in future research.

II. What determines soil temperatures during fire?

i. Soil properties

Consistent with previous studies (Busse et al., 2005; Campbell et al., 1995; Valette et al., 1994), Chapter 3 illustrates that soil temperatures during fire are highly determined by soil moisture content (Figure 8.1): increased soil moisture content significantly reduces maximum soil temperatures, as well as the depth and duration of sustained high temperatures. This explains why fire damage to soils (discussed in Chapter 2) increases with decreasing soil moisture content.

By acting as heat sources and sinks, rock fragments also influenced soil temperatures (Figure 8.1), which supports previous observations of diurnal soil temperature fluctuations in rocky areas (Childs and Flint, 1990; Li, 2003; Mehuys et al., 1975). This research revealed that the effect of rock fragments highly depends on their location in the profile (incorporated into the soil matrix, or at the soil surface), and the soil moisture content. Surface rock fragments tend to decrease maximum soil temperatures but increase the duration of sustained temperatures above 60°C. The effect of incorporated rock fragments is however more complex, and highly dependent on soil moisture content and the presence of a rock fragment cover.

Because of the complex interrelationship between rock fragments and soil moisture, prediction of fire damage to rocky soils will benefit from further analysis of soil heating in soils with varying quantities of rock fragments and different soil moisture levels. Such experiments could possibly reveal threshold moisture or rock fragment contents above or below which soil temperatures are adversely affected. Understanding the effect of rock fragments on soil heating during fires is relevant, particularly because the findings of this thesis indicate that degraded areas with skeletal soils are likely to be more prone to high soil temperatures than lush areas with lower rock fragment content or cover (Chapter 4).

ii. Aboveground conditions and fire behavior

Despite the key role that soil thermal properties play in controlling heat penetration into soils, results of the Valtorto catchment experimental fire (Chapter 4) indicate that soil heating during fire is largely determined by what happens aboveground. This chapter shows that while fuel load and fire intensity may be reasonable predictors of soil heating

at plot and hillslope scales (Gimeno-Garcia et al., 2004a; Molina and Llinares, 2001b), the same does not hold true at the more complex landscape scale. Instead, soil temperatures can actually be inversely related to fuel load and fire intensity. The aboveground conditions and behavior of the fire, e.g. the direction of the heat flux, flame residence time and fuel moisture, have a major impact on the degree of soil heating (Figure 8.1). High litter moisture content, determined using the Canadian Fire Weather Index System (FWI, see Table 5.2, Van Wagner, 1987), plays an additional role in preventing the soil from heating. When the lower litter is not available for burning (in the Valtorto catchment indicated by a litter layer of up to 5 cm remaining after the fire), litter acts as a heat sink rather than a source. These findings again indicate the importance of studying the relationships between multiple factors that exist during fires and in fire prone areas.

The inverse relation between fire intensity and soil temperatures was in fact not surprising to fire scientists (personal communication Derek Chong, Miguel Cruz), although it is counterintuitive to those working in the field of soil, erosion and water science. This emphasizes the value of multi- or interdisciplinary research in addition to multifactor research. Joint efforts between fire and soil experts will allow major progress to be made in both forecasting and hindcasting fire-induced soil heating at the landscape scale. That in turn has the potential to improve the efficiency of post-fire restoration measures. For example, the fact that the FWI moisture values for the area were in accordance with the relatively low soil temperatures measured in most of the catchment suggests that FWI codes could be used to broadly forecast soil heating during fires. However, since pronounced soil heating did occur in xeric areas, accurate spatial prediction of soil heating through FWI codes can only be obtained when spatial variation in fuel and litter moisture and depth is taken into account. As another example, fire-induced soil heating could be better hindcasted by incorporating spatial variation in fuel moisture and soil conditions into fire behavior models. These models currently predict fire behavior characteristics from weather, fuels and topography, and therefore already take heat transfer and fire spread rate into account (Pastor et al., 2003). Extension of these models with fuel moisture and soil components would allow for site specific differentiation of soil heating and subsequent degradation risks, which can increase the efficiency of mitigation measures and to protect natural resources, lives and property.

The findings presented in Chapter 4 radically change the understanding of the relation between fuel load and vulnerability of soils to high temperatures during fire. The data show that, contrary to current understanding, densely vegetated or lush areas can stay surprisingly cool during intense fire, while more sparsely vegetated and degraded areas are more vulnerable to high soil temperatures. These areas consequently require specific

attention during prescribed burns and wildfire suppression operations. Finally, Chapter 4 shows that spatial differences in resilience and state of degradation within a watershed can be exacerbated by fire. Because high soil temperatures negatively affect post-fire recovery, the already degraded areas – which are more vulnerable to high soil temperatures – will be prone to further degradation. At the same time, the resilience of more densely vegetated areas will not be affected when soils stay cool in lush areas.

III. What is the relation between fire intensity and fire impact, in terms of soil and surface properties, runoff and erosion risk?

Despite the high fire intensity observed in certain parts of the catchment, the experimental fire did not significantly change soil physical properties like bulk density, organic matter content, porosity and saturated hydraulic conductivity (Chapter 5). This is not surprising as soil temperatures in most of the catchment (Fig. 4.1, 5.3) remained far below the 200-300°C threshold for soil changes (Badía and Martí, 2003; García-Corona et al., 2004; Chapter 2, Figure 8.1). It is furthermore consistent with the generally low impact of (controlled) burns (Ferreira et al., 2009; Franklin et al., 2003; Shakesby, 2011; Shakesby et al., 2010b).

The data presented in Chapter 5 stress that fire intensity alone is not a good predictor of fire-induced soil changes (soil burn severity) and related runoff and erosion risk. This supports recent findings by Doerr et al. (2010) who reported that the extreme 2009 Australian wildfires had little impact on the soil system. Yet, the Valtorto data also indicate that low soil burn severity does not necessarily imply low erosion risk. Fire-induced vegetation and litter removal and post-fire soil exposure significantly reduce surface roughness and overland flow resistance (Figure 8.1), increasing the risk and erodibility of overland flow (Chapter 5). Erosion risk after low-severity fire is therefore the result of direct fire impact and ecosystem responses (cf. Keeley, 2009). The increased susceptibility to runoff and erosion even when soil physical properties remain largely unchanged indicates that the risk can be underestimated when only soil physical changes are assessed, because ground cover has such an important role in preventing erosion (Cerdà and Robichaud, 2009; Ghahramani et al., 2011; Nunes et al., 2011). Therefore, for low-severity fires, assessment of soil surface changes ('surface burn severity') is very important and will result in a more accurate prediction of post-fire erosion risk. In contrast, erosion risk after high-severity fire is likely a combination of both soil and surface changes.

IV. Does fire alter the temporal evolution of soil water repellency, and what is the role of vegetation removal?

Chapter 6 supports a large number of studies indicating that soil water repellency is ubiquitous in (long) unburned lands (DeBano, 2000b; Dekker et al., 2005). Despite the perception amongst many fire scientists and managers that soil water repellency only occurs as a result of fire, this chapter reveals that soil water repellency in the Valtorto catchment is the rule rather than the exception – both before and after fire. Temporal monitoring of burned and unburned shrub and maritime pine covered soils in various parts of the Portuguese schist region (personal observation) indicated that the existence of water repellent soil is typical for this type of ecosystem.

Furthermore, the fact that fire increased soil water repellency (Fig. 5.4, 6.3) even at soil temperatures far below the commonly reported threshold of 175°C (e.g. DeBano, 1981) indicates that soil temperature is not the only factor involved in determining fire-induced soil water repellency. Further analysis of the probable causes of this increase, namely the drying of a thin surface layer during the fire, or the presence of potentially water repellent ash (Figure 8.1), will shed light on the longevity of fire-induced soil water repellency.

