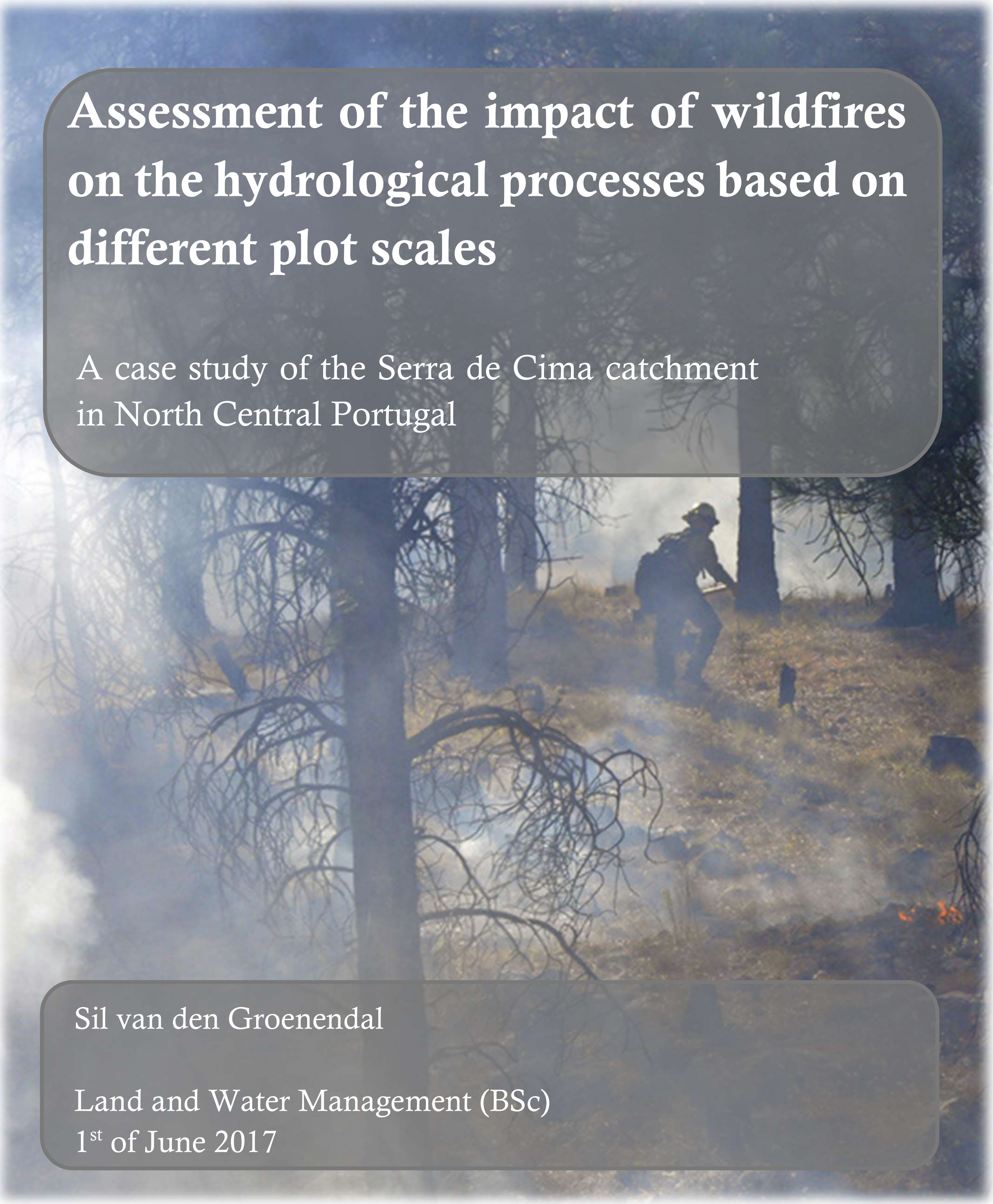
- BACHELOR THESIS -



Assessment of the impact of wildfires on the hydrological processes based on different plot scales

A case study of the Serra de Cima catchment
in North Central Portugal

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Land and Water Management (BSc)

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FOREWORD

This bachelor thesis, with the subject 'Assessment of the impact of wildfires on the hydrological processes based on different plot scales', is part of the research project HIDRIA and is intended for the Department of Environment and Planning (as part of Universidade de Aveiro) and the Centro de Estudos do Ambiento e do Mar (CESAM). The thesis describes a case study of the Serra de Cima catchment in North Central Portugal, and focuses on the hydrological impacts due to wildfires.

The graduate traineeship has been carried out as part of the Bachelor programme Land and Water Management (specialisation Applied Hydrology & International Water Management) at Van Hall Larenstein University of Applied Sciences in Velp. The report is an individual product and it is meant to assess the theoretical knowledge and skills which have been applied in practice. The responsible person for the assessment of the report is Mr. Groenhuijzen, being the internal assessor from Van Hall Larenstein University of Applied Sciences.

Throughout the process of the research I have been supervised and guided by Mr. Martinho Martins, which was my internal supervisor. Furthermore, dr. Jan Jacob Keizer supervised the progress of the thesis and overlooked written paragraphs to monitor the progress. During the traineeship period, I have taken the initiative to assess the research and request feedback every two weeks from the supervisors at the university and the internal supervisor of Van Hall Larenstein University of Applied Sciences.

Overall, I would like to thank some persons which have been involved in the process of this thesis. First off I would like to thank my supervisors at Universidade de Aveiro. Both Mr. Martins and dr. Keizer have contributed to my research and helped me to look critical at my work, gain knowledge about the subject and most importantly made me enthusiastic to work on it. This helped me to stay motivated throughout the period of my traineeship.
This also applies for the supervisor of Van Hall Larenstein University of Applied Sciences, dr. Eeman. She helped me by giving feedback on the research and making sure I maintained to have the correct aim for my thesis. Also, I would like to thank the rest of the persons working at the Department of Environment and Planning for welcoming me in their team and helping me where necessary.
At last, I would like to thank the ESN department in Aveiro for organising several activities, helping me to meet new people and see the beauty of Portugal.

I hope you enjoy reading this thesis.

Sil van den Groenendal
Aveiro, June 2017

SUMMARY

Portugal is the most wildfire affected country in Europe, with 3% of the rural area being subjected to wildfires. One of the biggest fires of the decade occurred in summer 2016. This fire burned an experimental catchment of the University of Aveiro, called 'Serra de Cima'. Wildfires have a direct effect on the hydrological processes in a catchment, including the presence of ashes, land degradation, vegetation removal and the increased risk of runoff and erosion. Furthermore, it is challenging for land managers in affected areas to prevent or minimize the negative effects caused by wildfires.

The effects of wildfires on runoff and erosion are already known, but most of these researches are based on the comparison between burned areas and neighbouring unburnt areas. It is uncommon for hydrological analysis to take place in one specific area, and comparing the results based on pre- and post-fire hydrological processes. This research will investigate how the 2016 wildfire affected the hydrological processes and which changes occur based on different plot scales (slope plots and micro-plots). Based on literature study, the effects and value of post-fire land management practices are also being discussed.

This case study in the 'Casa do Padre' study site, which is part of the experimental catchment, uses an experimental set-up containing six slope plots and nine micro-plots (of which six are located in the low severity burned area and three in the high severity burned area). In this set-up, a 1- or 2-weekly collection of runoff and sediment samples, soil moisture data and 4-weekly assessment of ground cover help to compare the dataset of the pre-fire period (07-10-2015 till 30-06-2016) with the post-fire period (16-09-2016 till 30-03-2017). Since there is no erosion data available for the pre-fire period, this comparison will be solely based on the post-fire results.

The results show that both runoff and erosion increase significantly in the period following the wildfire. The overland water flow increases with 3.5% for the slope plots and 19% for the micro-plots. Regarding the erosion, the micro-plots have 18 (low severity) and 142 (high severity) times more sediment losses. The organic matter content is the highest in the slope plots (52%) compared to the low severity micro-plots (49%) and the high severity micro-plots (10%). The main driver for the hydrological processes is the 30-min maximum rainfall intensity (I_{30}), having the strongest correlation with the processes. Only the organic matter content is more related to the runoff coefficient. The decrease of ashes is the largest in the low severity micro-plots, and vegetation is recovering the fastest in the high severity micro-plots. The soil moisture is the highest in the high severity micro-plots and at 7.5 cm depth, being 22%.
Results of this research were comparable with other studies in general, with the quantitative results being discussed more in detail.

In conclusion, the research shows that the wildfire has a clear impact on increasing runoff and erosion within the catchment. However, if applied at the correct time, land management practices can mitigate the effects of such wildfires and could therefore be valuable in increasing the sustainability of affected areas. For further research it would be valuable to use comparable datasets for the assessment of pre- and post-fire effects, based on similar precipitation amounts.

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INTRODUCTION

1.1. Wildfires

Current climate change has an effect on the general temperature of the Earth, and causes climate zones to shift and meteorological conditions to intensify. Natural phenomena such as wildfires have always been part of various climate zones, but the concern arises that the intensified fire regime, which is already present in Portugal, will impair the ecosystem's resilience (Santos et al., 2016).

In the past 50 years, wildfires have been increasing throughout Europe, and in Portugal wildfires have always been a common phenomenon throughout the country (Shakesby, 2011). Due to its Mediterranean climate with warm temperate weather, large areas have been affected by wildfires in the past. Each year, 3% of Portugal's rural area is subjected to wildfires, which makes it the most wildfire affected country in Europe (Mateus, P. & Fernandes, P.M., 2014). In several parts of the Portuguese mainland the temperature can rise up to 40 degrees Celsius, and in combination with local weather conditions, wind and dry underbrush, this can lead to uncontrolled blazes that have an impact on acres of land.

During the summer of 2016, wildfires tormented the inland of Portugal, which led to a burned area of 160,490 ha (INCF, 2016). Herewith, an experimental catchment area of the University of Aveiro ('Serra de Cima' or SDC) was burnt (Figure 1.1). This area consists of different study sites, with the 'Casa do Padre' (or CDP) having the main focus in this research. It has been a referential and long-unburnt location for the university to assess hydrological factors based on measurements in a ploughed area, including erosion, runoff, rainfall amounts, soil moisture and soil water repellency. The wildfire of 2016, which reportedly occurred due to human activity, gave an insight in the response of the catchment to such fires.

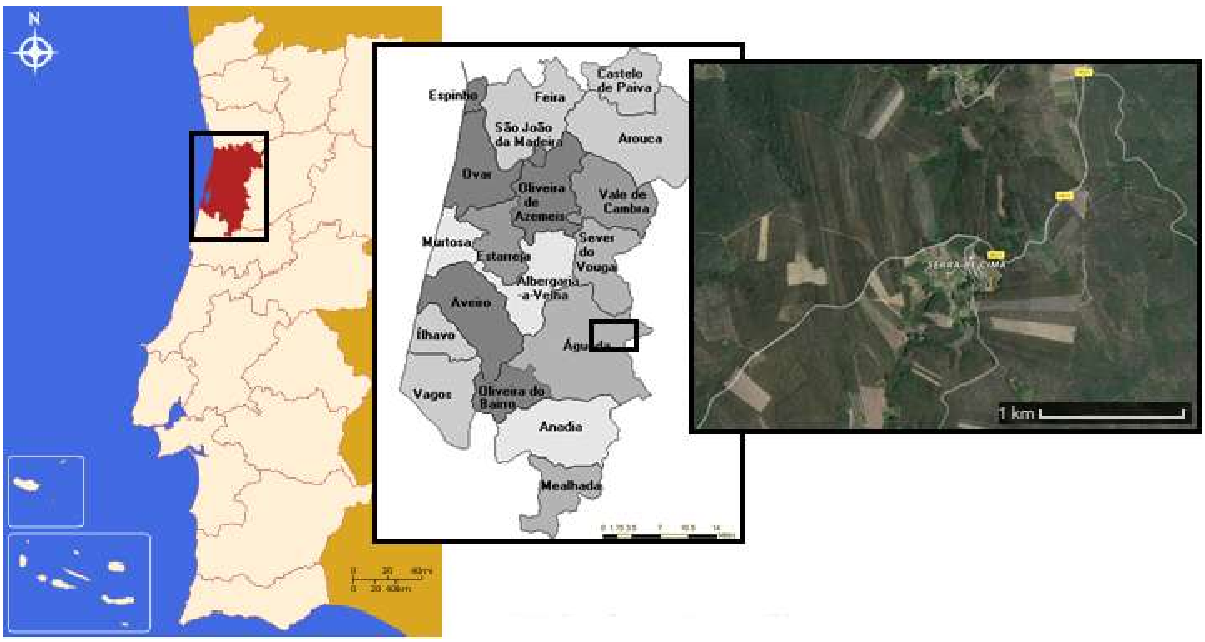

Figure 1.1 - Location of the Serra de Cima catchment in North Central Portugal

1.2. Effects of wildfires

1.2.1. Hydrology

Wildfires are known to have an effect on the degradation of hill slopes, but the hydrological effects of this natural phenomenon are difficult to assess (Stoof et al., 2015). The hydrological effects of a wildfire are based on the landscape's vulnerability to runoff and erosion. This is caused by the change in the physical properties of the soil and the shortage of vegetation, which both affect the water flow and the stability of the soil. Wildfires can reduce the organic matter on top of the soil, the soil's porosity and essentially decrease the soil's water retention and infiltration capacity (Stoof et al., 2015). The combined effects of the posterior physical state of the soil induced by the wildfire and the hydrological changes increase the risk of overland water flow. Furthermore, the loss in stability and strength of the soil increases erosion risk (Shakesby, 2011).

Wildfires can pose a significant threat to a catchment area and its natural state, properties and human lives. These threats are initiated by erosion and flooding events, which are a result of the wildfire (Stoof et al., 2015). The events could affect the natural resources in the catchment area and, both on the short- and long-term, this could affect aspects such as the (ground)water quality and the availability of drinking water downstream of the affected area (Shakesby, 2011).

