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*Photo by Sérgio Brito*

**COIMBRA - PORTUGAL**

« GEOMORPHOLOGY AND GLOBAL CHANGE »

# Geomorphological changes in fire affected landscapes: field and laboratory techniques for soil erosion analysis.

## ICG 2022 IAG-EGU Intensive Course for Young Geomorphologists

17-20 September 2022

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## Geomorphological changes in fire affected landscapes: an introduction

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### Introduction

Soils existing at the surface of the Earth are of extreme importance, an indispensable resource for the survival of living beings, which is being exhausted till its limits, especially by human activities and that needs urgent care and conservation.

Along its existence, humans have used the Earth resources in a reckless way, having little consideration for its importance, and for the future generations and their needs.

Soil is a medium where constant exchanges of energy and matter take place, being in constant formation and evolution. The process of soil formation is continuous, but it is also a process that requires a lot of time to complete. In fact, it takes thousands of years to have an inch of soil. It is for this reason that it is considered a non-renewable resource since its renewal goes far beyond the life span of a human being.

Considering the current rate of soil degradation promoted by human activities and that the current rates of soil erosion are orders of magnitude higher than the natural formation of the soil, this is a major threat to food security and to the viability of the ecosystems (Wuepper *et al*., 2020).

Productivity impacts of land degradation are due to a decline in land quality on site where degradation occurs (e.g. erosion) and off site where sediments are deposited (Eswaran *et al*., 2001).

Indeed, it is difficult to imagine an aspect of our natural world which encompasses such an immense measure of scale in both time and space as erosion of the earth's surface (Nearing *et al*., 2017).

Since the 1930s strategies to ensure the sustainable use of land have been adopted (Oldeman *et al*., 1991; Morgan, 1995). Consequently, it is urgent to promote adequate strategies and measures to promote soil conservation. Conservation and recovery measures aim to protect the soil, preventing the development of erosion processes, increasing the availability of water and nutrients, as well as promoting biological activity, allowing the recovery from the diverse disturbances that affects them.

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One of the primary environmental disturbances contributing to the increase of soil erosion and degradation, which often require the application of restoration measures, is wildland fires (Bento-Gonçalves *et al*., 2012).

Although the occurrence of forest fires and its impacts on Earth surface may be identified since the Carboniferous Period, some 300 to 350 million years before the present time (Pausas and Keeley, 2009), it is in the Holocene Epoch (the past 10,000 years), that it has been more significant, due to the major role humans have played in fire spread across the planet.

Wildland fires are a generalised and recurrent problem. Although wildland fires are characteristic of certain regions and seasons, they occur with varying regularity and severity across almost every biome on Earth.

Fire is an important Earth system process and the primary terrestrial ecosystem disturbance agent on a global scale and it depends on vegetation characteristics, climate, and human activities, and generates feedbacks by affecting biogeochemical cycles, vegetation composition and structure, land, atmosphere, water and heat exchanges, atmospheric chemistry and composition, and human health and property. Fire is also a significant evolutionary force, and is one of the first tools that humans used to re-shape their world.

Wildland fires are also an important factor for soil degradation, being a major cause of desertification in most of the fire-prone forest lands in the world. Soil erosion is a global problem and, although it is more severe in developing countries, it has now become more of a concern in more technologically advanced countries. When this process takes place at rates higher than those of weathering and those necessary for soil formation, its loss is irreversible. Erosive processes, facilitated by the development of rills and gullies, which have a significant impact on agricultural land, also produce adverse effects downstream, namely sedimentation and the clogging of the bottoms of valleys, which can result in the obstruction of communication routes and destruction of other infrastructure and properties.

With this perspective in mind, the International Association of Geomorphologists (IAG) promotes the organization of the ICG 2022 IAG-EGU Intensive Course for Young Geomorphologists devoted to "Geomorphological changes in fire affected landscapes: field and laboratory techniques for soil erosion analysis". The Intensive Course is dedicated to Early Career Scientists (ECS) and will be held in September 2022 in Guimarães (Northwestern Portugal), within the organization of the 10th International Conference of Geomorphology.

The northwestern region of Portugal is heavily affected by wildland fires, promoting significant impacts on soils, resulting in intense erosional processes occurring on slopes, especially during the first autumn rainfall events, contributing for an increased change on landforms and landscape transformation. Besides soil erosion, other geomorphological hazards are triggered after wildland fires, such as landslides and flash floods. This set of geomorphic processes, intimately related with the occurrence of wildland fires, threatens not only the quality and productivity of soils, but also the population and assets exposed to these recurrent events.

Being this region frequently affected by these hazards, it offers us an excellent field of work where we can observe and identify the effects of its occurrence. The area affected by the 2017 fire of Braga will be an area to visit, where we can witness the geomorphological consequences of forest fire followed by the storm Ana, characterized by intense rainfall (Vieira and Bento-Gonçalves, 2019).

Consequently, this Intensive Course will offer the possibility for ECS to train their skills in field recognition and survey of soil erosion in fire affected areas, in combination with laboratory techniques (soil analysis) and implementation of geospatial technologies (GIS and RS).

The present-day challenges associated to soil erosion and other interconnected geomorphological hazards management require young researchers in geomorphology to combine field activity with digital skills for data analysis and modelling, especially in geographical information systems, statistics, computer programming and remote sensing. Accordingly, the Intensive Course will also provide the participants with practical exercises on some of the internationally used analyses of geomorphological data in the field of soil erosion and geomorphological hazards. Participants will learn how to translate the collected field data into useful information for a wide array of scientific applications and geo-spatial problems.