Chapter 6 indicates that the temporal dynamics of soil water repellency are highly related to the removal of vegetation. Water repellency was developed and eliminated more quickly following fire (Figure 8.1), likely due to the exposed soil (from vegetation removal) being more sensitive to drying and wetting cycles. This is consistent with, and adds to, the understanding of soil moisture being a triggering factor for soil water repellency (Dekker et al., 2001). Vegetation removal also likely has an additional role in lower persistence of post-fire soil water repellency at a given soil moisture content. Various researchers have attributed the temporal decrease in post-fire soil water repellency to a reduced input of water repellent compounds (Ceballos et al., 1999; Doerr and Thomas, 2000), which could play a role in the Valtorto catchment as well. The reduction in soil water repellency over time following fire versus the reestablishment of soil water repellency as a result of regenerated vegetation would be a highly interesting subject for further study.

To conclude, fire alters the temporal evolution of soil water repellency not only by causing a direct increase, but also by removing vegetation cover, which removes the source of water repellent compounds and also results in increased wetting and drying dynamics and greater reception of rainfall. Although post-fire persistence of soil water repellency is less than pre-fire, fire considerably reduces the time needed to develop and

eliminate soil water repellency, and thereby increases its temporal variability. As such, fire can increase the hydrological significance of soil water repellency.

V.   Does fire result in increased runoff risk, and what is the cause of the hydrological changes?

Finally, Chapter 7 covers the hydrological changes that result from fire, and shows that by increasing the amount of streamflow per unit rainfall, fire increases the risk of flooding. The data support the commonly reported increase in runoff and flooding risk after fire (Shakesby and Doerr, 2006), and also indicate that post-fire hydrological processes are highly influenced by scale. Although the logistics are considerable, conducting research at the catchment scale provides otherwise unobtainable data of benefit to the study of fire effects on the environment.

Soil physical changes due to fire were not apparent at the catchment scale, although soil properties may have been changed locally where soil temperatures were more pronounced, or as a result of possible pore clogging by ash. There are however clear indications that increases in streamflow after fire are to a large degree caused by changes resulting from vegetation removal (Figure 8.1). Firstly, vegetation removal increases effective rainfall and decreases transpiration (Chapter 6) – thereby increasing the amount of water available for (sub)surface runoff. Secondly, vegetation and litter removal results in more rapid development of soil water repellency (Chapter 6, 7) and decreases surface water storage (Chapter 5) – increasing overland flow risk. Thirdly, it results in more rapid breakdown of post-fire soil water repellency (Chapter 5) – increasing infiltration during extended rain events. The net effects and the longevity of hydrological change are likely related to vegetation type, age, fire severity and the regeneration rate of the (soils and) vegetation.

The increased erosion that was observed after the Valtorto fire (Shakesby et al., 2010b) is therefore not solely the result of soil water repellency, but likely the combined effect of increased raindrop impact on the bare soil (Andreu et al., 1998; Mati, 1994), the change in soil surface properties resulting from the removal of litter and vegetation, and the increased overland flow risk resulting from the more rapid development of soil water repellency (Figure 8.1). This once again illustrates the value and importance of multi-factor research regarding fire impact.

8.2   General conclusions

This thesis investigated the effects of fire on soil, hydrology and erosion risk in the Valtorto catchment in north-central Portugal. While the insights gained in this study are

directly applicable to understanding fire impact in the Portuguese schist region, they are also valuable for understanding fire impact in areas with different soils, vegetation and fire characteristics:

- Direct effects of fire (soil heating) on soil physical properties can be significant and strongly related to temperature. A critical temperature threshold between 200 and 300°C can be apparent, above which soil properties are affected and below which they are not. Infiltration of ash during post-fire rain events can also change soil properties. Both soil heating and ash therefore have implications for the hydrological regime and the soil water balance.

- Soil moisture and rock fragments can play a significant role in soil heating during fire. Yet, soil temperatures during fire are for a large part determined by aboveground processes. High intensity fire does however not necessarily cause pronounced soil heating and related soil changes. Fire intensity and fuel load alone are therefore poor predictors of soil burn severity.

- Soil heating is not the only cause of fire-induced soil water repellency. Moreover, in areas where soils exhibit water repellency without fire, increased temporal dynamics of post-fire soil water repellency may increase runoff and erosion risk, particularly for short duration rain events.

- Fire leads to an increased amount of runoff and streamflow per unit rainfall, thereby increasing the risk of flooding. The net effects and the longevity of hydrological change are likely related to vegetation type, age, fire severity and the regeneration rate of the vegetation.

- Soil physical changes are not required to increase runoff and streamflow after fire. Vegetation removal is the primary cause of increased post-fire runoff and erosion because of its effects on effective rainfall, transpiration, soil water repellency dynamics and surface roughness. Yet, where present, fire-induced soil changes may amplify the increase in post-fire runoff and erosion.

- Both fire itself and hydrological effects are highly affected by scale and spatial variation, emphasizing the risk of misjudging fire impact when upscaling plot- or hillslope scale studies to the catchment scale.

- It is clear that the effect of fires on soil and hydrology depends on the interaction of multiple factors, thus emphasizing the importance of multi-factor and interdisciplinary research and collaboration for more accurate understanding of degradation risk and development of mitigation strategies.

8.3   Implications for mitigating fire-induced land degradation

8.3.1 Preventing fire

The aim of this thesis was to improve understanding of fire impact on soil and hydrology in order to prevent or mitigate land degradation in burned areas. Naturally, the best way to mitigate fire-induced land degradation is to prevent fires, for instance by reducing ignition sources (Moreira et al., 2010) and managing landscape flammability through wise landscape design (Direcção Geral das Florestas, 2002; Ferreira et al., 2009; Gill, 1979; Moreira et al., 2009).

One way of managing landscape flammability is through species selection. In north-central Portugal, the current landscape of *Pinus pinaster* and *Eucalyptus globulus* plantations is much more fire-prone than the native broadleaved forests (Moreira et al., 2009). A shift towards the natural vegetation of oak-chestnut forest can therefore decrease fire risk. However, because of the highly fragmented private ownership of rural areas, a poorly functioning cadastre, and the people's dependence on the income generated by the pine and eucalypt plantations (Silva et al., 2008), large scale land use conversions are hard to accomplish. Finding ways to resolve this conflict of interest would be a valuable step forward in long term management of these fire prone areas.

Another way to manage landscape flammability is controlling the amount and connectivity of fuel in the landscape (Direcção Geral das Florestas, 2002). Since it is impossible, but also undesirable, to completely ban fire from the landscape, fuel management will never stop fires altogether. Fuel management does however decrease fire intensity and rate of fire spread, and therefore not only facilitates fire suppression operations but also increase the likelihood that forest stands survive a fire (Fernandes and Botelho, 2004). Around the world, prescribed fire and mechanical measures are common ways of controlling fuel loads. Although their benefits are clear (Boer et al., 2009; Fernandes and Botelho, 2004), sustainable use of natural resources requires that management practices do not result in unnecessary degradation.

8.3.2 Implications and recommendations for the use of fire

Based on the results of this thesis, a number of conclusions can be drawn and recommendations can be made regarding the use of fire to fight fire, particularly in regard to the timing and scale of prescribed fires, and the sustainability of the current prescribed fire practice in Portugal.

Like in many European countries, prescribed fires in Portugal are performed following burning prescriptions, which entail a desired range of weather and moisture conditions,

fire behavior and burning season (Fernandes and Loureiro, 2010). Although they do account for litter moisture content, soil damage may still occur in places where the litter layer is thin and quickly dried out during fire. Soil moisture should therefore be explicitly accounted for in fire prescriptions, because of the significant role it plays in protecting the soil from heating (Chapter 2). Likewise, rock fragments should also be incorporated into controlled fire planning because of their impact on soil temperatures (Chapter 2). Explicit incorporation of soil properties in fire prescriptions will help managers to achieve defined goals of minimal or maximal soil heating and prevent undesirable damage.