1.2.2. Land management

After recurrent wildfires, the rehabilitation of the ecosystem is problematic and it could take several years to return in their original condition (Keesstra et al., 2017). Therefore, it is a key topic to support the development of activities related to the mitigation and environmental protection of post-wildfire sites (Karamesouti et al., 2016).
For local land managers in wildfire affected areas, the increased risk of flooding and soil erosion due to wildfires is an important concern (Prats et al., 2015). There have been several researches to the short-term erosional impacts of fire and forest fire prevention, but the use of alternative post-fire land management practices and the long-term effects of these operations on the soil and forest sustainability have received little attention (Shakesby et al., 1996).

Post-fire land management operations can make sure that catchment areas affected by wildfires will not deteriorate and help to restore sites in their original state. By doing this, the sustainability of affected areas can be improved and land managers in Portugal could have a durable solution to wildfire-related problems.

1.3. Problem statement

The risk of deterioration due to physical processes caused by wildfires could also occur in the CDP study site of the Serra de Cima catchment. Since the wildfire has affected the physical state of the area, factors such as erosion and excessive runoff can worsen within the study site.

Another concern for the CDP study site is the severity of the fire, and how this can stress the catchment even more. In the Serra de Cima catchment, the wildfire had a moderate severity. However, in some parts of the CDP study site the wildfire reached a high severity of burning. In locations with high severity burning of vegetation, the hydrological effects can intensify more than in parts with a lower degree of wildfire severity. This is due to the impact of the wildfire on the soil and its cohesion. This could lead to an increase in overland flow and erosion of soil material.

The effects on wildfires are heterogeneous in different parts of the catchment area as . It is clear that wildfires induce alterations to the chemical and hydrological state of an area, but the scale-dependence is more difficult to assess. The possibility exists that shifts on a small scale, which are linked among different plot sizes, could induce effects on a larger scale. Therefore, the impacts on a small scale can lead to a chain reaction within the catchment.

1.4. Aim

The overall aim of the research is to assess the hydrological impacts induced by wildfires, based on analysed data of the CDP study site and the catchment. Normally, the analysis of the wildfire's effects are mainly based on the comparison of simultaneous hydrological processes between burned areas and neighbouring unburnt areas.
It is therefore uncommon for hydrological analysis to take place in one specific area, and comparing the results based on pre- and post-fire hydrological processes (Santos et al., 2016). By carrying out this renewing form of research, the results offer an insight in the hydrological processes after the wildfire and the change in runoff and erosion of an affected area. Since data have been collected for several years, a clear view of the shift in hydrological processes in both the pre- and post-fire year is made visible and it helps to understand the natural adaptation of the catchment.

The data are compared for different plot-based scales (micro-plots and slope plots). By assessing and comparing the effects on different scales, the aim is to understand which differences occur and if there is a scale-dependence within the catchment after the impact of a wildfire. Also, it can give insight in hydrological processes that may only exacerbate in certain plot sizes.
Based on prior studies, there will also be an analysis as to which post-fire land management operations are being or have been researched, and could be used to mitigate the hydrological effects of burned areas. This analysis should help in diminishing the effects of a wildfire and protecting the natural and physical state of the catchment. The literature study has the aim to increase the sustainability of areas prone to wildfires by stating land management operations that could make areas more durable and resistant to the effects of wildfires in the near future.

1.5. Research questions

Main research question:
"What are the hydrological impacts of the 2016 wildfire on the catchment area Serra de Cima, based on different plot scales (micro-plots and slope plots)?"

The following sub questions will help in answering the main research question:
- *"To what extent did the hydrological processes (e.g. runoff, erosion and organic matter) within the Serra de Cima catchment differ in the pre- and post-fire year?"*
- *"Which aspects are drivers for the change in hydrological processes occurring in the Casa do Padre study site?"*
- *"Which post-fire land management operations could possibly mitigate the hydrological effects of a wildfire in a catchment area?"*
- *"To what extent is post-fire land management valuable for the Casa do Padre study site?"*

1.6. Research boundaries

This study is a plot-scale research, which focusses on the effects of wildfires on the hydrological processes and response. Due to time constrains it is impossible to make a comparison based on multiple pre- and post-fire years, or a selection based on years with comparable precipitation data. This research will therefore focus on the timespan of one year preceding the 2016 wildfire up till half a year after. Long-term effects and recovery of the catchment will not be considered.

Soil water repellency is an important effect caused by wildfires, which can affect the soil hydrology and enhance surface runoff. Since there already are relatable papers that address the impacts of soil water repellency in wildfire affected areas, and the time constrains for this research, the hydrological process will not be discussed in this thesis.

Although there are also positive effects to the catchment after a wildfire, e.g. the return of an area to its pioneer phase, the negative impacts on primarily the hydrological processes outweigh this. Therefore, the positive effects will not be further discussed in this research.

1.7. Structure

The research has been set up to investigate the hydrological effects of the Serra de Cima catchment in North Central Portugal. Firstly, the materials and methods section will describe the study area and its different aspects. This will also include the (geo)hydrological characteristics of the CDP study site. Secondly, the approach for retrieving data and results will also be defined in this section.

After this, the results of the research are being described and supported by the visual representation of the collected data. In the discussion, the results are being assessed and compared to results of other research papers with relating topics and methodology.
Lastly, the conclusion will give an overview of the research and will answer the research questions as stated in the introduction. There will also be some recommendations for improving this research and possible related research topics in the future.

2. MATERIALS AND METHODS

2.1. Study area

2.1.1. Location

The Serra de Cima catchment area is located in the Baixo Vouga region, approximately 30 km east of Aveiro (Boulet et al., 2015). With a surface area of 51.6 ha, it is a small catchment in the Caramulo Mountains in North Central Portugal (Figure 2.1). The Serra de Cima catchment is one of the areas belonging to the Alfusqueiro River Basin, which is part of the Vouga e Ribeiras Costeiras River Basin.

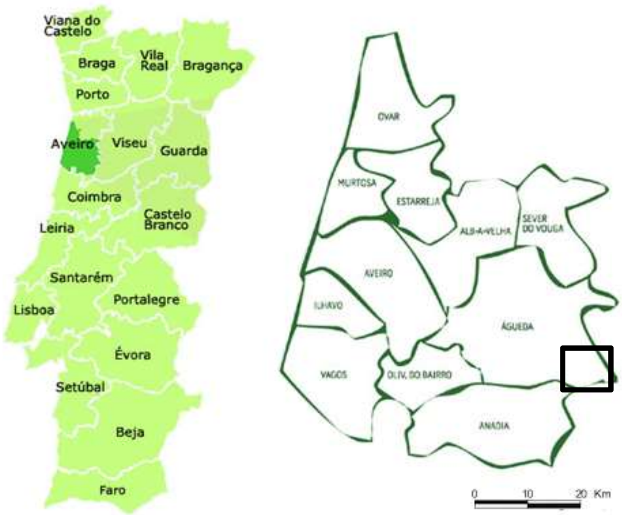

Figure 2.1 - Outline of the Baixo Vouga region with the SDC catchment

Universidade de Aveiro has started research projects in the Serra de Cima catchment in the 1990s (called the Caramulo project). The motivation for these research projects was a wildfire in the catchment area in 1986. The first researches were very basic to measure runoff and discharge. With the start of the HIDRIA project in 2010, a flume was built in the catchment and reliable data have been collected.

2.1.2. Climate

The study area has a humid Mediterranean climate (Nunes et al., 2016), with precipitation varying between 1000 and 2000 mm. The average precipitation in the Serra de Cima catchment is around 1600 mm/year (Martins, M.A. et al., 2013). Since the winter season is the main rainfall season in Portugal, 70% of the precipitation in the study area occurs between August and January (Methorst, M., 2016).

The average temperature in the region of the study area range from 6 °C in January to 20 °C in August (Santos et al., 2013).

2.1.3. Geology

The soils of the catchment area are mapped as a complex of Humic Cambisols and, to a lesser extent, Dystric Litosols (Boulet et al., 2015). These are thin coarse soils (Santos et al., 2013) and are made up out of sand (23%), clay (20%), silt (57%) and the top soil contains organic matter (>10%) (Nunes et al., 2016; Boulet et al., 2015).

The catchment area is located in the foothills of the Caramulo Mountains, with the slopes typically being very steep (>20 degrees). The soils are stony, weakly-structured and shallow, and the slopes are facing west (Boulet et al., 2015). Furthermore, the slopes of the study site have been ploughed horizontally and, since the wildfire event occurred, logging companies have started salvage logging to remove the burned trees and creating terraces for new eucalypt plantations.

2.1.4. Wildfire event

As stated earlier in this paragraph, the study site has been set up following a major fire in 1986. Since this wildfire event, the Serra de Cima catchment has been monitored to assess the hydrological impacts on the area. In 2016 the catchment was completely burned by a wildfire, which lasted from 08-08-2016 until 13-08-2016. A total area of 7,926 ha of surrounding areas had been burnt as a result of this wildfire (Effis, 2016).

Figure 2.2 shows an image mapped by Effis, with the location of Serra de Cima being completely in the wildfire affected area. The catchment has been assessed for its wildfire severity, which ranged between parts being scorched and light severity to moderate severity.
Within the CDP study area however, the severity is locally variable. In parts of the area, trees have been burned completely (due to high severity), next to trees with brown leafs (moderate severity). The edges of the study area still have trees with green leafs, which is a sign of low severity or no fire impact.

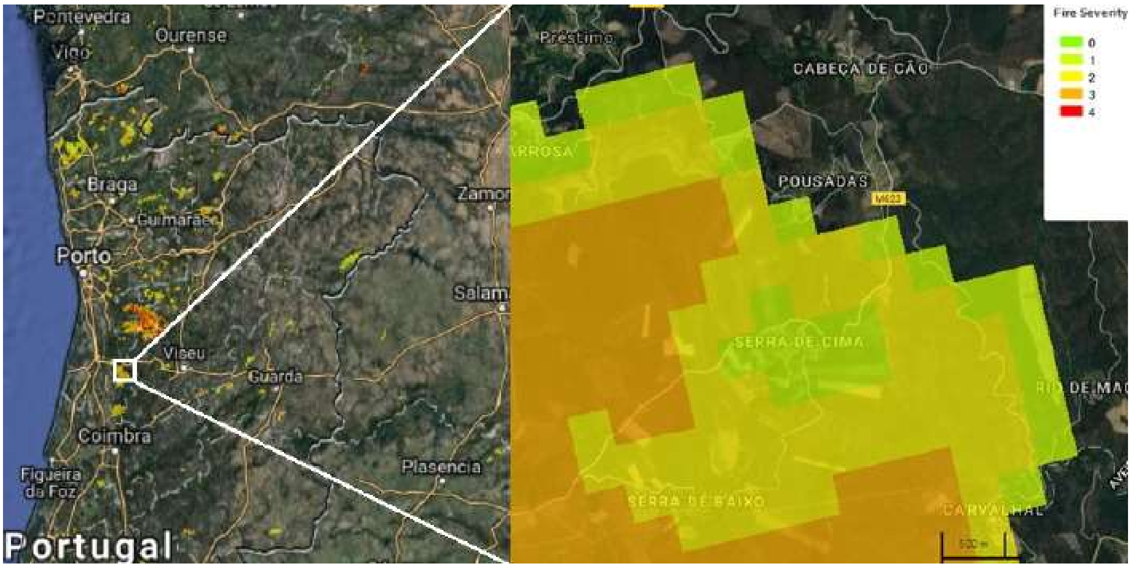

Figure 2.2 - Map with degrees of severity for the 2016 wildfire in the Serra de Cima catchment

2.1.5. Processes

Soil hydrology

An important factor of soil hydrology is the percentage of soil moisture in an area. Soil moisture (and also soil water repellency) can change throughout the year due to local climate conditions. This leads to an inconsistent saturation of the soil, which affects the connectivity of the soil.
The soil moisture and connectivity are different in humid or arid regions due to amount of precipitation. The runoff that occurs is dependable on the rainfall properties such as intensity and duration.

Infiltration and overland flow

In Mediterranean areas such as Portugal, infiltration and overland flow also occur with a common seasonality. This is because of the climate and the shallow soil depths. Due to this shallow soil depth, overland flow is more frequent than infiltration. In the summer, and the combination of a dryer climate and soil moisture levels or soil water repellency, overland flow can occur without saturation of the soil. In the wetter seasons autumn and winter, the shallow soils can easily get saturated which also leads to overland flow during intense rainfall events (Boulet et al., 2015).

In earlier researches, it showed that infiltration reduced dramatically after wildfire. Robichaud (2000) noted a 40% reduction when comparing pre-fire and post-fire conditions, and Shakesby et al. (1993) found decreases of up to 60% (Neris et al., 2013).
Likewise, complete or partial removal of vegetation and litter cover due to wildfire can lead to a larger percentage of rainfall available for overland flow. Furthermore, there is less resistance to the rainfall's movement over the soil and the time between the rainfall event and flood peak (Shakesby et al., 2011).

Vegetation and litter

The effects of a wildfire, including the reduction of vegetation and soil organic material across the area, are important to a catchment. Vegetation and litter play a key role in the area's geological and hydrological state. This prevents the soil from eroding and assures the maintenance of the soil's 'roughness'. Surface roughness plays an important role in the resistance of the overland water flow (or as referred to by Manning as 'n') and water retention in a catchment area. Wildfires can affect the soil's roughness and increase the possibility of soil erosion (Stoof et al., 2015).

Wildfire severity

The burning of vegetation during a wildfire can be defined by different fire intensities (e.g. temperatures or release of energy), whereas the impact of a wildfire is referred to as severity (León, J., et al., 2013). The result of a wildfire, or the wildfire severity, is ranged from low severity to moderate severity or high severity (Moody, J.A., et al., 2016). This depends on the (type of) fuel, weather conditions, topography etc. (León, J., et al., 2013). The different severities of wildfire can lead to a change in vegetation debris and soil loss, which affects the runoff and erosion of catchment areas (Neary, D.G., 2011).

2.1.6. Post-fire land management operations

Several studies have concluded that runoff and the associated export of sediment, organic matter and nutrients are the highest immediately after the wildfire, and that these processes can remain high throughout the first two years after a wildfire (Shakesby et al., 2011). Because erosion causes a large portion of the post-fire sediment losses, it is important to understand the relationship between post-fire runoff and erosion rates. This step is critical in designing and assessing the effectiveness of post-fire mitigation treatments (Prats et al., 2015).

2.1.6.1. Types of operations

It is important for land managers in burned areas to understand which post-fire land management operations are most suitable for the specific state of an area, and the consequences of a wildfire to the natural processes. This is essential for defining post-fire management practices, especially in areas with a high risk of erosion (Vieira et al., 2016). The main concerns for land managers after a fire include reducing the erosion rates and the effect of contaminated runoff on aquatic systems, capturing the economically valuable wood through timber harvesting. Therewith insect outbreak can be prevented among fire-stressed trees, reducing the potential for a severe reburn and ensuring tree regeneration (Mazza, R., 2007).

In recently burnt areas, a lot of different management operations have been applied to reduce the hydrological impacts and help restore the original state of an area. These management operations range from tree harvesting, to soil tillage in preparation of new plantations, to restauration actions such as seeding (Maia et al., 2014).
Another way of operating after a wildfire, to enhance the biodiversity and cultural value or reducing biotic and abiotic hazards, is to converse to native broadleaved or mixed forests (Moreira et al., 2013).

Multiple forestry operations are being used in areas with frequent wildfires or eucalypt plantations. These operations vary from terracing, to ploughing or salvage logging. Mulching, the practice where forest residue (mulch) is being applied to burned soil, is also a measure to prevent runoff and erosion. However, this measure is not being applied in the CDP study site. All these forestry operations include the altering of the (burned) vegetation and soil post-fire.

Terracing is being used when planting eucalypt trees, to make the sites more accessible. Figure 2.3 shows an aerial picture of the SDC site, with eucalypt trees planted onto the terraces (Stoof et al., 2012).

Figure 2.3 - Post-fire drone picture of the Casa do Padre study site with terraces on the slope

Figure 2.4 - Slope plot with ploughing, picture taken during fieldwork in Casa do Padre

The forestry operation ploughing is used in cultivation for soil preparation, where the top soil is being ploughed to bring up nutrients (Figure 2.4). In wildfire affected areas, ploughing (also referred to as rip-ploughing) is done prior to planting eucalypt seeds and timber felling (Ferreira et al., 1997).

Salvage logging is the logging of burnt wood in a forest plantation after a fire, to save some of the wood's value. Salvage logging is being done to remove damaged trees and encourage reforestation, and the prevention of forest diseases and pests. If there is a potential danger for another wildfire, potential fuel load is removed from a forest by salvage logging (Fernández & Vega, 2016).

2.1.6.2. Effects of operations

Many of the post-fire land management practices have both positive and negative implications, especially for the hydrological processes. For land managers it is important to assess the effects of operations on the catchment in a post-fire situation, and to determine whether the positive effects of the land management operations outweigh the negative.

Although terracing is useful for storing water within a catchment, it is found that erosion increases considerably in areas containing terraces. This is both for eucalypt and pine forests after fire. (Martins et al., 2013).

Based on research, the effects of ploughing on the erosion rates in a catchment depends on whether the operation is being done before or after a wildfire. It has been clear that ploughing after a wildfire increases runoff and erosion (Ferreira et al., 1997). But when the ploughing practices have been done prior to a wildfire, the ploughed sites show less runoff and erosion compared to unploughed sites after a fire (Malvar et al., 2011).

The most common operation in the burned catchment of Casa do Padre is salvage logging. This operation is in conflict with the effect on the hydrological processes. Previous research, which has been carried out on plot-scale, shows that salvage logging can lead to an increase in erosion and it is therefore not a very durable post-fire land management operation (Fernández & Vega, 2016).

2.1.6.3. Value of land management operations

Despite the existence of prevention measures, fire activity is not expected to decrease in Portugal in the nearby future. This is not only due to the fact that highly flammable tree species are being used continuously, which are economically important for the paper pulp industry, but also because of climate change projecting an increase in fire-prone conditions (Vieira et al., 2016). Therefore it will be important to assess the methods to recover wildfire affected areas the fastest.

The value of land management operations in the Casa do Padre study site will further be addressed in the discussion of this research.

2.2. Study site

2.2.1. Experimental set-up

In the first set-up of the HIDRIA project, prior to the 2016 wildfire, plots were installed on a slope in the CDP study site in the Serra de Cima catchment area. This set-up (see Figure 2.5) consisted out of three micro-plots (of 1 by 1 meter) and three hillslope-scale sediment fence plots, which were roughly 2 metres wide and 8 metres long (± 16 m^2). The micro-plots were double-bounded by sheet metal and the slope plots were bounded by silt fence fabric to eliminate run-on into the plots (Prats et al., 2016). Each micro-plot is located next to its corresponding slope plot, and they were arranged in three blocks across the hillslope. The study site was instrumented with two totalizing rainfall gauges before any substantial rainfall.

After the 2016 wildfire affected the catchment area of Serra de Cima, new plots were installed along the hillslope to analyse the impacts of the wildfire on the hydrological processes and erosion. Most of the new micro-plots and slope plots have been located adjacent to the existing ones, with the exception of slope plot SF1. The most recent plot has been located downwards of the existing plot, on the other side of the road. This has been done to assess the hydrological processes on a steeper part of the hillslope, since the previous plot (P1) did not generate a lot of runoff which could be explained by the flatter slope.

In order to analyse the severity of the wildfire, three more micro-plots have been placed on the same hillslope. These micro-plots are located easterly of the other micro-plots, because the severity of the wildfire was higher on this location. By analysing the hydrological impact of wildfire severity in these micro-plots, and comparing them to the plots with a lower severity of combustion, an insight in the effects on the hydrological processes based on wildfire severity can be made.

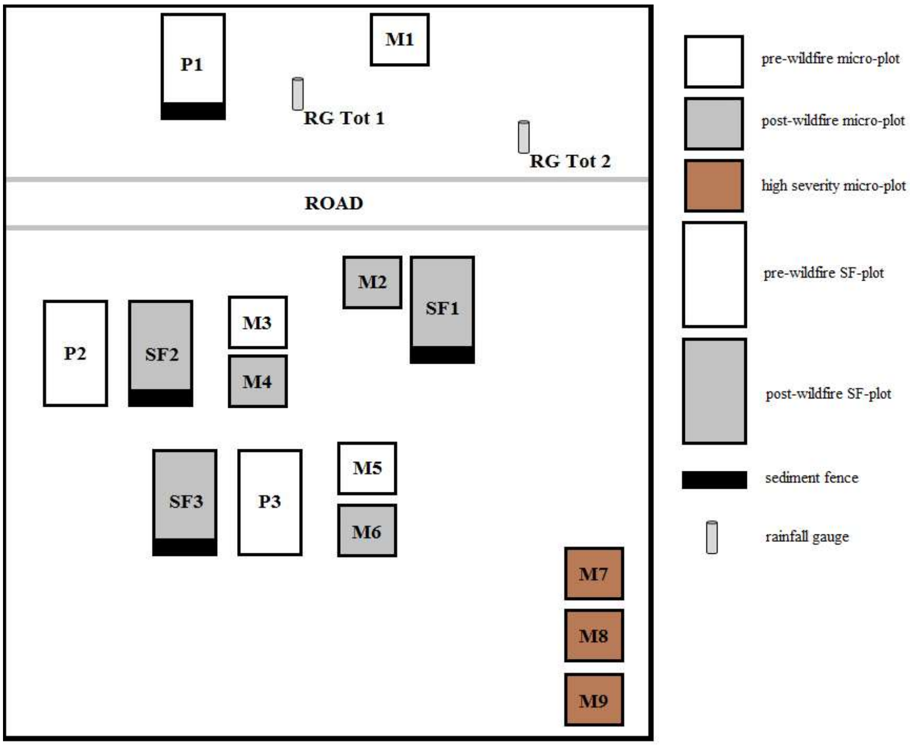

Figure 2.5 - Experimental set-up of the Casa do Padre study site

2.2.2. Geology

Table 2.1 shows the geological characteristics of the Casa do Padre study site. The slope angles are 18 degrees for the slope plots and the low severity micro-plots, and the high severity micro-plots have a slope angle of 25 degrees. The soil texture of the different plots is similar, and only the high severity micro-plots shows different fire severity indicators compared to the other plots. The complete study site has been ploughed, including the soil inside the micro-plots and slope plots.

Table 2.1 - Geological characteristics of the Casa do Padre study site

	Slope		
	SP*	MP LS**	MP HS***
General characteristics			
Aspect	West	West	West
Slope angle (°)	18	18	25
Average plot area (m^2)	17.0	0.28	0.28
Soil characteristics			
Texture			
Silt (%)	60	60	60
Sand (%)	20	20	20
Clay (%)	20	20	20
Organic matter in top soil (%)	10	10	10
Fire severity indicators			
Consumption of tree crowns	Partial	Partial	Total
Consumption of shrub layer	Total	Total	Total
Consumption of herbs/litter	Partial	Partial	Total
Ash colour	Black	Black	Brown/Yellow

* SP: Slope plots
** MP LS: Micro-plots, low severity
*** MP HS: Micro-plots, high severity

2.3. Fieldwork data collection

In each micro-plot, runoff is collected and routed to a 70 L storage tank (Figure 2.6). In slope plots P2 and P3, the runoff is directed through several outlets and then stored into 500 L tanks. Runoff volumes in each tank are being measured at a 1- to 2-week interval. (Prats et al., 2016).
Soil losses are being determined from the micro-plots and slope plots using either subsamples (1.5 L water samples) from the runoff tanks, or by measuring and subsampling the sediment and organic matter collected in the sediment fence (Prats et al., 2016).

Figure 2.6 - Micro-plot with corresponding storage tank, picture taken during fieldwork in Casa do Padre

Ground cover is being assessed on the micro-plots with different types of wildfire severity. This is done with grids on the micro-plots and the slope plots. The cover is assessed on a 1 by 1 m grid extending over the entire micro-plot or slope plot, with eucalypt stems being removed to increase homogeneity. One of the five cover categories (stone, ash, bare soil, litter or vegetation) is being assigned to each point on the grid (Prats et al., 2016).

Another aspect which is being measured in the study area is soil moisture. This is being measured using an EC-5 sensor. This data is being at collected at an approximately 2-weekly interval (Prats et al., 2016).

2.4. Laboratory data collection

Sediment concentration is determined from the 1.5 L runoff subsamples via filtration through 2 μm filter paper and drying of the filters for 24 hours at 105 °C. The total amount of sediment, which deposited on the sediment fence, is being weighed in the laboratory and a subsample is being taken for water content. Organic matter content is being determined for 2 g of each sediment sample by the loss on ignition method. The sediment concentration sampling followed the same frequency as the runoff sampling explained earlier and the subsampling of deposited sediment occurs approximately once a month (Prats et al., 2016).

2.5. Data analysis

For analysing data, the values for runoff and soil losses are digitally stored using Excel. This data are being used to assess both the average and cumulative runoff (in mm), soil loss (in g/m^2) and organic matter loss (g/m^2). The runoff, soil loss and organic matter have a different scale ratio based on the plot value divided by the area of the plot (Prats et al., 2016).

2.5.1. Runoff

To assess the effects of runoff, based on pre- and post-fire periods and scale-dependence, the data which have been analysed are from the period 07-10-2015 up until 30-03-2017. The data provided are derived from the rainfall gauges and hydrometric stations in this area. The volumes of runoff in the tank are measured in millilitres, but for the analysis the data are being converted to millimetres with equation 2.1.

$$runoff\ [mm] = (runoff\ [mL] * 10^{-3}) \ /\ plot\ area\ [m^2] \qquad \text{(Equation 2.1)}$$

The runoff in the area is the percentage of rainfall which leads to overland flow, or the so called runoff coefficient. The precipitation in the study area, which is monitored by the rainfall gauges, leads to the runoff coefficient with equation 2.2.

$$runoff\ coefficient\ [\%] = (runoff\ [mm]\ /\ precipitation\ [mm]) * 100\% \qquad \text{(Equation 2.2)}$$

The results of the data analysis are being used to make the comparison between the pre- and post-fire period, where the amounts of millimetres runoff also lead to the runoff coefficient. By evaluating the runoff values, an indication of the exacerbation in overland water flow can be made.

2.5.2. 30-min maximum rainfall intensity (I_{30})

For every fieldwork readout, the 30-min maximum rainfall intensity (or I_{30}) is being calculated to determine the intensity of the precipitation in the study area during this period.

This I_{30} gives an indication of the rainfall intensity during the course of the precipitation events and is based on the rainfall data from the totalizers (or tipping bucket). The totalizers record every 0.2 millimetre of rainfall as one tip, with all the tips being added for each readout.

With the help of an Excel sheet, the amount of precipitation in millimetres (for confirming the rainfall amounts measured in the field) and I_{30} in millimetres per hour are being calculated with equation 2.3.

*total precipitation [mm] = (cumulative tips [-] * 0.2 [mm])*

*rainfall intensity [mm/h] = (cumulative tips in 30 min. [-] * 0.2 [mm]) *2*

(Equation 2.3)

The 30-min maximum rainfall intensity is derived from the highest rainfall intensity during the week of the readout.
The reason to calculate the I_{30} with the data of the totalizers is to assess if the erosivity in the area is being caused by intensive rainfall.

2.5.3. Soil losses

Water has been filtrated with semi-permeable filtration paper to filter the sediment from the runoff samples in the 1.5 L bottles. Subsequently, the filters are dried at 105 °C in the oven for 24 hours and, after cooling down in the desiccator, weighed for their mass. The crucibles are separately weighed and then filled with the sediment sample.
To determine the amount of sediment in the runoff, the weight of the dry sample is divided by the volume of the runoff sample in the 1.5 L bottle (equation 2.4).

sediment amount [g/L] = dry sample [g] / volume runoff sample [L]
*sediment amount [g/m²] = sediment amount [g/L] * runoff [mm]*

(Equation 2.4)

After weighing the combined mass of the crucible with soil, the sediment samples are being put in the furnace for 4 hours at 550 °C for the determination of the organic matter content. The incinerated amount of sediment is compared to the total sediment amount with equation 2.5.