The inverse relation between fuel load and soil temperature observed in Chapter 4 provides valuable insight into the potential negative impact of fire, and strongly indicates that managers should be careful with applying fire in sparsely vegetated and already degraded areas. Resilience of these areas to fire is likely lower than that of lush areas, because the higher soil temperatures will cause structural soil damage and also negatively affect the regeneration potential. Even when soil heating is not pronounced, degraded areas have lower potential to recover from fire (Ruiz-Sinoga et al., 2011) because of shallower soils and poorer soil quality. This thesis therefore indicates that prescribed fire should preferably be avoided in fragile areas, to avoid irreversible changes.

Results furthermore indicate that the optimal timing of prescribed fire varies within the landscape. South-facing slopes receive more incoming radiation and are also often characterized by sparser vegetation than north-facing slopes (Bennie et al., 2008), resulting in a more rapid drying of fuel and soils (Iverson and Hutchinson, 2002). Assuming fire-induced soil changes are to be avoided, as is for instance the case in Portugal, the optimal moment to burn south-facing (xeric) slopes is therefore closer to the last rainfall than that of north-facing (mesic) slopes. The importance of the combined effects of fuel moisture and soil moisture in determining fire behavior and soil heating on the one hand, and the spatial variation of moisture content on the other hand strongly advocates for precision fire management. To avoid fire-induced soil damage, prescribed burns should not be performed at full catchment scales. Instead, it would be best to burn areas under the most optimal moisture conditions required to achieve defined goals and minimize undesired damage. This supports the current practice along these lines in some countries, like Portugal, and is a message for other countries where large-scale fires are still conducted because of practical reasons, such as Australia (e.g. Price et al., 2007).

Finally, our findings shed light on the sustainability of the prescribed fire practice in Portugal. Although the experimental fire did certainly not comply with recommended prescribed fire practice (Fernandes et al., 2002) some conclusions can be drawn regarding the potential impact of winter burns that are performed according to the

prescribed fire guidelines in Portugal. When performed under the right conditions (Fernandes et al., 2002), mineral soil heating during prescribed fires in similar shrubland or underneath maritime pine (*Pinus pinaster*) can be limited to ~35°C, thus avoiding soil physical changes (personal observation). In addition, Chapter 4 and 5 report that even when a winter fire is performed under more adverse conditions (high-intensity fire on a fairly dry day), soil heating can still be limited. Soil burn severity may therefore be low even for a worst-case scenario prescribed fire, which indicates that the present burning guidelines are rather accurate in terms of avoiding direct fire impact on the soil system. None the less, as pointed out in Chapters 5, 6 and 7, even low-severity burned areas are at increased risk of runoff and erosion because of the effects of vegetation and litter removal and related soil surface changes. Since prescribed fires also remove vegetation and part of the litter layer, this suggests that, though to a lesser degree than wildfires, areas burned by prescribed fire are also at risk of increased runoff and erosion. This may seem like bad news for managers aiming at the sustainable use of fire in the landscape, as management practices should ideally have no negative effects. However, the reality is that any fuel treatment removes vegetation cover, which then implies that a certain degree of erosion is inherent to fuel management. Since it is impossible to prevent erosion and avoid negative impact, managers should therefore aim at minimizing the risks instead. This can be achieved by improving prescribed fire strategies as outlined above and by including precision fire management in the landscape.

8.3.3 Mitigating fire effects

As fire prevention efforts have clearly not (yet) been sufficient to reduce fire incidence (Pausas, 2004; Silva et al., 2008) and fire risk will increase with the expected effects of climate change (IPCC, 2007), mitigation of the negative impact of fire is essential for safeguarding natural resources, lives and property in fire-prone regions.

Our findings indicate that vegetation cover and soil surface roughness are two factors that play a key role in the increased runoff and erosion risk observed after the fire. The data indicate that efficient mitigation strategies should focus on: 1) stimulating (re)growth of the vegetation, for instance through seeding and replanting where appropriate, and banning grazing from burned landscapes where necessary, and 2) increasing surface roughness. As vegetation cover reduces the raindrop impact on bare soil and the amount of rainfall that is converted into streamflow, rapid vegetation recovery will reduce runoff and erosion in burned landscapes and therefore mitigate post-fire land degradation and flooding events. Until the vegetation cover is reestablished, increased surface roughness can contribute to a reduction in the risk and erosivity of overland flow. As such, the benefits of straw or wood shred mulching and post-fire

needle fall in increasing soil protection have been recognized in the literature (Cerdà and Doerr, 2008; Cerdà and Robichaud, 2009). While it is common practice in Portugal to remove dead pine trees in burned areas because of a loss of timber value and fears of infestation by bark beetles (Paulo Fernandes, personal communication), the protective role of soil cover and roughness suggests that land degradation may be mitigated when burned areas are not completely stripped bare after fire. Although leaving a certain amount of slash after post-fire harvesting increases the fuel load and therefore fire risk, it can potentially be very beneficial for mitigating post-fire erosion by protecting soils, acting as a sediment trap, and creating a favorable microclimate for the regeneration of vegetation.

8.4   Research challenges and future research directions

By assessing the impact of multiple fire related factors on soil and hydrology at a range of scales, this thesis has contributed to a better understanding of the causes of post-fire runoff and erosion. While I hope that this work will contribute to safeguarding natural resources in fire-prone areas, a number of topics remain to be assessed in greater detail in order to more fully understand, tackle and reverse post-fire land degradation, namely:

- Feedbacks between fire impact on soil, hydrology and vegetation vs. the rate and degree of their recovery.
- Prediction of fire-induced soil changes and degradation risk.
- The role of ash in post-fire runoff and erosion.
- The dynamics and implications of soil water repellency as areas recover from fire.
- How to best predict catchment-scale impacts of fire on hydrological and other processes from small-scale studies, taking into account the significant effects of scale.

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English summary

Fire can significantly increase a landscape's vulnerability to flooding and erosion events. By removing vegetation, changing soil properties and inducing soil water repellency, fire can increase the risk and erosivity of overland flow. Mitigation of land degradation and flooding events after fire can help safeguard natural resources and prevent further economical and ecological havoc, but can benefit from an improved understanding of its drivers. The aim of this thesis was to improve the understanding of the effects of fire on soil and hydrology. Laboratory and field studies focused on the relation between fire, soil, vegetation and hydrology as well as the effects of scale, in order to find the drivers of post-fire flooding and erosion events. This thesis presents the results of a unique field experiment in which the Portuguese Valtorto catchment was burned by experimental fire.

After the general introduction (Chapter 1), Chapter 2 discusses the potential effects of fire and ash on soil physical properties and soil water retention in particular. Laboratory burning and heating experiments demonstrated that soil heating above 200°C can significantly impact soil physical properties, increasing dry bulk density and reducing soil organic matter content, particle size and water retention capacity. The hypothesized infiltration of ash particles into soils was assessed in ash infiltration and incorporation experiments. Despite the fact that the majority of the ash remained on the soil surface, ash infiltration significantly increased soil water retention. Results therefore suggest that ash can indeed wash into pores, but to what extent this results in pore clogging such that infiltration is hampered remains to be investigated.

Given the key role that soil temperature plays in determining soil changes during fires, Chapters 3 and 4 investigate the drivers of soil heating. Chapter 3 focuses on the role of soil properties. In laboratory burning experiments, the effect of rock fragments and soil moisture was investigated. Soil moisture significantly reduced maximum temperatures, as well as the depth and duration of sustained temperatures above 60 and 175°C. While a rock fragment cover similarly protected the soil from high maximum temperatures and decreased the depth at which 60°C was exceeded, it did increase the duration of heating at the soil surface. The effect of incorporated rock fragments was highly related to soil moisture and the presence of a rock cover. The data suggest that belowground fire impact depends on soil moisture content and the presence of rock fragments in and on

the soil. This further implies that, to achieve defined goals, soil moisture and rock fragments should be considered in prescribed burning guidelines.