*organic matter content [g/L] = sediment amount [g/L] * ((dry sample [g] - incinerated sample [g]) / dry sample [g])*
*organic matter content [g/m²] = organic matter content [g/L] * runoff [mm]*

(Equation 2.5)

Subsequently, the percentage of organic matter is also determined from the incinerated amount of the sediment sample (equation 2.6).

*organic matter content [%] = ((dry sample [g] - incinerated sample [g]) / dry sample [g]) * 100%*

(Equation 2.6)

The soil losses and organic matter content are being calculated to assess the amount of sediment that deposited into the runoff tanks from the plots. This gives an indication of the impact on the hydrological process of erosion in the study site, and the (change in) relationship between erosion and runoff.

2.6. Literature study

To mitigate the deterioration of wildfire affected areas and create sustainable solutions for land managers, the post-fire land management operations are an aspect that is being addressed in this research. In order to assess the best solution for a catchment, it is important to compare research that has been done related to land management practices.

Universidade de Aveiro and the Centre for Environmental and Marine Studies have done several researches regarding post-fire land management practices and the effects of these measures on hydrological processes such as runoff and erosion. These research papers are the guideline for the literature study of this research. Table 2.2 shows the research papers regarding post-fire land management operations and their corresponding topic of interest.

Table 2.2 - Literature related to post-fire land management operations

Author	Research paper	Land management practice
Fernández, C. & Vega, J. (2016)	Effects of mulching and post-fire salvage logging on soil erosion and vegetative regrowth in North-West Spain	Salvage logging
Ferreira, A.J.D. et al. (1997)	Sediment and solute yield in forest ecosystems affected by fire and rip-ploughing techniques, Central Portugal: a plot and catchment analysis approach	Ploughing
Maia, P. et al. (2014)	Post-fire plant diversity and abundance in pine and eucalypt stands in Portugal: Effects of biogegraphy, topography, forest type and post-fire management	Soil tillage / seeding
Malvar, M.C. et al. (2011)	Post-fire overland flow generation and inter-rill erosion under simulated rainfall in two eucalypt stands in North-Central Portugal	Ploughing
Martins, M.A.C. et al. (2013)	Runoff and inter-rill erosion in a maritime pine and a eucalypt plantation following wildfire and terracing in North-Central Portugal	Terracing
Mazza, R. (2007)	Managing forests after fire	Salvage logging
Moreira, F. et al. (2013)	Occurrence of native and exotic invasive trees in burned pine and eucalypt plantations: Implications for post-fire forest conversion	Conversion of forests
Stoof, C.R. et al. (2012)	Hydrological response of a small catchment burned by experimental fire	Terracing

3. RESULTS AND DISCUSSION

3.1. Overall results

In this paragraph, the overall results of the complete research period are shown. These results include the cumulative amounts of runoff, sediment loss and organic matter loss. The values display the accumulation for both the pre-fire period (07-10-2015 till 30-06-2016) and the post-fire period (16-09-2016 till 30-03-2017), for the slope plots and the micro-plots (with the distinction between low and high severity micro-plots in the post-fire period).

For the discussion in this paragraph, the comparison is made with other relatable research papers, that have a similar approach and address the effects based on micro-plot and slope plot scale. Table 3.1 shows the different research papers used to compare the results of this research, and their corresponding experimental set-ups and conditions. The findings named throughout the discussion of this chapter can be referred to these sources.

Table 3.1 - Results of relatable research papers used in discussion

	Malvar et al. (2015)	Prats et al. (2015)	Prats et al. (2016)
Conditions			
Plots	4 micro-plots	4 micro-plots 1 slope plot	4 micro-plots 1 slope plot
Plot sizes (m^2)	0.28	0.28 (micro-plot) 83 (slope plot)	0.28 (micro-plot) 95 (slope plot)
Land management	ploughed	control	control
Slope angle (°)	15	23 (micro-plot) 19 (slope plot)	23 (micro-plot) 20 (slope plot)
Results			
Rainfall amount (mm)	1,048	1,475	1,475
Rainfall intensity (mm/h)	21 (I_{15})	31 (I_{30})	31 (I_{30})
Runoff amount (mm)	228	956 (micro-plots) 58 (slope plot)	956 (micro-plots) 58 (slope plot)
Runoff coefficient (%)	25	65 (micro-plots) 4 (slope plot)	65 (micro-plots) 4 (slope plot)
Sediment loss (g/m^2)	112	-	953 (micro-plots) 462 (slope plot)
Organic matter loss (g/m^2)	-	-	535 (micro-plots) 189 (slope plot)
Organic matter content (%)	-	-	56 (micro-plots) 41 (slope plot)
Soil moisture (%)	10-14 (2-3 cm depth)	24 (0-5 cm depth)	20 (0-5 cm depth)

The precipitation in the Casa do Padre study site (Table 3.2) is variable over the period of one year pre-fire and half a year post-fire. The precipitation data show that the amount of rainfall was higher in the pre-fire period than in the period post-fire, with the difference being 936 mm. It has to be noted that the pre-fire period can be described as a wet year and that the period of measurement was longer in the pre-fire period.

The overall comparison (Table 3.2) of the runoff and overland flow (for both pre- and post-fire) shows that the volume of runoff increases in the post-fire phase of the research period. Likewise, the runoff coefficient increases after the wildfire.
For the erosion in the study area, which is only available for the post-fire period, the table's data clearly show that the cumulative soil losses are larger in the micro-plots compared to the slope plots. Compared to the slope plots, the cumulative erosion values in the micro-plots for the low and high severity are respectively 18 and 142 times larger. Even within the micro-plots the difference between low and high severity is notable.

Table 3.2 - Overall results for the research period in the Casa do Padre study site

		Rainfall[a]	Runoff		Sediment loss		Organic matter loss		
		Amount (mm)	Volume (mm)	Overland flow (%) [b]	Total (g/m^2)	Specific ($g/m^2/mm$)	Total (g/m^2)	Specific ($g/m^2/mm$)	Percentage OM (%)
Pre-fire	Slope plots	1,866	3	0.6					
	Micro-plots		15	3.5					
Post-fire				4.1		0.27	3	0.12	52
	Slope plots		29		8				
	Micro-plots (LS)	828	201	23.0	142	0.71	63	0.31	49
	Micro-plots (HS)		203	22.2	1,133	5.60	80	0.40	10

[a] The maxima I_{30} were for the pre-fire period 30.9 mm h^{-1} and for the post-fire period 27.7 mm h^{-1}
[b] Mean weekly runoff divided by mean weekly rainfall amount

3.1.1. Total runoff pre- and post-fire

Results

When the total amounts of runoff in pre- and post-fire state are compared in Table 3.2, it shows that there is a larger increase in the amount of millimetres runoff. Both in the micro-plots and slope plots, an increase occurs in the runoff due to overland flow. The micro-plots show a large difference, with the runoff volume being 14 times larger in the post-fire period. For the slope plots, the runoff volume is 10 times larger in the post-fire period compared to the pre-fire period.
For the pre-fire period, the micro-plots show a bigger amount of runoff as opposed to the slope plots (Figure 3.1a). On average, the amount of runoff in the micro-plots is five times larger than the slope plots. Also, the runoff coefficient is six times higher for the micro-plotsIn the period following the wildfire, there is a clear difference between the micro-plots and slope plots regarding the amount of runoff (Figure 3.1b). Where the slope plots only have a marginal amount of runoff, the micro-plots show a much higher amount. On average, the micro-plots have a seven times higher volume of runoff. In order to assess the effects of the wildfire severity in the micro-plots, a comparison is made to note the differences in runoff volumes. Here it shows that the difference in runoff is only 3 millimetres. The difference in overland water flow is 0.8%, which is minimal.

Discussion

Because this research focuses on the pre- and post-fire state of the same study site, and this is rather uncommon for researches regarding wildfire, there is only a limited amount of research to compare and discuss the results found between the runoff in pre- and post-fire state in this thesis. There is not enough literature available to assess whether the difference between pre- and post-fire period is to be expected, therefore the only cause of this difference may be attributed to the change in processes due to the lack of vegetation and the degradation of soil structure caused by the wildfire severity.
The research's data match with what was found in literature by Prats et al. (2015) who found that the upscaling effect leads to a decrease in the overall runoff. He found a total runoff of 956 mm at the micro-plot scale and 58 mm at the slope plot scale during the first year post-fire, which means

that the micro-plots generate 16 times more runoff than the slope plots. This differs from the results in this research, where the micro-plots have 7 times more runoff. This could be caused by the larger amount of rainfall in the research of Prats et al. (2015) or the longer measurement period.

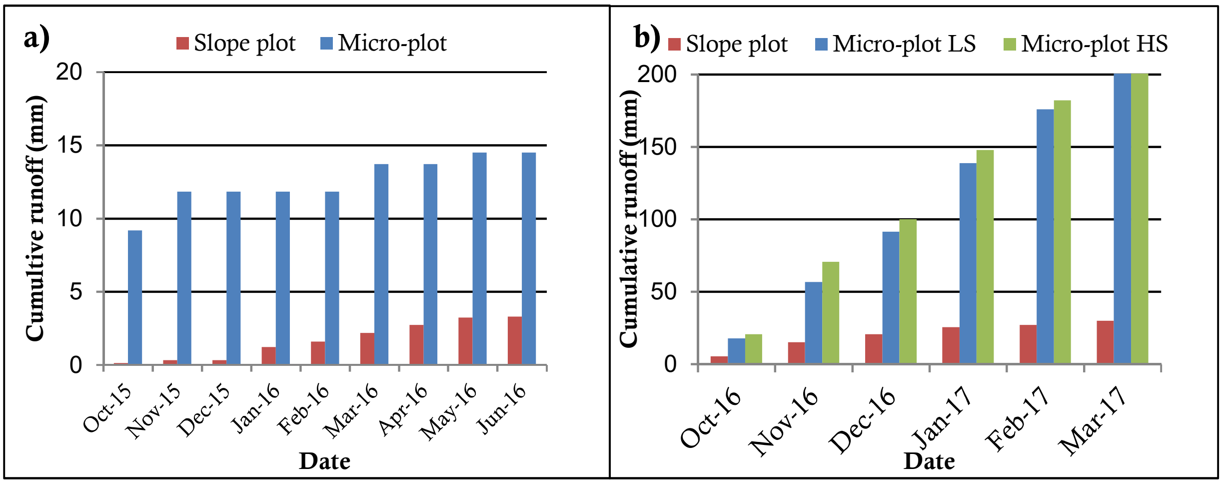

Figure 3.1 - Cumulative runoff pre-fire (a) and post-fire (b). NOTE: y-axes have different scales

Another reason for the change in runoff could be due to the ploughed plots in this research. Since the slope plots are more uneven, overland water flow tends to be less because it will be stopped by the ploughed soil. Therefore it can be possible that runoff will not reach the bottom of the plot. The smaller micro-plots have a shorter and more even surface which tends to cause more runoff.

3.1.2. Total sediment losses post-fire

Since there is no erosion data pre-fire, the comparison of the total runoff and erosion (for sediments and organic matter) is based solely on the data post-fire. With this data, the comparison is made between the micro-plots and slope plots. Furthermore, the difference between the micro-plots in low severity and high severity is being assessed.

Results

As for erosion during the post-fire period, there is a clear difference visible between the micro-plots and the slope plots (Figure 3.2). The cumulative erosion in the slope plots is marginal (8 g/m^2), whereas the micro-plots produce a greater amount of erosion during the research period (16-09-2016 till 30-03-2017).

The difference between the micro-plots and the slope plots is substantial, with the amounts in the low severity micro-plots being 18 times larger and in the high severity micro-plots 142 times larger than the slope plots.

There is a clear difference in erosion rates between the low and high severity plots (seen in Figure 3.2), since the cumulative sediment loss over six g/m^2. This is a significant difference, knowing that the cumulative runoff is almost the same. The erosion amounts in the high severity micro-plots are eight times larger than those of the low severity micro-plots.

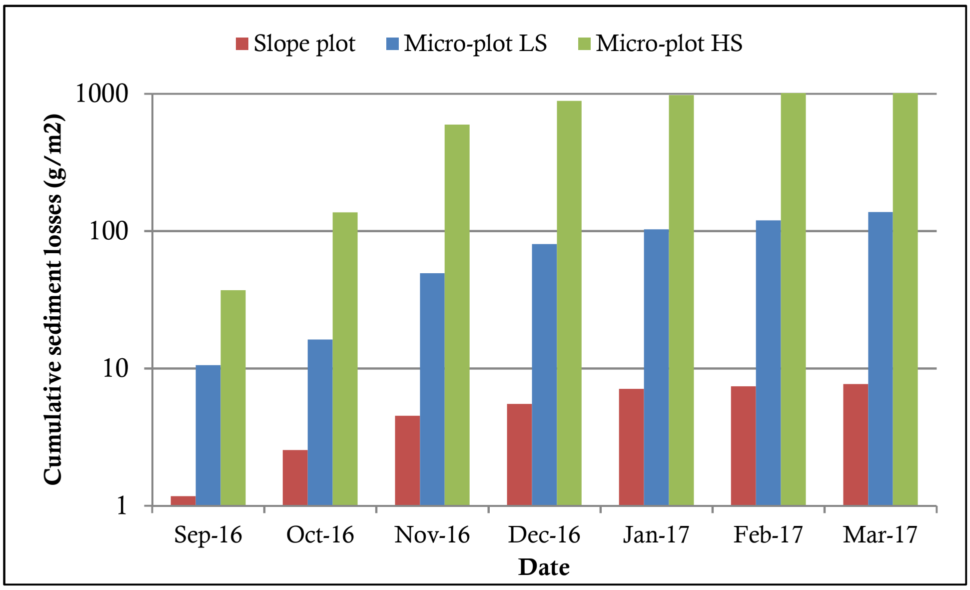

Figure 3.2 - Post-fire monthly cumulative sediment losses. NOTE: y-axis has a logarithmic scale

Discussion

Prats et al. (2016) found that the total sediment losses in the first year post-fire were 953 g/m^2 for the micro-plots and 462 g/m^2 for the slope plots. The values for the micro-plots are in line with the amount of sediment loss in the high severity micro-plots of this research, whereas the sediment loss for the low severity micro-plots are lower in this research.

This may be explained by the fact that the micro-plots of Prats et al. (2016) share the same post-fire characteristics as the high severity micro-plots of this research, which lead to similar amounts of sediment losses.

Malvar (2015) showed that the amount of sediment loss in the first post-fire year of her research were only 112 g/m^2 for the ploughed micro-plots. Since the micro-plots in this research are also located in a ploughed area, the results for the low severity micro-plots of this research are in line with the findings found by Malvar (2015).

The difference between the results found by Malvar (2015) and the high severity micro-plots of this research could be related to the degree of burning, which made the soil stability in the high severity plots much lower thus enhancing erosion. However, there are only few researches which address the differences in soil stability due to fire severity.

The sediment losses for the slope plots are much larger in the research of Prats et al. (2016), which might be due to the larger area of experimental slope (83 to 131 m^2 for Prats et al. (2016) and 16 m^2 for this research) or the steeper slopes (25° versus 18°).

For the upscaling effect, the sediment loss in the micro-plots were 2 times higher in the research of Prats et al. (2016). This differs from the upscaling effect in this research, with the micro-plots having 18 (low severity) and 145 (high severity) times more sediment loss than the slope plots. This may be caused by the difference in experimental set-up, with the slope plots of Prats et al. (2016) being larger and accummulating more erosion, thus making the difference between the micro-plots and the slope plots smaller. In this research, the amount of erosion in the slope plots is more marginal, which may also be caused by the ploughing of the plots which stops soil particles from moving.

3.1.3. Total organic matter losses post-fire

Results

The cumulative values (Figure 3.3) of the organic matter losses in the erosion show that the high severity micro-plots have a higher organic matter content. The total amount of organic matter content for the high severity plots is 80 g/m^2, whereas the total amount for the low severity plots is 63 g/m^2. The total amount of organic matter loss is much lower for the slope plots, with just 3 g/m^2.

The sediment losses are also respectively 8 and 142 times larger for the high severity micro-plots compared to the low severity micro-plots and the slope plots. Therefore, it is also important to look at the percentage of organic matter in the sediment losses. This gives a clear insight as to how much percent of the eroded material is actually organic matter.
Table 3.2 shows that the slope plots have an organic matter content of 52%, whereas the eroded material in the micro-plots is 49% for the low severity plots and only 10% for the high severity plots.

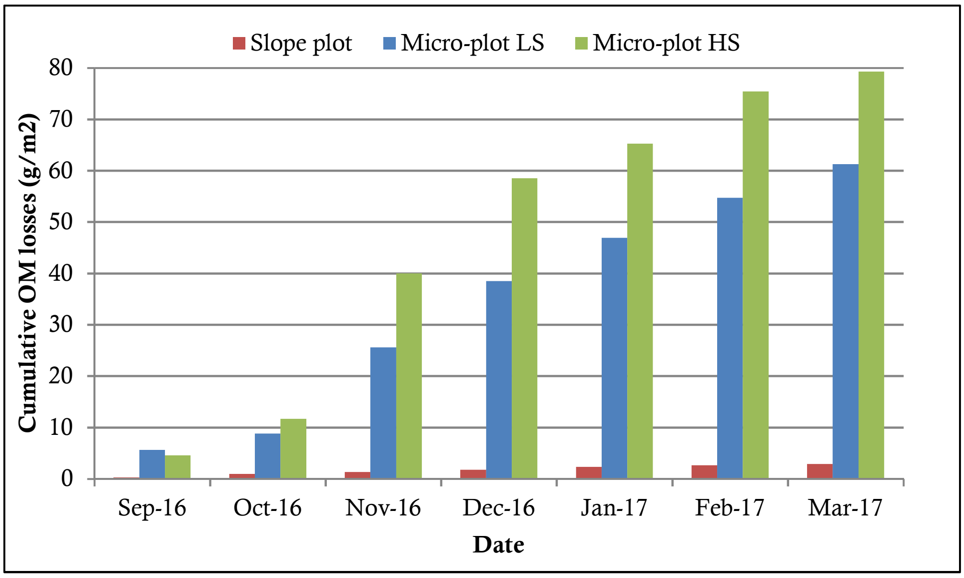

Figure 3.3 - Post-fire monthly cumulative organic matter losses

Discussion

The losses in organic matter are lower than the literature, which shows that Prats et al. (2016) has a cumulative organic matter loss of 535 g/m^2 for the micro-plots and 189 g/m^2 for the slope plots in his results. Because the plot sizes in his research are larger then those in this research, it is better to assess the differences in the percentage of organic matter content. When you look at the percentage of organic matter in the sediment losses, Prats et al. (2016) shows organic matter contents of 56% (micro-plots) and 41% (slope plots) in his results. For this research, the organic matter content is respectively 10% (high severity) and 49% (low severity) for the micro-plots and 52% for the slope plots. This shows that, although the plot sizes differ in the slope plots, and the amounts of sediment losses are also higher found in Prats et al. (2016), a similar amount of organic matter can be found in the sediment losses.
The difference regarding mainly the high severity plots could be due the degree of burning, and as a result the organic matter content has decreased in the soil leading to a lower percentage. However, this can not be supported by literature since there are no referential results from other researches regarding the effects of a higher wildfire severity.

Scale dependant, the results of Prats et al. (2016) show that the organic matter loss is 3 times higher in the micro-plots. This is much lower than the results of this research, which shows a ratio of 22 times more organic matter in the micro-plots compared to the slope plots. This might be different because of the slope scales for the slope plots. Because of the larger plots (and more erosion and organic matter loss), the upscaling effect could be more minimalized in the research of Prats et al. (2016).

The role of the land management operation ploughing can also be discussed. As stated in the literature by Malvar et al. (2011), ploughing helps to lessen the effects of runoff and erosion. Since ploughing has more impact on the larger slope plots compared to the small micro-plots, it can be seen in the results that the amount of runoff and sediment loss is lower throughout both the pre- and post-fire period. This could be caused by the ploughed study site, which can suggest that land management operations are valuable to such areas affected by wildfires.

3.2. Temporal patterns

The temporal patterns in rainfall (and rainfall intensity) are dependent on the seasonal changes in the Portuguese climate. With a repetition of wet winters and dry summers, the temporal patterns can reach opposite extremes throughout the year. These temporal patterns have an effect on the runoff and erosion in the study area. This paragraph will assess the temporal patterns that occur in the study area during the research period.

3.2.1. Pre- and post-fire temporal patterns of rainfall and I_{30}

As seen in Figure 3.4, the precipitation amount in the period preceding the wildfire (which is from 07-10-2015 till 30-06-2016) is much higher than the post-fire period. It must be noted that the 2015 winter was wetter than the one of 2016, and the post-fire data does not include a complete year.

Although the precipitation amount is higher, the 30-min maximum rainfall intensity (I_{30}) is uniform for both the pre- and post-fire period (Figure 3.4). The most intense rainfall events are still in the pre-fire period, but the values for the maximum rainfall intensity does not significantly differ.

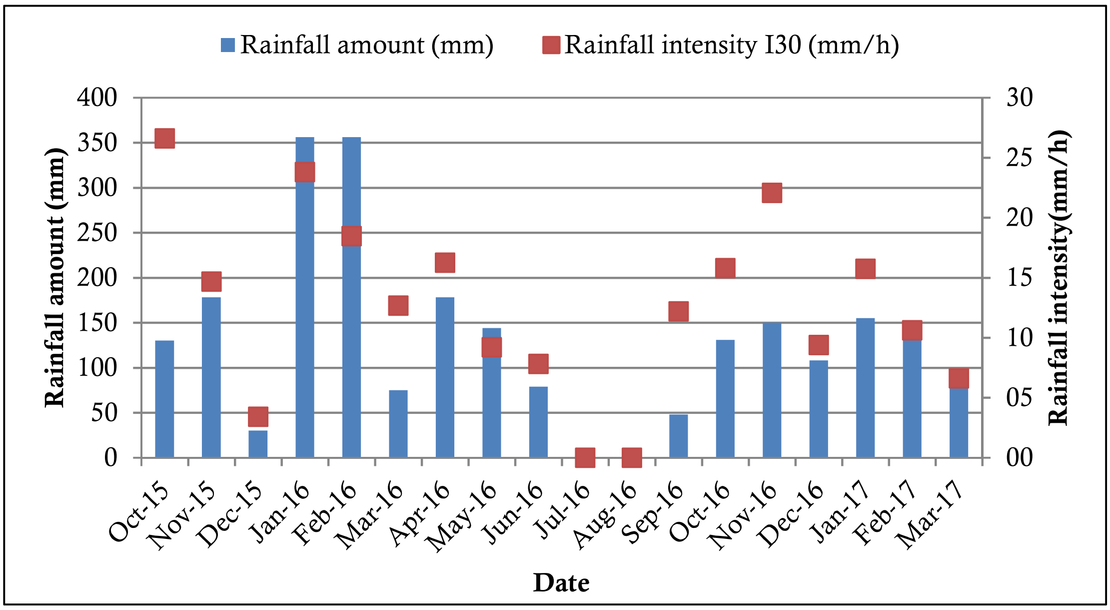

Figure 3.4 - Monthly rainfall amount and monthly maximum 30-min rainfall intensity (I_{30})

For the pre- and post-fire period, it is important to assess the temporal distribution of rainfall, which causes runoff and erosion within the micro-plots and slope plots. In the pre-fire period, the most rainfall has occurred in January and February. The rainfall distribution is uniform throughout the post-fire period.

3.2.2. Pre- and post-fire runoff comparison

Results

Although paragraph 3.2.1 shows that the precipitation amounts and the rainfall intensity (I_{30}) were relatively higher in the pre-fire period, this did not lead to an increase in the temporal average runoff (Figure 3.5a and 3.5b). The runoff for the micro-plots is very marginal in the pre-fire period.
The graph (a) shows that where the runoff in the pre-fire period does not respond to higher rainfall intensities during wetter periods, the runoff in the post-fire period increases much more rapid when the maximum rainfall intensities are higher (b).

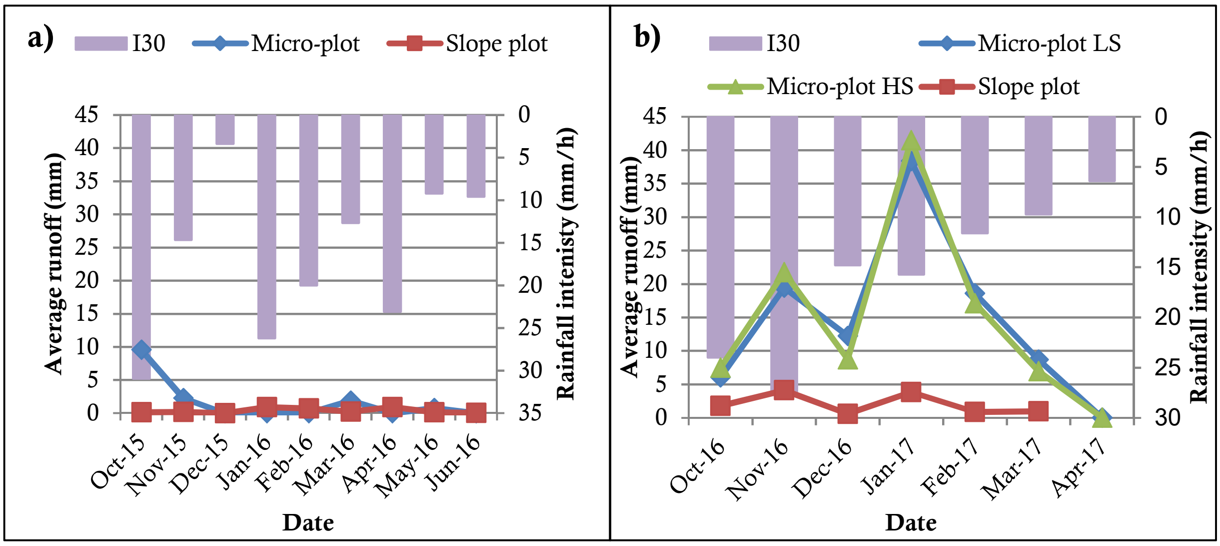

Figure 3.5 - Average runoff and maximum rainfall intensity (I_{30}) in pre-fire (a) and post-fire (b) period

In the comparison based on the scale dependence, the visualisation of the data shows that there is a large difference between the runoff of the micro-plots compared to the slope plots. For the pre-fire period (a), this difference is more limited. The micro-plots show a small reaction to rainfall, whereas the slope plots have a minimal runoff.
This pattern is not visible for the post-fire period (b), where the micro-plots show a fast response throughout time. The slope plots show a larger response compared to the pre-fire period, but compared to the micro-plots the runoff is still marginal.
The difference between the low and high severity plots is marginal for the runoff amounts (Figure 3.5b). Although the low severity micro-plots have a larger runoff coefficient, the plots react similarly to precipitation events. The difference in runoff coefficient is only 0.8%, and is therefore acceptable.

Discussion

For the comparison between the pre- and post-fire period regarding runoff, there is no relatable literature present to evaluate the results. The differences between the periods may be caused by the lack of vegetation after the wildfire. The results show that, although the pre-fire period has some intense precipitation events, the runoff does not clearly respond to these events. In the post-fire period, the response of runoff is much more evident. This suggests that the lack of ground cover makes the plots more prone to runoff.

The pattern in the post-fire period is in line with the findings of Prats et al. (2015). The maximum amount of average runoff in his research is 230 mm, which occurs at the highest I_{30} of 31 mm/h during the first year post-fire. The highest amount of average runoff in this research does not occur at the highest I_{30}, but rather at a later time in the research period. The highest amount of average runoff is 40 mm at a maximum rainfall intensity of 15 mm/h during that month.
The micro-plots still show a response when the rainfall intensity is higher, but is not as evident as the relationship found in Prats et al. (2015). His research shows that each time the I_{30} increases, the average runoff in the plots become larger. This could suggest that the micro-plots' runoff in this research is not as dependent of the maximum rainfall intensity, whereas the results of Prats et al. (2015) show a much clearer response.
Malvar (2015) states that the ploughed micro-plots also show little response to higher maximum rainfall intensities. Only at a rainfall intensity of 40 mm/h the results show a response with 75 mm runoff. After that, the amount of runoff keeps declining despite rainfall events. This pattern could be due to the ploughed plot areas. It must be noted that the maximum rainfall intensities in Malvar (2015) are a 15-minute interval (I_{15}) and not a 30-minute interval as in this research.
For the slope plots, there is a clear difference compared to Prats et al. (2015). In his research, the slope plots show a response during higher rainfall intensities (12 mm, 10 mm and 8 mm at an I_{30} of respectively 31 mm/h, 26 mm/h and 23 mm/h). Our research did not show this relationship, with only a small response of 4 mm runoff during the highest rainfall intensity but no other response to precipitation events. This could be caused by the ploughed plots in this research, which delimitate the amount of runoff even at higher rainfall intensities.