Chapter 4 focuses on the role of aboveground conditions and fire behavior. In a catchment-scale fire experiment, the Valtorto catchment was burned to study the drivers of soil heating in relation to fire intensity and fuel load. Despite the high fire intensity (up to 15.000 kW/m), soils stayed surprisingly cool; although maximum soil temperature was locally as high as 800°C, soil temperatures in most of the catchment remained below 100°C. The inverse relationship between soil temperature, fuel load and fire intensity may result from a combination of reduced downward heat transfer, limited flame residence time, and moist fuels in areas where fire intensity was high. Contrary to current understanding, densely vegetated or lush areas can therefore stay surprisingly cool during intense fire, while more sparsely vegetated and already degraded areas are more vulnerable to high soil temperatures, and, therefore, further degradation.

Chapter 5, 6 and 7 address the impact of the experimental fire on soil and hydrology. Chapter 5 covers the fire's impact on soil and surface properties, and discusses the implications for runoff and erosion risk. Soil physical changes were not apparent, which was consistent with the relatively low soil temperatures observed during the fire. Soil surface properties like surface roughness and Manning's n decreased as a result of fire and post-fire soil exposure, suggesting that fire increased the risk and erosivity of overland flow in the Valtorto catchment. To summarize, results indicate that fire intensity and fuel alone are poor predictors of soil burn severity. Nevertheless, the consequences of the changes in soil surface properties imply that even when soil burn severity is low, post-fire degradation can be an issue.

Chapter 6 investigates the effects of fire and vegetation removal on the dynamics of soil water repellency in a 2.5-year monitoring study. Soil water repellency appeared to be the rule rather than the exception, both before and after fire, and was strongly related to soil moisture and organic matter content. Surprisingly, despite the low soil temperatures observed at the sampled sites (60°C) and the lack of direct soil moisture changes, fire significantly increased the occurrence (Chapter 5) and persistence (Chapter 6) of soil water repellency (WDPT), suggesting that fire-induced soil water repellency may not only be determined by soil temperature. Vegetation removal played a key role in determining post-fire water repellency, and considerably reduced the time needed for both development and elimination of water repellency. Where soil water repellency already exists in unburned systems, post-fire land degradation may not be as directly caused by soil water repellency as sometimes suggested in the literature. Yet, fire-induced vegetation removal may increase the hydrological significance of soil water repellency in

burned landscapes.

Chapter 7 assesses the impact of the fire on hydrology at the subcatchment and catchment scale. Rainfall, canopy interception, streamflow and soil moisture were monitored pre- and post-fire, using paired catchments (Valtorto and an adjacent control) and a nested approach. By increasing the amount of streamflow per unit rainfall, the fire increased the risk of flooding, particularly at the small scale. Results verify that fire impact on hydrology is largely affected by scale, and emphasize the risk of overestimating fire impact when upscaling plot-scale studies to the catchment-scale. Finally, results provide new information suggesting that fire-induced hydrological changes can occur even when soil temperatures during fire remain low and soil physical changes are not apparent. Vegetation removal is likely the most significant cause of the observed hydrological changes because of its effects on effective rainfall, plant transpiration, soil water repellency fluctuation and surface roughness.

Finally, Chapter 8 presents a synthesis of the results and conclusions of the previous chapters. Fire impact on soil can be significant, and is highly determined by the soil temperatures reached. While soil temperatures are affected by a soil's thermal properties, they are above all determined by aboveground processes. The Valtorto experimental fire showed that fire intensity and fuel load are poor predictors of soil temperature and related soil burn severity – considerably changing current understanding. Similarly, given the fact that soil surface properties may change even in low-severity fire, soil burn severity is a poor predictor of erosion risk. Fire-induced soil water repellency and increased temporal dynamics may result in increased runoff and erosion risk during small rain events – even in areas where pre-fire soil water repellency is ubiquitous. Fire impact on hydrological processes is greatly affected by scale, and where soil physical changes are absent, vegetation removal is likely the most significant cause of increased post-fire runoff and erosion risk.

In order to prevent or mitigate post-fire land degradation, this thesis has contributed to a better understanding of the causes of post-fire flooding and erosion by assessing the impact of fire on soil and hydrology at a range of scales. Naturally, the best way to mitigate fire-induced land degradation is to prevent fires, for instance through land use change or fuel management. Chapter 8 therefore presents recommendations for prescribed fire management, focusing on incorporation of soil moisture and rock fragments in burning guidelines, and precision fire management rather than catchment-scale burns. Finally, Chapter 8 concludes with recommendations for mitigating land degradation in burned areas where fire prevention was unsuccessful, which should focus on stimulating (re)growth of the vegetation, and increasing surface roughness.

Sumário português

Os incêndios florestais aumentam significativamente a vulnerabilidade dos ecossistemas a ocorrências de cheias e erosão, em resposta à remoção da vegetação, da alteração das propriedades do solo e da indução da repelência do solo à água. Em resultado dessas alterações, o fogo induz um aumento do risco de ocorrência de escorrência superficial e da sua erosividade. A mitigação da degradação do solo e das cheias após o fogo poderá ajudar salvaguardar os recursos naturais e prevenir danos económicos e ecológicos a jusante, podendo também beneficiar de uma melhor compreensão dos factores críticos indutores de degradação. Este estudo tem como objectivo melhorar a compreensão dos impactos do fogo na degradação da água e dos solos. Estudos laboratoriais e de campo centram-se na relação entre o fogo, solo, vegetação e hidrologia, bem como nos efeitos de escala, de forma a identificar os factores críticos indutores de picos de cheias e de erosão pós-fogo. Esta tese apresenta os resultados de um trabalho experimental original, no qual a bacia hidrológica portuguesa de Valtorto foi queimada num fogo experimental.

Após a introdução geral (Capítulo 1), o Capítulo 2 discute os impactos potenciais do fogo e das cinzas nas propriedades físicas do solo e na sua capacidade de retenção de água. Ensaios laboratoriais após queima e aquecimento demonstraram que o solo aquecido acima dos 200°C altera significativamente as propriedades físicas do solo, aumentando a densidade e reduzindo o conteúdo de matéria orgânica do solo, o tamanho das partículas, e a capacidade de retenção da água. A hipótese de as cinzas se poderem infiltrar nos solos foi analisada através de experiências de infiltração e incorporação das cinzas. Apesar da maioria das cinzas terem ficado à superfície do solo, a infiltração das cinzas aumentou significativamente a retenção de água pelo solo. Os resultados sugerem que as cinzas podem de facto preencher os poros do solo; no entanto o impacto que as cinzas provocam sobre a obstrução dos poros e a redução da capacidade de infiltração ainda necessita de mais investigação.

Dado o papel fundamental que a temperatura do solo desempenha na determinação de alterações do solo durante os fogos, os Capítulos 3 e 4 investigam os factores chave do aquecimento do solo.

O Capítulo 3 foca o papel das propriedades do solo. Em ensaios laboratoriais de queima, foi investigado o impacto dos fragmentos de rocha e da humidade do solo. A humidade

do solo pode reduzir significativamente as temperaturas máximas, bem como a profundidade e duração de temperaturas acima dos 60 e 175ºC. De igual modo, uma cobertura de rochas protege o solo de temperaturas máximas elevadas e diminui a profundidade a que a temperatura de 60ºC é atingida, embora essa cobertura aumente a duração de aquecimento da superfície do solo. O efeito da incorporação de fragmentos rochosos está intimamente relacionado com o conteúdo da humidade do solo e a presença de fragmentos rochosos dentro e sobre o solo. Isto implica que, para atingir os objectivos definidos, a humidade do solo e fragmentos rochosos devem ser considerados nos procedimentos de fogos controlados.

O Capítulo 4 aborda o papel das condições à superfície do solo e o comportamento do fogo. A bacia de Valtorto foi queimada num fogo experimental, de forma a estudar os agentes de aquecimento do solo relacionados com a intensidade do fogo e a carga de combustível à escala da bacia hidrográfica. Apesar da elevada intensidade do fogo (que atingiu 15.000 kW/m), os solos permaneceram surpreendentemente frescos; apesar da temperatura máxima dos solos atingir localmente temperaturas acima dos 800°C, na maior parte da bacia os solos permaneceram abaixo dos 100°C. A relação inversa entre a temperatura do solo, a carga de combustível e a intensidade do fogo poderá resultar de uma combinação entre uma reduzida transferência de calor descendente, um tempo reduzido de residência de chama e a humidade dos combustíveis em áreas onde a intensidade do fogo foi elevada. Ao contrário do esperado, áreas com vegetação densa ou viçosa poderão permanecer surpreendentemente frescas durante um fogo intenso, enquanto áreas de vegetação mais esparsa ou degradadas são mais vulneráveis a temperaturas elevadas do solo e, consequentemente, poderá resultar num aumento da degradação.

Os Capítulos 5, 6 e 7 abordam o impacte do fogo experimental no solo e na hidrologia.

O Capítulo 5 aborda o impacte do fogo sobre as propriedades do solo superficial, discutindo as implicações para a escorrência e o risco de erosão. As alterações físicas do solo não são aparentes. Este resultado é consistente com as temperaturas do solo relativamente baixas verificadas durante o fogo. As propriedades do solo superficial, tais como a rugosidade e o coeficiente de rugosidade de Manning, diminuíram como resultado da exposição do solo ao fogo e processos subsequentes, sugerindo que o fogo aumentou o risco e erosividade da escorrência na bacia hidrográfica de Valtorto. Em resumo, os resultados indicam que a intensidade do fogo e combustível são, por si só, fracos indicadores da severidade da queima do solo. Contudo, as consequências das alterações das propriedades da superfície do solo implicam que, até quando a severidade de queima do solo é baixa, a degradação pós-fogo poderá constituir um problema.

O Capítulo 6 investiga os efeitos do fogo e da remoção da vegetação na dinâmica da repelência dos solos à água, através de um estudo de monitorização que se estendeu por dois anos e meio. A repelência do solo à água constitui mais a regra do que a excepção, tanto antes como depois do fogo, e está fortemente relacionada com a humidade do solo e o conteúdo de matéria orgânica. Surpreendentemente, apesar das baixas temperaturas do solo observadas nos locais de amostragem (60°C) e da falta de dados directos de alterações na humidade do solo, o fogo aumentou significativamente a ocorrência (Capítulo 5) e persistência (Capítulo 6) da repelência do solo à água, sugerindo que a repelência induzida pelo fogo poderá não ser apenas determinada pela temperatura do solo. A remoção da vegetação desempenha igualmente um papel importante na indução da repelência do solo à água após o fogo, além de diminuir consideravelmente o tempo necessário tanto para o desenvolvimento como para a eliminação da repelência. Onde a repelência do solo à água já existe em sistemas não ardidos, a degradação dos solos após o incêndio pode não possuir uma relação causal com a repelência dos solos à água tão forte como a sugerida pela maior parte da bibliografia sobre o tema sugere. No entanto, a remoção de vegetação induzida pelo fogo poderá aumentar a significância da repelência do solo à água sobre a resposta hidrológica em áreas ardidas.

O Capítulo 7 avalia o impacto do fogo na hidrologia à escala da bacia e das sub-bacias hidrográficas. A precipitação, intercepção pela vegetação, o caudal e a humidade do solo foram monitorizadas antes e após o fogo, utilizando um par de bacias hidrográficas (a de Valtorto, que foi queimada e uma de controlo, adjacente), bem como uma abordagem integrando várias escalas. Ao aumentar o caudal por unidade de precipitação, o fogo aumentou o risco de cheia, particularmente em pequenas áreas. Os resultados demonstram que o impacte na hidrologia é profundamente afectado pela escala, enfatizando o risco de sobrestimar o impacte do fogo quando se extrapolam os resultados de um talhão para a escala de uma bacia hidrográfica. Os resultados apresentados sugerem que as alterações hidrológicas induzidas pelo fogo podem ocorrer até quando as temperaturas do solo durante o fogo se mantêm baixas e as alterações físicas do solo não são aparentes. A remoção da vegetação é provavelmente a causa mais significativa das alterações hidrológicas observadas devido aos seus efeitos na precipitação efectiva, na transpiração da vegetação, na flutuação da repelência do solo à água e na rugosidade da superfície.

Por fim, o Capítulo 8 apresenta uma síntese dos resultados e conclusões dos capítulos anteriores. O impacto do fogo nos solos poderá ser significativo e é antes de mais determinado pelas temperaturas atingidas pelo solo. As temperaturas do solo são afectadas pelas suas propriedades térmicas, e acima de tudo pelos processos acima do solo. O fogo experimental de Valtorto mostrou que a intensidade do fogo e a carga de

combustível são fracos indicadores da temperatura do solo e da severidade dos impactos do fogo sobre o solo – no que constitui uma mudança face aos paradigmas aceites nesta área do conhecimento. Dado que as propriedades da superfície do solo poderão sofrer alterações mesmo em fogos de baixa severidade, a severidade da queima do solo constitui um fraco indicador do risco de erosão. A repelência do solo à água induzida por fogo e o incremento das dinâmicas temporais poderão induzir um aumento da escorrência e do risco de erosão durante pequenos episódios chuvosos – mesmo em áreas onde a repelência do solo à água antes do fogo é ubíqua. O impacte do fogo nos processos hidrológicos é fortemente afectado pela escala, e onde não ocorrem alterações físicas ao solo, a remoção da vegetação é presumivelmente a causa mais significativa do aumento da escorrência e do risco de erosão após o fogo.

De modo a prevenir ou mitigar a degradação do solo pós-incêndio, esta tese contribui para uma melhor compreensão das causas dos picos de cheias e da erosão pós-incêndio pela avaliação do impacto do fogo no solo e nos processos hidrológicos a varias escalas. Naturalmente, a melhor forma de mitigar a degradação do solo provocada pelos incêndios é prevenir que ocorram, através, por exemplo, da alteração do uso do solo ou da gestão da carga combustível. O Capítulo 8 apresenta, por isso, recomendações para a gestão através da utilização de fogo controlado, abordando a incorporação de elementos como a humidade do solo e os fragmentos de rochas nas metodologias da técnica. De referir igualmente a necessidade de usar a técnica do fogo controlado para gerir o combustível através de fogo de precisão, não sendo aconselhável a queima de áreas demasiado extensas, nomeadamente de bacias hidrográficas. Por fim, o Capítulo 8 apresenta recomendações para a mitigação da degradação do solo em áreas ardidas, onde a prevenção não teve sucesso, que se deverão concentrar no estímulo ao (re)crescimento da vegetação, e no aumento da rugosidade do solo.

Nederlandse samenvatting

Bosbranden kunnen het landschap gevoeliger maken voor overstromingen en erosie. Naast het feit dat brand de vegetatie verwijdert, kan de hitte van het vuur ook bodemeigenschappen veranderen en de bodem waterafstotend maken. Branden verhogen daardoor niet alleen de kans op, maar ook de kracht van oppervlakte-afvoer. Als na bosbranden landdegradatie en overstromingen kunnen worden voorkomen, kunnen natuurlijke grondstoffen worden behouden en kan verdere economische en ecologische schade worden beperkt. Hiervoor is een beter begrip noodzakelijk van de onderliggende oorzaken van overstromingen en erosie na brand. Het doel van dit proefschrift is daarom om beter te begrijpen wat de effecten zijn van brand op bodem en hydrologie. In laboratorium- en veldstudies zijn de relatie tussen vuur, bodem, vegetatie en hydrologie en de effecten van schaal bestudeerd. Dit proefschrift presenteert de resultaten van een uniek veldexperiment waarin het Portugese Valtorto-stroomgebied werd verbrand tijdens een experimentele brand.