Compared to the literature by Prats et al. (2015), there is a large difference regarding the upscaling factor. The response of runoff to increased maximum rainfall intensities is clear, with the maximum runoff between micro-plot (230 mm) and slope plots (12 mm) occurring at the same time throughout his research. Other responses also occur with a similar pattern.
This pattern is not visible in the results of this research. Where the micro-plots show a reaction, the slope plots show little to no reaction to higher rainfall intensities. In Prats et al. (2015), the upscaling factor is 19 times regarding the maximum runoff amount between micro-plots and slope plots. For this research, the upscaling factor is only 10 times (40 mm for the micro-plots compared to 4 mm for the slope plots). This difference could be explained by the limited amounts of runoff through time in this research. Also, as stated in other parts of the discussion, the ploughed slope plots are more uneven which could stop runoff in these plots.

It shows that post-fire land management operations could be valuable in this situation. The degradation of the slopes and the lack of vegetation lead to a larger response in terms of runoff. When applied correctly, post-fire land management operations could help to increase the sustainability of this area and diminish the amounts of runoff in the post-fire period.

3.2.3. Post-fire erosion comparison

<u>Results</u>

Figure 3.6 shows that the amount of erosion throughout the post-fire period is the highest in the micro-plot, specifically in the high intensity micro-plots. Here large peaks in the temporal erosion amounts are visible. Whereas the erosion is not relevant in the slope plots and the low severity micro-plots, the erosion amounts are great in the micro-plots.

Discussion

The results of this research are in line with the literature of Malvar (2015). Here the maximum sediment loss is 150 g/m^2 which occurs at the highest maximum rainfall intensity of 70 mm/h. This can be compared to the response of the sediment loss in the high severity micro-plots of our research. The reason why only the high severity plots show a similar response can be derived from the fact that the degree of burning has made the soil stability lower which makes the soil more erodable during precipitation with a higher intensity.

It must be noted that the similar response of sediment loss only occurs in the unploughed plots of Malvar (2015). This might indicate that the soil structure of the unploughed plot areas are comparible to the high severity micro-plots of our research.

Another remark should be that the results of Malvar (2015) are based on a maximum rainfall intensity with a 15-minute interval (I_{15}). This could lead to a higher or lower maximum rainfall intensity, since the amount of tips counted is only for a period of 15 minutes instead of 30 minutes.

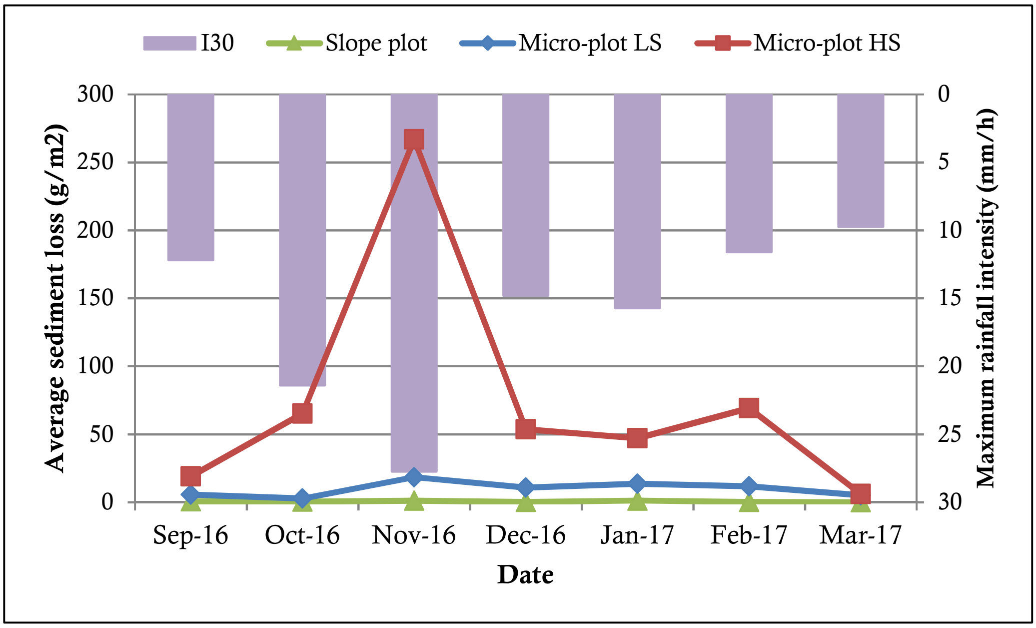

Figure 3.6 - Average monthly sediment losses with the 30-min maximum rainfall intensity (I_{30})

The main difference in results between the high severity micro-plots and the other plots of this research may be related to the burning severity. This impairs the soil's structure, making it easier to erode during intense precipitation events. Figure 3.5 also shows this relationship, with the larger response of the high severity micro-plots.

3.2.4. Post-fire organic matter losses comparison

Results

The average distribution of organic matter content (Figure 3.7) shows that there is a higher amount of organic matter in the erosion of the slope plots and low severity micro-plots. Especially the slope show peaks of organic matter content, up till 69% in October 2016. The average organic matter content is the lowest in the high severity micro-plots, with 23% being the highest average amount of organic matter content during the post-fire period.

Figure 3.7 shows that the organic matter content in the erosion is on average higher in the slope plots. For almost every readout, the amount of organic matter in the slope plots exceeds the amounts in the low severity plots.

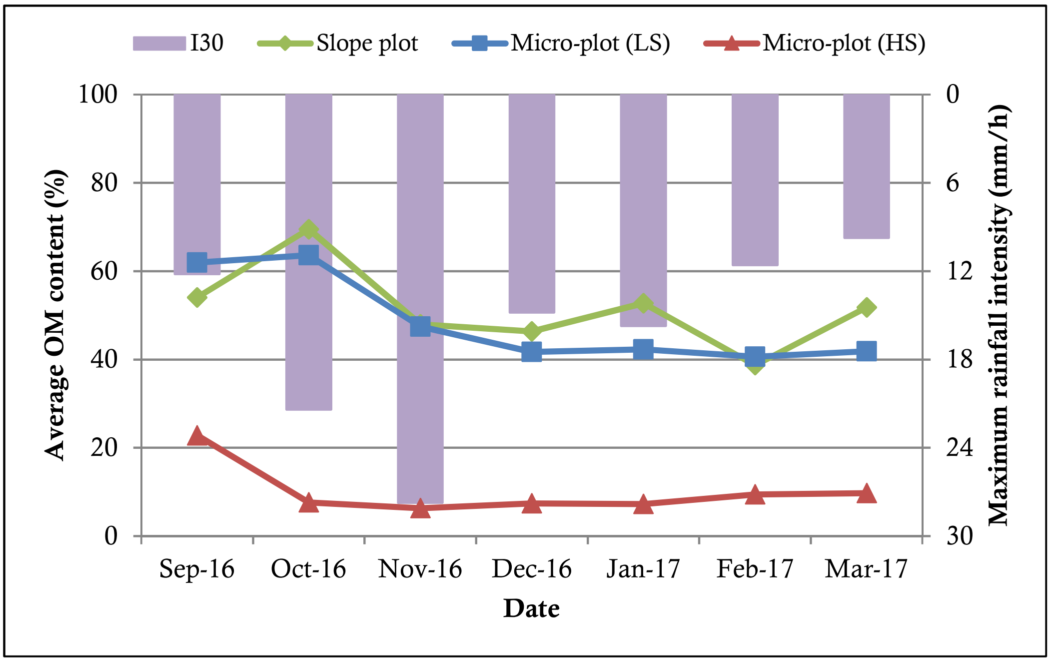

Figure 3.7 - Average monthly percentage of organic matter content with the 30-min maximum rainfall intensity (I_{30})

Discussion

The organic matter losses are the largest in the high severity micro-plots, but this could be caused because of the higher amount of sediment losses. Looking at the percentages of organic matter in the sediment losses (Table 3.1), it shows that the high severity micro-plots have the lowest amount of organic matter content in the soil losses (10%).

It was expected that with the most eroded material in the high severity plots should have the most organic matter. But it has become clear that the high severity of burning in these plots may have caused significant changes to the organic matter present in the soil.

3.3. Runoff and erosion drivers

To establish a clear interpretation of the runoff and erosion in the study area, it is important to see which factors trigger these processes. This paragraph gives the results for some of the runoff and erosion drivers that lead to the overland flow and the sediment losses in the Casa do Padre study site. A possible relationship can be found which is being discussed in the paragraphs.

To understand this relationship, and possible changes occurring during the research period, the correlation between the hydrological processes can help. This correlation gives a clear insight in the relationship between the causes and effects shown in the results. This statistical analysis is based on the coefficient of determination (R^2), which is shown in Table 3.3 for each plot in the graphs of the runoff and erosion drivers.

The correlation is based on this coefficient of determination. If the correlation is lower than 0.1, the correlation is very weak. Between 0.1 and 0.25 the correlation is still weak. Between 0.25 and 0.5 the correlation becomes more stronger. If R^2 approaches 1, it means a strong correlation is present between the processes.

Table 3.3 - Correlation between the different processes based on the coefficient of determination

Relationship	Figure nº.	Plot	R^2
Rainfall vs. runoff coefficient	3.8	*Pre-fire*	
		Slope plot	0.07
		Micro-plot	0.07
		Post-fire	
		Slope plot	0.07
		Micro-plot LS	0.08
		Micro-plot HS	0.15
I_{30} vs. runoff coefficient	3.9	*Pre-fire*	
		Slope plot	0.04
		Micro-plot	0.70
		Post-fire	
		Slope plot	0.28
		Micro-plot LS	0.16
		Micro-plot HS	0.56
Runoff coefficient vs. sediment losses	3.10	*Post-fire*	
		Slope plot	0.39
		Micro-plot LS	0.51
		Micro-plot HS	0.28
I_{30} vs. sediment losses	3.10	*Post-fire*	
		Slope plot	0.76
		Micro-plot LS	0.20
		Micro-plot HS	0.44
Runoff coefficient vs. organic matter content	3.11	*Post-fire*	
		Slope plot	0.46
		Micro-plot LS	0.40
		Micro-plot HS	0.28
I_{30} vs. organic matter content	3.11	*Post-fire*	
		Slope plot	0.34
		Micro-plot LS	0.20
		Micro-plot HS	0.27

3.3.1. Precipitation and 30-min maximum rainfall intensity

The precipitation and 30-min maximum rainfall intensity (I_{30}) play a key role as a trigger for runoff and erosion in the study area. Since rainfall causes the motion of soil particles and the saturation of the soil, it can be seen as the most important driver for the processes.

3.3.1.4. Relationship with runoff

<u>Results</u>

As can be seen in Figure 3.8, there is a change in relationship between the rainfall and the runoff coefficient when comparing the pre-fire period to the post-fire period. For the micro-plots, there is no clear relationship between the rainfall and the runoff coefficient in the pre-fire period. This changes after the wildfire, where the runoff coefficient responds to higher amounts of rainfall. Where the runoff coefficient in the pre-fire period does not exceed 10%, the post-fire micro-plots show 30 to 40 percent of runoff coefficient during increased rainfall amounts. Still, the correlation between the rainfall and the runoff coefficient does not increase significantly. Only the high severity micro-plots show a bigger correlation, but this is still not a strong relationship.

The slope plots in the post-fire period show no change of relationship. Although the post-fire slope plots have a response of a higher runoff coefficient during rainfall, the relationship between the amount of rainfall and the average runoff coefficient in both the pre- and post-fire period is not evident for the plots.

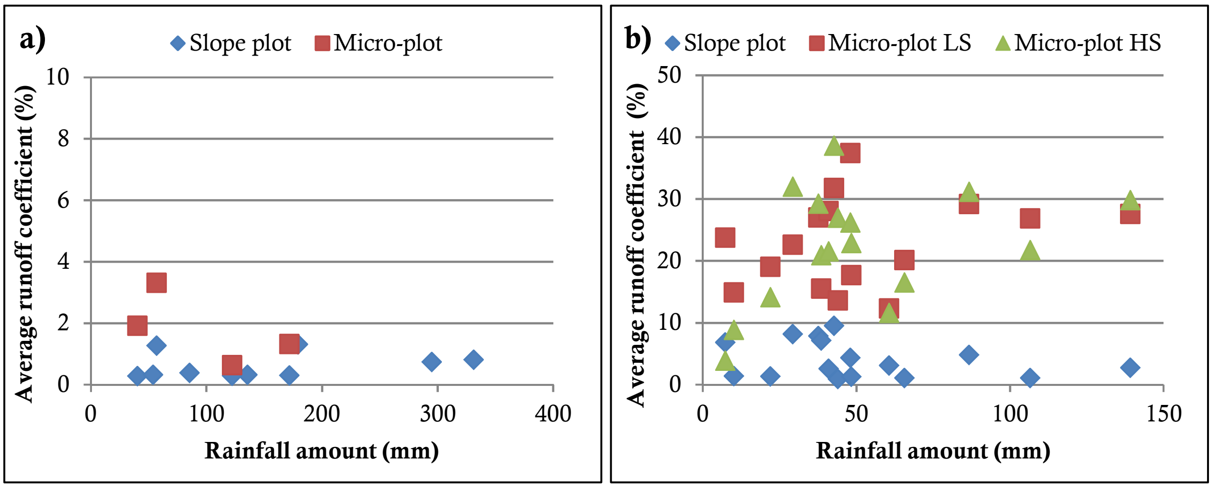

Figure 3.8 - Rainfall vs. runoff coefficient for pre-fire (a) and post-fire (b) period. NOTE: y-axes have different scales

Regarding the 30-min maximum rainfall intensity (I_{30}), the graphs in Figure 3.8 show that the relationship with the runoff coefficient changes during the research period. For the micro-plots, Figure 3.9 and Table 3.3 show that for the micro-plots the correlation between the rainfall and runoff coefficient has become less in the post-fire period, changing from 0.70 to 0.16 (low severity) and 0.56 (high severity).