Na de algemene introductie (Hoofdstuk 1), bespreekt Hoofdstuk 2 de mogelijke effecten van vuur en as op bodemfysische eigenschappen, en de bodemvochtkarakteristiek in het bijzonder. Tijdens laboratoriumexperimenten werd grond verhit (in de oven) of verbrand (met een gasbrander). De resultaten laten zien dat verhitting boven 200°C de fysische eigenschappen van een bodem significant kan veranderen en leidt tot een verhoging van de droge bulkdichtheid en een verlaging van het organisch stofgehalte, de korrelgrootte en het vochthoudend vermogen. Met infiltratie en meng-experimenten werd vervolgens getest of asdeeltjes de grond in kunnen spoelen, iets wat wordt gesuggereerd in de literatuur. Ondanks dat het grootste deel van de as op het bodemoppervlak bleef liggen leidden de infiltratie-experimenten tot een significante verhoging in het vochthoudend vermogen. De resultaten wijzen er daarom op dat as inderdaad de grond in kan spoelen. In hoeverre dit poriën kan blokkeren waardoor infiltratie wordt geremd behoeft aanvullend onderzoek.

Omdat de temperatuur van een bodem tijdens brand sterk grote invloed heeft op de mate waarin veranderingen optreden in de bodem richten Hoofdstuk 3 en 4 zich op de factoren die bodemtemperaturen bepalen tijdens brand.

Hoofdstuk 3 gaat over de rol van de bodem zelf. Tijdens brandexperimenten in het laboratorium werd het effect van stenen en bodemvocht op bodemtemperaturen tijdens brand bepaald. Bodemvocht verlaagde de maximumtemperatuur significant, en zorgde verder voor een afname van de diepte en de tijd dat de bodem heter was dan 60 en 175°C. Terwijl een stenenbedekking een vergelijkbaar beschermend effect had op maximumtemperaturen, en ook de diepte verlaagde waarop de grond heter werd dan 60°C, verlengde het de tijd waarop het bodemoppervlak deze temperaturen overschreed. Het effect van stenen in de grond was sterk gerelateerd aan het bodemvochtgehalte en de aanwezigheid van stenen op het oppervlak. De data suggereren dat het effect van brand op bodems afhangt van bodemvocht en de aanwezigheid van stenen in en op de bodem. Het is daarom raadzaam om bodemvocht en stenen mee te nemen in richtlijnen voor het uitvoeren van gecontroleerde branden, zodat beheerders hun doelen halen.

Hoofdstuk 4 gaat over de rol van bovengrondse factoren en het vuurgedrag. In een grootschalig brandexperiment werd het Valtorto stroomgebied verbrand om te onderzoeken hoe de aanwezige brandstof en de intensiteit van het vuur de temperatuur van de bodem bepalen tijdens een brand. Verrassend genoeg bleef tijdens de hete brand, waarin de vuurintensiteit opliep tot 15.000 kW/m, de bodem relatief koel. Alhoewel er plekken waren waar de bodemtemperatuur tot 800°C reikte, bleef de bodem in het grootste gedeelte van het stroomgebied koeler dan 100°C. Het inverse verband tussen bodemtemperatuur, brandstofhoeveelheid en vuurintensiteit kan verklaard worden door een verminderde neerwaartse warmtestroom, een beperkte verblijftijd van de vlammen, en doordat de brandstof vochtig was op de plekken waar vuurintensiteit hoog was. In tegenstelling tot de huidige kennis, kunnen dichtbegroeide of weelderige plekken daarom verrassend koel blijven tijdens intense brand, terwijl meer dunbegroeide en al gedegradeerde plekken gevoeliger zijn voor hoge bodemtemperaturen, en daarom voor verdere degradatie.

Hoofdstuk 5, 6 en 7 zijn gericht op de impact van de experimentele brand op de bodem en de hydrologie.

Hoofdstuk 5 gaat over de impact van brand op de bodem en het bodemoppervlak en de gevolgen voor het risico van oppervlakte-afvoer en erosie. Als gevolg van de brand werden geen veranderingen in bodemfysische eigenschappen geobserveerd, wat overeen kwam met de relatief lage bodemtemperaturen tijdens de brand. Het bodemoppervlak veranderde echter wel: zowel tijdens als na de brand, toen de bodem was blootgesteld aan de elementen, namen bodemruwheid en Manning's n af, wat suggereert dat de brand het risico en de kracht van oppervlakte-afvoer heeft vergroot. Al met al wijzen de resultaten erop dat brandstofhoeveelheid en vuurintensiteit alleen slechte voorspellers

zijn van de impact van brand op de bodem (de *soil burn severity*). Desondanks wijzen de veranderingen in het bodemoppervlak erop dat branden zelfs tot landdegradatie kunnen leiden als de impact op de bodem zelf laag is.

Hoofdstuk 6 onderzoekt het effect van brand en een vegetatiedek op de waterafstotendheid van de bodem in een 2.5-jaar durende volgstudie. Waterafstotendheid bleek de standaard in plaats van de uitzondering, zowel voor als na de brand, en was sterk gerelateerd aan de bodemvochtigheid en de hoeveelheid organische stof in de bodem. Verbazingwekkend genoeg zorgde de brand voor een toename van het vóórkomen (Hoofdstuk 5) en de mate (Hoofdstuk 6) van de waterafstotendheid, ondanks het feit dat de bodemtemperatuur op de bemonsterde locaties laag was gebleven (60°C) en het bodemvochtgehalte niet significant was veranderd. Dit suggereert dat waterafstotendheid die ontstaat of versterkt tijdens brand niet alleen bepaald wordt door bodemtemperatuur. Verwijdering van de vegetatie speelde een hoofdrol in de variatie van waterafstotendheid na de brand, en verkortte sterk de tijd die nodig was om waterafstotendheid te ontwikkelen én af te breken. In gebieden waar waterafstotendheid ook voorkomt bij onverbrande bodems wordt landdegradatie na brand niet zo direct veroorzaakt door waterafstotendheid als wordt gesuggereerd in de literatuur. Desondanks kan de verwijdering van vegetatie door brand de hydrologische gevolgen van waterafstotendheid vergroten.

Hoofdstuk 7 bespreekt de impact van brand op stroomgebied en substroomgebiedsschaal. Regen, interceptie, beekafvoer en bodemvochtgehalte werden gemonitord voor en na de brand, gebruikmakend van gepaarde stroomgebieden (Valtorto en een nabijgelegen controlegebied) en een geneste studie-opzet. De Valtorto-brand heeft de hoeveelheid afvoer per eenheid regenval verhoogd, en daarmee de kans op overstromingen vergroot – vooral op kleine schaal. De resultaten bevestigen daarmee dat het effect van brand op de hydrologie sterk wordt beïnvloed door het schaalniveau, en benadrukken dat het extrapoleren van plot-metingen kan leiden tot een overschatting van de effecten van brand op de stroomgebiedsschaal. Tenslotte verschaffen de resultaten nieuw inzicht dat suggereert dat brand zelfs tot hydrologische veranderingen kan leiden als bodemtemperaturen laag blijven en bodemfysische veranderingen niet optreden. De verwijdering van vegetatie is waarschijnlijk de belangrijkste oorzaak van de geobserveerde hydrologische veranderingen, vanwege de effecten op effectieve neerslag, plant transpiratie, de veranderingen in de waterafstotendheid van de bodem, en de ruwheid van het bodemoppervlak.

Als laatste omvat Hoofdstuk 8 een synthese van de resultaten en conclusies van de voorgaande hoofdstukken. Brand kan significante effecten hebben op de bodem, en de

impact van brand is sterk bepaald door de behaalde bodemtemperaturen. Ook al worden bodemtemperaturen beïnvloed door de warmte-eigenschappen van de bodem, ze worden voornamelijk bepaald door bovengrondse processen. De experimentele brand in Valtorto liet zien dat vuurintensiteit en brandstofhoeveelheid slechte voorspellers zijn van bodemtemperatuur en de gerelateerde impact van brand op de bodem. Dit verandert sterk de huidige opvatting over wat bodemtemperaturen bepaalt tijdens een brand. De impact van brand op de bodem is vervolgens een slechte voorspeller van het risico op erosie na brand, omdat erosierisico deels is bepaald door het bodemoppervlak, wat ook verandert in branden die weinig impact hebben op de bodem zelf. De (variatie in) waterafstotendheid die ontstaat door en na brand kan leiden tot grotere oppervlakte-afvoer en meer erosie tijdens kleine regenbuien – zelfs in gebieden waar onverbrande bodems veelvuldig waterafstotendheid zijn. De effecten van brand op hydrologische processen is sterk beïnvloed door schaal, en waar bodemfysische veranderingen niet optreden is de verwijdering van vegetatie waarschijnlijk de grootste oorzaak van de verhoging van het risico op oppervlakte-afvoer en erosie na branden.

Met als doel landdegradatie na branden te verminderen of te voorkomen draagt dit proefschrift bij aan een beter begrip van de oorzaken van overstromingen en erosie na branden door het effect van brand op bodem en hydrologie te bestuderen op verschillende schaalniveaus. De beste manier om landdegradatie na brand te voorkomen is natuurlijk het voorkomen van brand zelf, bijvoorbeeld door landgebruiksveranderingen of het beheer van de hoeveelheid en verdeling van brandstof (i.e. vegetatie) in de natuur. Hoofdstuk 8 bevat daarom aanbevelingen rond het gebruik van gecontroleerde branden in natuurbeheer. Om beheersdoeleinden te behalen wordt aangeraden bodemvocht en de aanwezigheid van stenen in en op de bodem mee te nemen in de brandrichtlijnen, en precisie-branden uit te voeren in plaats van branden op stroomgebiedsschaal. Hoofdstuk 8 sluit tenslotte af met richtlijnen voor het verminderen van landdegradatie in verbrande gebieden waar het voorkomen van brand niet succesvol was. Aanbevolen wordt technieken te focussen op de (terug)groei van de vegetatie en het vergroten van de ruwheid van het bodemoppervlak.

Dankwoord

"Are you looking for gold up there?" Of course the villagers of Cerdeira were wondering what I was doing up that mountain in the summer heat, winter cold or during the heaviest rains. Naturally, by the time the fire came they knew what it was all about. Four years, three hometowns on two continents, more than 16,000 car-kilometers (I don't dare count the plane-kilometers), roughly 30 fires and burned areas that we did or did not sample, ~5,500 soil samples, roughly 160 kg of hand-sieved soil and over 11,000 WDPT tests: it's done. Students and locals are key to successful fieldwork campaigns, but there are more to thank. The tremendous amount of work done to make this thesis possible would never have been accomplished without the help of many others, all of whom I would like to thank here.

Het begon allemaal in de zomer van 2006, toen ik door het DESIRE projectvoorstel las over de grote impact van vuur op ecosystemen. Ik was geïntrigeerd, en Coen, jij gaf mij de kans en de financiële middelen om mijn eigen onderzoek te bedenken, uit te voeren en te communiceren. Jij weet hoe je onderzoek moet verkopen, stimuleerde mijn media-activiteiten, en was altijd bereid mee te denken bij weer een interview of uitzending. Dank voor de vrijheid die je me gaf mijn eigen richting te kiezen, zowel wat betreft mijn onderzoek als het land waar ik dat op dat moment uit wilde voeren, en dank voor je creativiteit, je enthousiasme, en je vertrouwen. António, you were the person with the incredible idea: burning a catchment for science. Thanks for your hospitality in Coimbra, your introduction to the Portuguese fire problem, but most of all thanks for having me perform this amazing experiment. Jan, dank voor je begeleiding tijdens de eerste helft van mijn project, en de handige software die je 'eventjes' voor me gebouwd hebt. Demie, geweldig bedankt voor je (taal)hulp en morele steun, in good and bad times!

Like I said, students and locals are the key to success in ambitious field campaigns. First Carla: thanks for all your help in the field and your hospitality at home, en in chronologische volgorde al mijn studenten - voor wie Portugal niet écht een vakantie-bestemming was: Ayolt, Wouter, Jonathan, Annemieke, Simon and Erik, duizendmaal dank voor al jullie harde werk in het veld! Also thanks to my Swansea colleagues and Carla and Célia for taking up the erosion work in Valtorto. Rick Shakesby and Rory Walsh thanks moreover for your help with constructing the concrete weir in Espinho and for

and for giving me the tools to use it. Mijn dank gaat ook uit naar Erik van den Elsen, voor zijn hulp bij het kalibreren van de bodemvochtsensoren in Valtorto, Louis Dekker, voor al zijn kennis over waterafstotendheid, en Rudi Hessel, voor zijn uitleg van Manning's n metingen (als iemand mij ooit daarover vraagt: bezint eer ge begint). Daarnaast dank ik ook Joost Iwema en Jan van Linge voor hun bijdrage in de hydrologie en de modellering, Leo Stroosnijder voor zijn overkoepelende blik, and Stefan Doerr for his useful insights during the proposal-writing stage of my research. Jac Niessen, dank voor je enthousiaste hulp bij de communicatie van mijn onderzoek naar de media, Rik Kuiper (Quest), Bart Reterink (Netwerk) en tal van andere journalisten voor jullie geslaagde bijdragen aan mijn onderzoek in de media, en Erik Kroes voor het ontwerpen van de omslag. Verder dank aan Wim van der Putten voor schrijfadvies bij Hoofdstuk 4, Paul Torfs voor discussie, Judith Risse voor hulp met MySQL, Floris van Ogtrop for R assistance, and Klaas Oostindie, Piet Peters, Veronica Morales, Harm Gooren, Gerben Bakker, Eduard Hummelink, Jaap Nelemans, Eef Velthorst and Phil Bevan thanks for help in the lab. En natuurlijk mijn vuurvrienden in Nederland: Ester, Jelmer, Henk, Mathijs, Alette en sinds kort ook Winand: laten we samen aan de slag blijven om de problematiek rond natuurbranden in Nederland op de kaart te zetten. Colleagues and roommates that I didn't mention yet in Wageningen (Simone, Manuel, Saskia K. en V., Feras, Jantiene, Marnella en vele anderen), Coimbra and Sydney, thanks for sharing four years of ups and downs, lunches and teas. En Kathleen en Nadine, dank dat jullie mijn paranimfen willen zijn!

En dan was er een groep vrienden en familie die me een beetje weinig gezien heeft de afgelopen vier jaar. In welk land ik zou zitten was zelfs voor mij vaak een vraag, laat staan voor anderen. Mam, pap, Irene en Winold, Oma van Vliet en Oma Haas, de Vermeulen family, Kathleen, Nadine, Janneke, Francien, Marieke, Rutger en Nynke, Lex, en Klaartje, dank voor jullie support de afgelopen jaren, in de vorm van telefoontjes, sms, peptalks, sauna of kroegbezoek, krantenknipsels en radiofragmenten, een luisterend oor, of gewoon een bord eten of een kop thee en een ander onderwerp.

Peter, ik weet dat je niet van plan bent coach te worden, maar je zou echt een goede zijn. Ver weg maar zo dichtbij, dank voor je steun en je doordachte inzichten, van planning en wetenschappelijk schrijven tot communicatie en de media. En ook al werken langeafstandsrelaties best, toch ben ik blij dat ons volgende avontuur op hetzelfde continent zal zijn, in het zelfde land, zelfs in dezelfde stad. 1+1= zeker 2, waar ook ter wereld, en vanaf binnenkort zelfs op dezelfde plek. Super.