For the slope plots in the pre-fire period, there is also a change of relationship visible. The post-fire slope plots show a much larger response to the rainfall intensity, a relationship which was not present in the results of the slope plots in the pre-fire period.

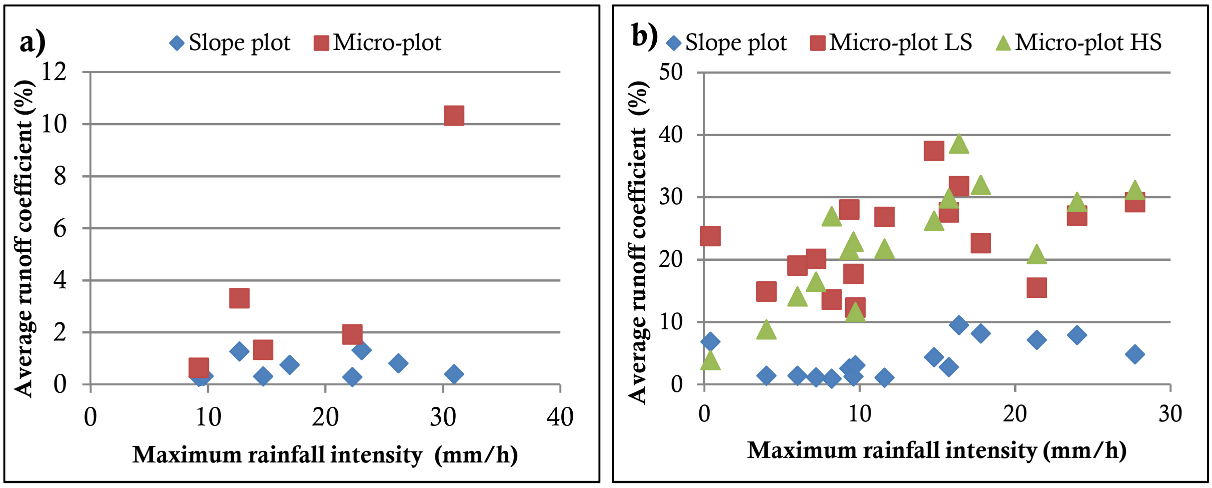

Figure 3.9 - I_{30} vs. runoff coefficient for pre-fire (a) and post-fire (b) period. NOTE: y-axes have different scales

<u>Discussion</u>

The change in relationship found in the results are comparable to the results of Prats et al. (2015). The micro-plots in his research also show that the response of runoff to rainfall amount was higher in the micro-plots than the slope plots, with the slope plots still showing some relationship.

Furthermore Prats et al. (2015) also shows that the runoff coefficient is related to the I_{30}, with the smaller plots reflecting a greater runoff coefficient.

The results and correlation can also be related to the ground cover (Paragraph 3.3.2. – 'Ground cover'). It is clear that cover in the form of vegetation can provide interception and since there is no vegetation immediately after the wildfire, this can increase the runoff and relationship with the I_{30}. This may be an important factor causing the change of relationship in the slope plots.
For the micro-plots, the change in relationship is different for the rainfall and 30-min maximum rainfall intensity. This could also be caused by vegetation, but it may also seem possible that the soil is not that repellent and therefore overland water flow is limited.

3.3.1.5. Relationship with sediment losses

Results

Figure 3.10a shows that the relationship between sediment loss and the runoff coefficient is only clearly visible in each of the research plots, with the low severity micro-plots having the strongest correlation (with a R^2 of 0.51).
A different pattern appears when looking at the relationship with the 30-min maximum rainfall intensity. Here it shows that the relationship with the sediment losses are the most evident in the slope plots. The low severity micro-plots show a weaker relationship with the 30-min maximum rainfall intensity, as opposed to the strong relationship with the runoff coefficient.

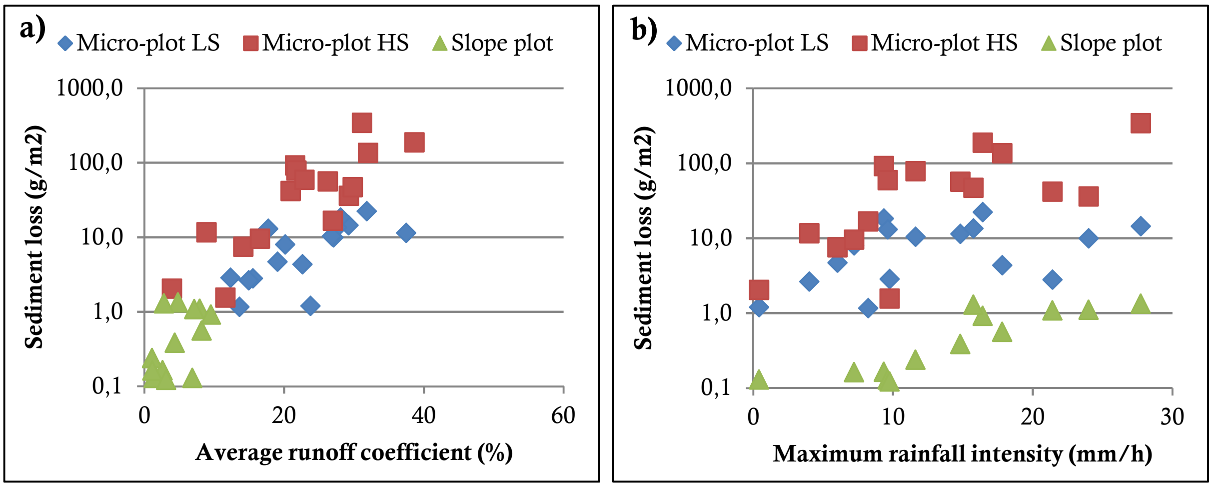

Figure 3.10 - Post-fire sediment losses vs. runoff coefficient (a) and I_{30} (b). NOTE: y-axes have a logarithmic scale

Discussion

The results found regarding the relationship between the sediment loss and the runoff coefficient and maximum rainfall intensity are comparable to the results found in Malvar (2015). For the maximum rainfall intensity, she found that the amount of erosion increased with higher values of the maximum rainfall intensity (which is I_{15} in her research).

Also Prats et al. (2016) found that the runoff coefficient was related to the I_{30} in the first post-fire year, with a greater interaction in the smaller plots. This acknowledges the results found in our research, with mainly the low severity micro-plots showing a clear relationship with the runoff coefficient. The reason for this might be that the conditions of the plots used in Prats et al. (2016) share the same characteristics with the low severity micro-plots of this research.
The relationship between the 30-min maximum rainfall intensity for the high severity micro-plots may also be caused by the loose soil particles caused by a higher degree of burning. The impacts of the severity cannot be clearly stated. However, the results show that due to the impact of rainfall intensity, the erosion tends to increase in such conditions.

3.3.1.3. Relationship with organic matter losses

Results

Regarding the organic matter losses, the most evident relationship visible for the runoff coefficient and the maximum rainfall intensity is with the slope plots (Figure 3.11). For both the runoff coefficient and 30-min maximum rainfall intensity, the correlation is the largest in these plots being respectively 0.46 and 0.34.

For the micro-plots, there relationship regarding the organic matter content is not very strong for both processes.

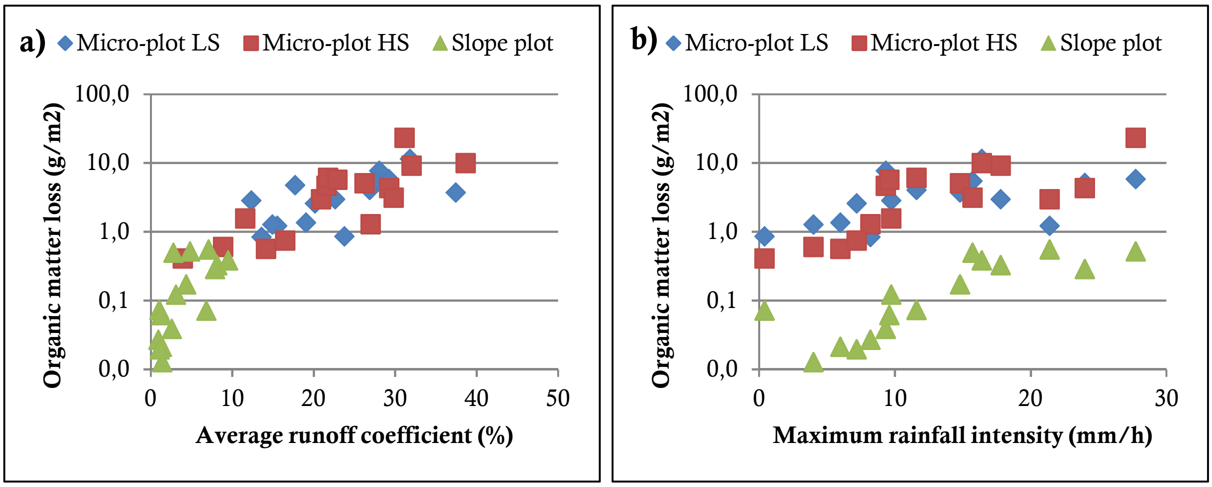

Figure 3.11 - Post-fire organic matter losses vs. runoff coefficient (a) and I_{30} (b). NOTE: y-axes have a logarithmic scale

Discussion

Malvar (2015) shows results that are in line with the data of this research. The organic matter content was related to the maximum rainfall intensity in her research. This also occurs in the plots of this research, with the difference being that the strongest relationship is visible in the slope plots for this research. The strongest correlation in Malvar (2015) occurred in the micro-plots.

It may also be possible that the burning of vegetation has left debris in the plots, causing the organic matter content to be 52% for the slope plots, 49% for the low severity micro-plots and 10% for the high severity micro-plots. Although the relationship with the runoff coefficient and 30-min maximum rainfall intensity are not that strong, the correlation is visible in the percentage of organic matter found in the sediment losses.

3.3.2. Ground cover

Results

The graphs in Figure 3.12 show the alteration of ground cover for the study area, in the period from 25-08-2016 till 13-04-2017. The distinction is made between the micro-plots and the slope plots. The visualisation shows that the decrease of ashes is the largest in the low severity micro-plots (Table 3.4). In the high severity micro-plots, the vegetation is recovering the fastest and the bare soil is also most frequent here. Stones show an evenly distributed increase throughout time, whereas litter increases the most in the slope plots of the study area.

Table 3.4 - Percentages of ground cover in the Casa do Padre research plots

	Aug-16			Oct-16			Dec-16			Feb-17			Apr-17		
	SP	LS	HS	SP	LS	HS	SP	LS	HS	SP	LS	HS	SP	LS	HS
Vegetation (%)	0	0	0	6	0	0	8	2	8	12	4	15	15	17	19
Litter (%)	6	5	1	14	10	5	26	18	8	27	17	7	24	16	5
Stones (%)	5	9	8	14	19	8	14	16	10	16	19	10	19	26	26
Ashes (%)	90	86	91	64	70	88	50	61	67	43	53	55	38	31	40
Bare soil (%)	0	0	0	1	0	0	2	3	6	1	7	12	5	11	10

SP: Slope plots / LS: Micro-plots, low severity / HS: Micro-plots, high severity

Discussion

The pattern in the surface cover is in line with the pattern found in the literature by Malvar (2015). Here, the results also show that the pattern of cover changes from the removal of the ash layer, to exposing a stone lag and the development of vegetation and a litter layer. In the results of our results these findings are similar, with a decrease in the amount of ash and the increase of mainly vegetation in February and April 2017.

Prats et al. (2015) has found that immediately after fire, the micro-plots and slope plots already had respectively 21% and 29% bare soil. This pattern is not visible in the results of our research, where there is almost no bare soil present in the first two months after the wildfire. In the high severity micro-plots, it even takes four months for bare soil to be exposed. This difference in ground cover could be explained by the wildfire severity, which was more severe in parts of this study site.

Ground cover plays an important role regarding the amount of runoff and sediment losses. As stated earlier in Paragraph 3.2.1.1. – 'Relationship with runoff', these processes can increase in the post-fire period due to a lack of ground cover in the form of stones or vegetation. The graphs in Figure 3.11 also show a clear difference between the low and high severity micro-plots. In the months following the wildfire, the low severity micro-plots show a higher amount of litter and stones. This could be one of the reasons why the peak in mainly the sediment losses is higher in the high severity micro-plots, and this has led to a larger cumulative value for the erosion in these plots.