About the author

Short biography

Cathelijne Reinilde Stoof was born in Zwolle, the Netherlands, on 21 January 1981. From 1993 to 1999 she attended secondary school at the Twickel College in Hengelo, where she graduated in the courses Dutch, English, French, Physics, Chemistry, Mathematics-B, Music and Geography.

In 1999 she started the Soil, Water Atmosphere program at Wageningen University, and in 2001 she attended Sogn og Fjordane University College in western Norway for a 4-month interdisciplinary course on the geology and ecology of that region. Cathelijne specialized in soil science and hydrology. Her first Masters thesis focused on the hydrogeology of a small mountain stream in Tatra Mountain alluvium near Liptovský Mikuláš, Slovakia, and her second and main Masters thesis focused on the effects of topography and land use on soil hydraulic properties of a hummocky till on the Saskatchewan prairie in Canada. This latter project was performed at the University of Saskatchewan in Saskatoon, Canada in 2004. Cathelijne then took a year off to be an active member of the Progressive Student Fraction PSF in the University's Student Council, of which she later became the chairperson. In 2006 she completed her degree with an internship at the Soil Physics and Land Use Team at Alterra Green World Research. She received her MSc diploma, with distinction, in August 2006.

After a short position as junior researcher, Cathelijne started with her PhD research at Wageningen University in 2007. She was given the opportunity to write her own research proposal within the EU project DESIRE, which resulted in this thesis on the effects of fire on soil and hydrology. A substantial part of this thesis project was performed at Escola Superior Agrária de Coimbra in Portugal and the University of Sydney in Australia.

During her PhD research, Cathelijne received six awards and scholarships, including an International Association of Wildland Fire scholarship in 2008, third prize in the PE&RC Best Publication Award 2010 for her first 1st-authored scientific paper (Stoof et al, 2010, Geoderma), and first prize in the biannual Storm-Van der Chijs award for the most talented female PhD researcher of Wageningen University.

Cathelijne will continue her scientific career with a post-doc at Cornell University (USA).

Publications related to this thesis

·   **Stoof, C.R.**, Wesseling, J.G., Ritsema, C.J. (2010). *Effects of fire and ash on soil water retention.* Geoderma 159 (3-4), p. 276-285.

·   **Stoof, C.R.**, De Kort, A., Bishop, T.F.A., Moore, D., Wesseling, J.G., Ritsema, C.J. (2011). *How rock fragments and soil moisture affect soil temperatures during fire.* Soil Science Society of America Journal 75, p. 1133-1143.

·   **Stoof, C.R.**, A.J.D. Ferreira, W. Mol, J. Van den Berg, A. De Kort, S. Drooger, E.C. Slingerland, A.U. Mansholt, C.S.S. Ferreira, T.C.J. Esteves, and C.J. Ritsema (2011). *Soil surface changes increase erosion risk after low-severity fire*. International Journal of Wildland Fire (in review).

·   **Stoof, C.R.**, J.J. Stoorvogel, P.M. Fernandes, D. Moore, R.E.S. Fernandes, A.J.D. Ferreira, and C.J. Ritsema. 2011. Hot fire, cool soil (in preparation).

·   **Stoof, C.R.**, D. Moore, C.J. Ritsema, and L.W. Dekker. 2011. *Natural and fire-induced soil water repellency in a Portuguese shrubland*. Soil Science Society of America Journal (accepted).

·   **Stoof, C.R.**, R.W. Vervoort, J. Iwema, E. van den Elsen, A.J.D. Ferreira, and C.J. Ritsema. 2011. *Hydrological response of a small catchment burned by experimental fire*. Hydrology and Earth System Sciences Discussions 8, p. 4053-4098.

Besides these peer-reviewed articles, parts of this research were disseminated to the scientific community by more than 20 presentations at national and international conferences (see following pages). Moreover, because I think that research that devises solutions for problems in society deserves public exposure and requires raising public awareness, I also communicated my research to the general public through the media, using tv, radio, magazines, newspapers and websites.

PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)
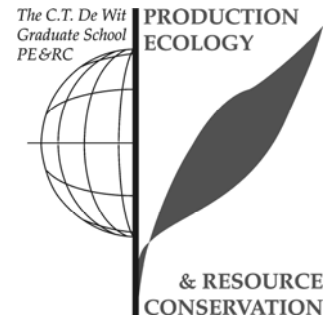
Review of literature (5 ECTS)
- Fire effects on soil and hydrology (2007)

Writing of project proposal (4.5 ECTS)
- Fire effects on soil water movement (2007)

Post-graduate courses (3.6 ECTS)
- Fire ecology; PE&RC, United Nations University (2008)
- Sampling for natural resource monitoring; Alterra (2008)
- Forest fire, hydrology and geomorphic processes: a SE Australian perspective; the University of Melbourne, Australia (2008)

Laboratory training and working visits (4.5 ECTS)
- Effects of prescribed, experimental and wildfires;
  Escola Superior Agrária de Coimbra, Portugal (2007-2010)
- Prescribed fires; Grupo de Análise do Uso do Fogo (GAUF), Portugal; (2008-2009)
- Post-fire soil erosion and debris flows; the University of Melbourne, Australia (2009)
- Fire effects on catchment hydrology; the University of Sydney, Australia (2009-2011)
- Effects of ash on pore-scale water movement; Cornell University, USA (2010)

Invited review of (unpublished) journal (1 ECTS)
- Geoderma (2008)

Deficiency, refresh, brush-up courses (2.7 ECTS)
- Basic statistics (2007)
- Erosion processes and modelling (2007)
- Biometry, applied statistics (2009)

Competence strengthening / skills courses (1.6 ECTS)
- Scientific publishing; WGS (2007)
- PhD competence assessment; WGS (2007)
- Project and time management; WGS (2007)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.5 ECTS)
- PE&RC weekend (2007)
- PE&RC day, intelligent communication: on the origin of communication (2009)
- PE&RC day, selling science: why and how scientists sell science (2010)

Discussion groups / local seminars / other scientific meetings (4.7 ECTS)

- Dutch wildfire information network (2010-2011)
- Symposium natuurbranden, NIFV; Schaarsbergen (2010)
- Veldwerkplaats gecontroleerde branden; Harskamp (2010)
- Stakeholder meeting, efficiency of fire breaks; Góis, Portugal (2009)

- Incêndios florestais, 5 anos apôs 2003; Coimbra, Portugal (2008)
- Bessensap; science meets the press; Amsterdam (2008, 2009)
- European science night Discovery '09; Amsterdam (2009)
- Spatial methods discussion group (2007, 2008)
- Nederlands Aardkundig Congres NAC'10 (2010)
- Bodembreed; Lunteren (2009)

International symposia, workshops and conferences (9 ECTS)

- COST 634 conference; Aveiro, Portugal (2008)
- European Geosciences Union; Vienna, Austria (2008, 2011)
- KNAW Academy colloquium: Fire in human evolution, human history, human society; Amsterdam (2009)
- International meeting of fire effects on soil properties FESP II; Marmaris, Turkey (2009)
- Geomorphology; Melbourne, Australia (2009)
- IV International Conference on Forest Fire Research; Coimbra, Portugal (2010)
- International meeting of fire effects on soil properties FESP III; Guimarães, Portugal (2011)

Lecturing / supervision of practical's / tutorials (1.5 ECTS)

- TUNEX – Field trip erosion and soil & water conservation, and irrigation and water management Tunisia; 10 days (2008)

Supervision of 4 MSc and 9 BSc students; 45 days (3 ECTS)

- Effect of wildfires on soil properties and preferential flow
- Soil temperatures and impact of prescribed fires
- Soil temperatures in a catchment-scale experimental fire
- Fire effects on catchment hydrology
- Effect of rock fragments and soil moisture on soil temperature profiles during fire

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