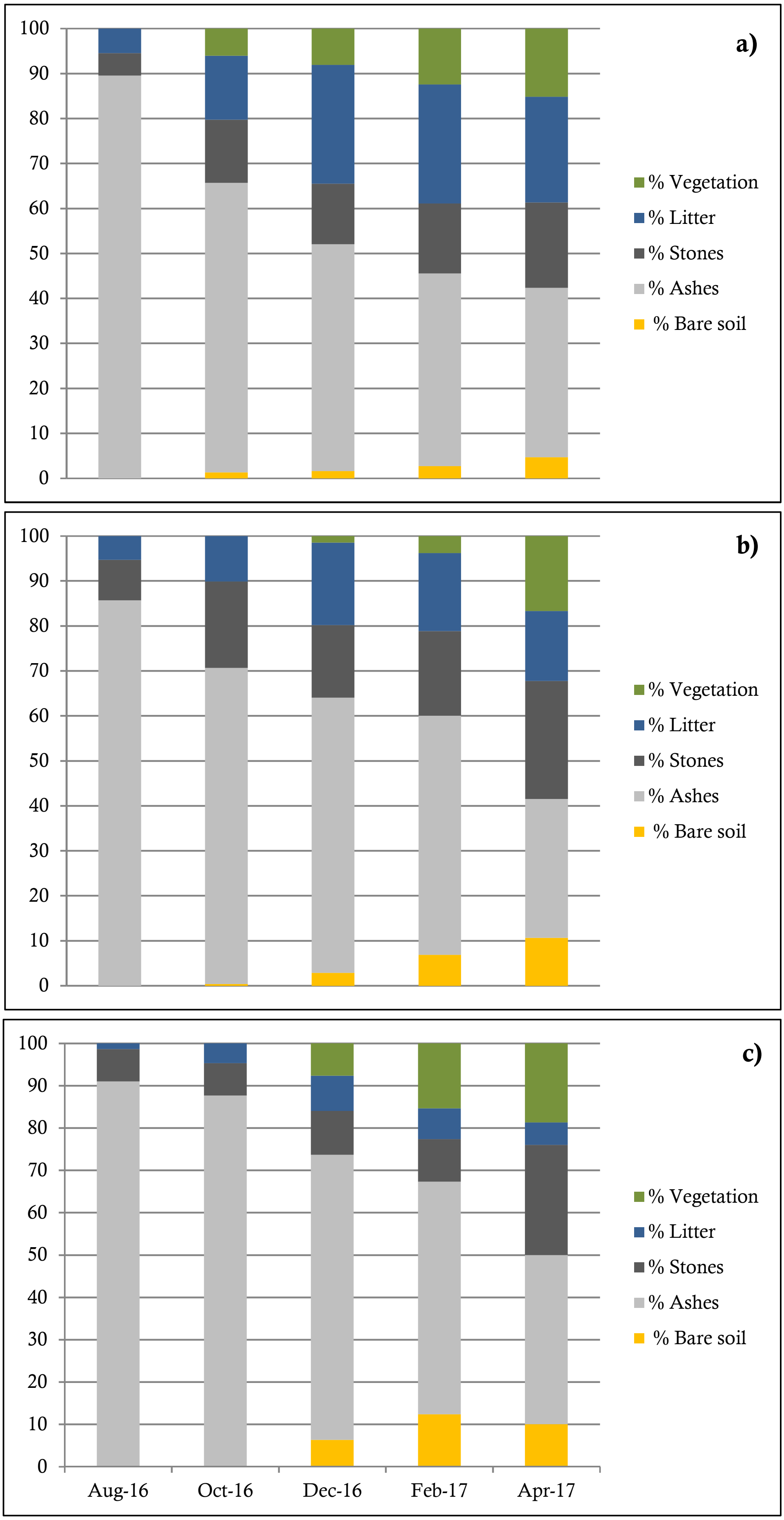

Figure 3.12 - Cover data for slope plots (a), low severity micro-plots (b) and high severity micro-plots (c)

3.3.3. Soil moisture

Results

The graphs in Figure 3.13 show the average soil moisture through time, for the period 25-08-2016 till 22-03-2017. This data is for different depths in the top soil layer, namely at 2.5 and 7.5 centimetres. Three of the four EC-5 sensors have been placed in the low severity plot area, and the other sensor in the high severity plot area.

The data shows that the average soil moisture is higher in the high severity area, and that the soil moisture has a higher average value deeper in the top soil layer.

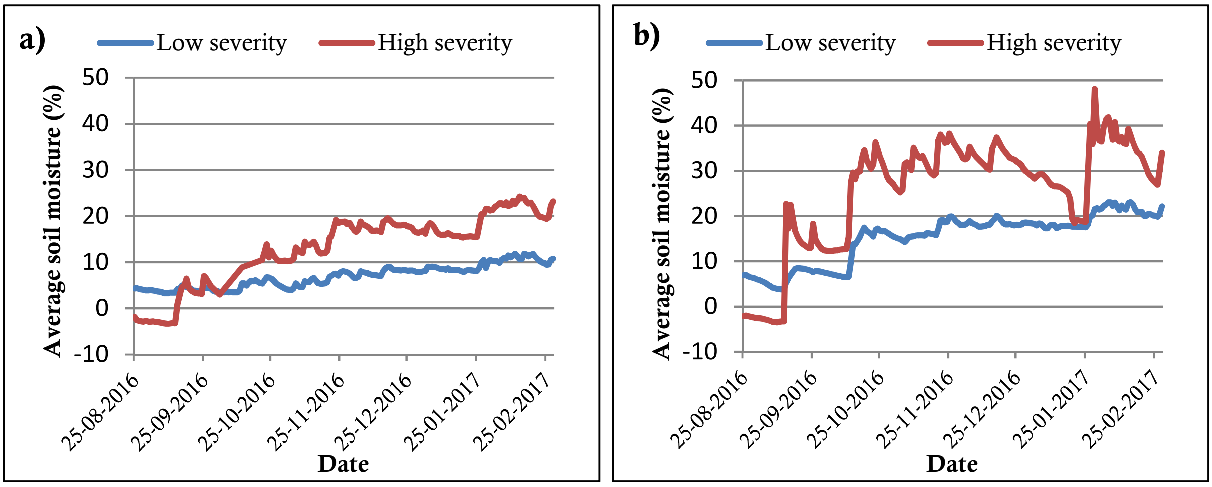

Figure 3.13 - Average soil moisture content for 2.5 cm depth (a) and 7.5 cm depth (b)

Discussion

Malvar (2015) found that the soil moisture content at 2.5 cm depth was around 6% during the first post-fire year. This is in line with the data from the low severity micro-plots, which also show these values for the soil moisture content. The high severity micro-plots show higher average values, which could be caused by a lower soil water repellency after wildfire.

The results of Prats et al. (2013) showed that the average soil moisture in the control plots were around 14.3%. The data of the high severity micro-plots at 2.5 cm depth and the low severity micro-plots at 7.5 cm are comparable to the results found in the literature, and have an average soil moisture content of 17%. It must be noted that the results found by Prats et al. (2013) were at a depth ranging from 0-5 cm.

The results show that in the high severity parts of the study area, the soil moisture is higher on average. This may be caused by hydrological processes such as soil water repellency which, suggested by these soil moisture results, are to be lower and therefore increasing the water content in the soil. Furthermore, the difference between the percentage of soil moisture on different depths could occur because of a better retention of infiltrated water at 7.5 cm depth. It could be possible that lower than 7.5 cm an aquitard is present which prevents the infiltrated water to go deeper into the soil.

4. CONCLUSION

The main conclusions of the assessment of the impact of wildfires on the hydrological processes based on different plot scales are described in this paragraph, and are based on the research questions and results of this research.

Regarding the difference of the hydrological processes within the Serra de Cima catchment between pre- and post-fire years, it can be concluded that there is a large increase in the cumulative runoff, sediment losses and organic matter losses caused by the wildfire. The results of the research show that the runoff is 10 times larger for the slope plots and 14 times larger for micro-plots in the post-fire period compared to the pre-fire period. Furthermore, the runoff coefficient increased with 3.5% for the slope plots and 20% for the micro-plots. This means that, although the precipitation amounts were higher in the pre-fire period, the amount of runoff generated by overland flow in the plots increased. The wildfire therefore had an effect on the structure of the soil which makes it more water repellent and enhances overland flow, which lead to the increasing runoff values.
For the cumulative sediment losses there are no pre-fire data. Nonetheless the post-fire data give a clear indication about the effects of the wildfire. Due to the fire's degradation of the hillslopes in the Casa do Padre study site and the different fire severity, the erosion processes have altered in the post-fire period. The results of the research show that especially the fire severity has had a great impact on the sediment losses. In the study site the amount of sediment losses are 8 g/m^2 for the slope plots, 142 g/m^2 for the low severity micro-plots and 1133 g/m^2 for the high severity micro-plots. It can be concluded that the wildfire (and different wildfire severities in some parts of the study area) has had its impact on the stability of the soil and has made it more vulnerable for erosion. Furthermore the loss of interception by vegetation, which has been incinerated during the wildfire, leaved the soil more exposed which triggered erosion processes.
The organic matter losses also back up the impact of the wildfire on the study area. Similar to the sediment losses, it also shows the pattern of large amounts of losses especially in the micro-plots. For the slope plots, the data showed 3 g/m^2 of organic matter losses and for the low and high severity respectively 63 g/m^2 and 80 g/m^2. However, with the larger amount of sediment losses, the organic matter content also becomes higher. This can be concluded from the organic matter content, which is the highest in the slope plots (52%) and the low severity micro-plots (49%) and the lowest in the high severity micro-plots (10%). Thus it can be concluded that the effects of the wildfire also play a role in the organic matter content eroding from the hill slopes, and that the fire severity has had an impact on the organic matter content throughout the study area.

Regarding the upscaling effect, it has become clear in this research that the hydrological effects are larger in the micro-plots as opposed to the slope plots. As stated earlier in this paragraph, the cumulative and temporal results show that the amounts of runoff, sediment losses and organic matter losses are several times larger. This means that the upscaling effect leads to a decrease in the impact of the wildfire on the hydrological processes. It must be noted that, due to ploughing in the study site, runoff and sediment is more easily withheld on the slope plots. This could explain why hydrological processes are less evident in the slope plots.

It can be concluded that the main driver for the hydrological processes is the 30-min maximum rainfall intensity (I_{30}), which shows the most correlation with the processes. But the impact of ground cover goes hand in hand with this correlation. With the lack of ground cover the results showed that, in the first months following the wildfire, the runoff and erosion were the highest.

The combination of the lack of ground cover and intense rainfall events has led to the exposure of the ground and an increase in hydrological processes.

Some post-fire land management practices are found to be helpful to help recover an area after being affected by a wildfire. Research regarding post-fire land management operations have shown that ploughing and mulching are two effective ways to mitigate hydrological effects on a burned area. In order for ploughing to be effective, it should already be done before a wildfire event. Mulching can be applied in different amounts, depending on the severity of the wildfire and the extent of the affected area. It can be concluded that especially ploughing, which was done in the Casa do Padre study site, has an effect on the impact on hydrological processes. In the slope plots, which show the least increase in hydrological effects, it showed that due to ploughing processes can be mitigated and can help contribute to the sustainability of the study area.

Post-fire land management practices have found to be a valuable asset for the recovery of an area affected by wildfire. For land managers in a wildfire affected area it is often difficult to assess which measures should be taken in order to improve the conditions of the catchment and minimize the negative impacts of the wildfire.
It is suspected that the amount of wildfires will not decrease in Portugal in the near future, and therefore post-fire land management practices are becoming more important to prevent the deterioration of areas due to these fires.
It can be concluded from this research that post-fire management operations are helpful to mitigate the impacts of a wildfire, and limit the increase of hydrological processes in areas such as the Casa do Padre study site. Ploughing in the slope plots has shown that this land management operation can successfully lessen the amounts of runoff and erosion due to wildfire. This is a positive result for land managers of comparable areas prone to wildfires, and can be implemented in future land use.

5. RECOMMENDATIONS

As a remark on this research, there are several recommendations which could improve and strengthen the research. These recommendations could possibly be implemented in future research regarding similar topics.

The research could be improved by using more comparable periods in terms of precipitation and using longer timespans. This research has been carried out with the data of the year preceding the fire. Now that it is known that this pre-fire period was remarkably wet, compared to the post-fire period which was relatively dry. A search can be done in the pre-fire data for a year that shows more similarities in terms of precipitation.

Another improvement to the research could be made if the post-fire period has the same timespan as the pre-fire period, and equal months could be compared to one another. In this way, a clear month-to-month comparison of the hydrological processes and the recovery of the catchment can be made.

In order to have an even better assessment of the effects due to the difference in fire severity, it would be mandatory to get a deeper understanding of the differences that occur between low and high severity burning of catchments. The processes that occur involving the change of soil structure and cohesion, and the impact on erosion post-fire, are interesting. As it can been seen in this research, there is a clear difference between low and high severity burned areas in terms of soil losses.

To have a more reliable assessment of the ground cover, it would be recommended to use a standardized software which can detect any of the five types of cover based on the pictures taken. By doing this, the research for ground cover would give results which are similar in terms of quality but do not involve a time-consuming process.

Other possible research could include combining the before- and after approach with a paired catchment. When these approaches are being combined, the (geo)hydrological alterations could be solely related to fire, whereas now the difference in precipitation (causing wetter and dryer years) can impair the before- and after approach. The approach does not completely clarify which effects are due to fire and which effects are due to a lack of precipitation.

EPILOGUE

It is important to assess the process and experiences of the graduate traineeship, and to find out what has been learned and which aspects should go different next time. Furthermore, I want to describe my views of the research and how these views have changed throughout the traineeship period.

First of all, it has been an absolute exciting period, which lasted for almost seventeen weeks. I am truly proud of the results and my thesis, which I have accomplished by myself. Of course I should not forget to mention that this result could not have been achieved without the proper supervision and cooperation from the research team. I am delighted to finish off this traineeship properly and to round off the graduation phase of the Bachelor degree Land and Water Management.

The most essential learning moment of the process has been to critically assess my work throughout the process. I have noticed that during the course of the traineeship period I have learned to implement this better into my working process. By being specific and clear about the research goals and planning, I could maintain a well-functioning workflow. With the intermediate feedback moments from my supervisors, I have learned to assess the comments and review my own work and the dependability of the results.

Another learning point I had set out to accomplish during the traineeship was to gain knowledge and experience about rainfall and runoff processes in another environment. I had to adapt to the situation in Portugal, and the effects wildfires have in this country. The hydrological processes are dependent on several factors which were fairly unknown to me. Further along the research period, I have learned to not only understand the problematic hydrological situation caused by wildfires but also to work with field data gathered in wildfire affected areas. The combination between the practical work (both in the field as in the laboratory) and the analysis of the results have resulted in a lot of new experiences in the field of scientific research.

I believe it was possible to improve the working process even more, by having an understanding of the final objectives for my research earlier. The first weeks I was really focused on adapting to the new environment and my tasks in the research team, which have led to a setback in maintaining the purpose of the research. Therefore the draft of both the research proposal and thesis changed more often than intended. But in the end these adaptions have led to results, conclusions and recommendations which are useful for both the HIDRIA project and the scientific research on the hydrological effects of wildfires in Portugal.

All in all, I am truly glad to have had this experience in Portugal and the possibility to do my graduate traineeship in such a nice environment. I believe this thesis will be a good conclusion to the Bachelor programme Land and Water Management, and the beginning of my working career.

Sil van den Groenendal
Aveiro, June 2017

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