This event is part of the IAG Training Programme and will be an extraordinary occasion for Early Career Scientists, and especially for those from less-favoured countries, to increase their knowledge in geomorphology and wildfires-related soil erosion and to do networking with experienced scientists and early career researchers in an informal and international context.

The event will be organized in collaboration with the EGU Geomorphology Division, based on the Memorandum of Understanding signed between the aforementioned and the IAG. It has also the support from the COMLAND - the Commission on Land Degradation and Desertification of the International Geographical Union and the French Geomorphology Group (GFG).

The Intensive Course will be focused on specific topics of soil erosion and other geomorphological hazards such as: Basic concepts on soil erosion and geomorphological hazards related with fire affected areas; Post-fire soil erosion; Geomorphological field survey and soil erosion monitoring methodologies; Laboratorial techniques for soil analysis; GIS and statistical analysis; Remote sensing methods applied to burnt areas and soil erosion analysis; Strategies for soil erosion mitigation techniques in fire affected areas; Burnt areas management strategies.

This Intensive Course counts with the participation of a group of experts who have developed intensive research on the problem of soil erosion and degradation, namely the one triggered by forest fires, its monitoring, modeling and evaluation of measures and strategies for impact mitigation.

This group of geomorphologists will present lectures and guide the field and laboratory work and is composed by: Maria José Roxo (New University of Lisbon, Portugal), Lea Wittenberg (University of Haifa, Israel), Sílvio Rodrigues (Federal University of Uberlandia, Brazil), Tomás de Figueiredo (Polythecnic Institute of Bragança, Portugal), Marcos Francos (University of Salamanca, Spain), António Vieira (University of Minho, Portugal), António Bento Gonçalves (University of Minho, Portugal), and Saulo Folharini (University of Minho, Portugal). This work will also have the support of young geomorphologists, namely José Rocha (University of Minho, Portugal), Sarah Santos (University of Minho, Portugal), Jorge Novais (University of Minho, Portugal), and Tiago Marques (University of Minho, Portugal).

The eight chapters that compose this book are the synthesys of the lectures and field and laboratory work that was planed for this Intensive Course.

We hope that these texts may be useful not only for the young geomorphologists participating in this course, but also to all those who have geomorphology as an interest and who are developing or will develop research on geomorphological dynamics related with soil erosion.

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# Chapter 1. Soil Erosion and Land Degradation Under Changing Environmental Conditions

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## Introduction

Climate Change and enhanced desertification are two of the main challenges that humanity is currently facing. The changing environmental conditions both weaken natural ecosystems and lead to vulnerable communities inhabiting them. The context of climate change mitigation and adaptation is fundamental towards a sustainable future that is resilient and fair. Within this context, erosional processes and land degradation gradients should be a priority for policy design and implementation: as the climate gets warmer and drier, the challenges for the production sectors will be surmounting, with decreasing agricultural yields, crop loss, water scarcity, all enhanced by negative feedback loops of GHG emissions.

The first step towards policy design that is concerned with soil erosion and land degradation is to understand the causes, effects and expected challenges under changing environmental conditions. Therefore, this chapter will focus on three main parts: 1) Mediterranean Climate and its Change over time; 2) Soil Water Erosion and Land Degradation in Mediterranean Ecosystems; 3) Impacts, Vulnerability and Adaptation. The analysis and description will follow a thread of thought that is concerned in Mediterranean Ecosystems; however, the main arguments and data will be centred in the Semiarid region of the Alentejo, in SE Portugal, but occasional examples from other literature will also be given.

## 1. Mediterranean Climate and its Change (context)

"There is a Mediterranean climate which is associated with long, warm, and dry summers, and moderate winters with relatively low total rainfall" (Ribeiro, 1998). There is more to the Mediterranean climate than these words may encompass, and which goes far beyond average values: the annual amplitude and variability of these precipitation totals can be as low as 200 in Murcia or 3000 in Galicia (Thornes and Wainwright, 2004). Furthermore, recent trends of reduction of these totals can be observed: for the 1970-2000 period, the Vale Formoso Station (Mértola, Alentejo, Portugal) registered a mean

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annual rainfall of 475mm, while for the period of 1990-2020 this value has dropped to 450mm, with the last ten years going on average below 390mm. Understanding how climate shapes lifestyles and enables or disables human activity and degradation gradients involves to comprehend that “the Mediterranean is the antithesis of the average, with variability being the only constant and even an essential source of specificity and diversity” (Casimiro, 1993).

In autumn, dry fields from the previously long summer are eroded by the first rains which may happen earlier or later due to the irregularity found in September (either a prolonged August – warm and dry - or an early October – with the first frontal systems and heavy rainfall). October is generally soft, even though the days start to get ever shorter and thermal amplitude increases with continentality. Rains may be interleaved with dry periods but increase in volume the closer they get to winter and mark the beginning of the first agricultural work of the year.

In late December comes winter, which is marked by cold and rain but may be considered ‘moderate’ for global standards. This season is particularly affected by low pressures and frontal systems that result in the highest rainfall volumes for the year. In the Mediterranean region, cyclogenesis occurs mainly in three regions: the gulf of Genova, SW Greece and in the Cyprus/Anatolia Region. This situation results in a strong thermal gradient between the Sahara and the Eastern Basin. In the Portuguese Mediterranean, the two most common situations are shiny and bright days, both dry and cold that can last for weeks (due to high pressures in the centre of the Peninsula), interleaved with the passage of low pressures from West to East which bring Atlantic humidity and some warmer air which cools as it advances to the interior and rains where it passes.

Spring starts with an increasing number of hours of daylight and is a season that marks the passage between winter and summer in a softer way than Autumn: March may be either dry or rainy, and the reduction of rainfall and increasing temperatures are gradual as higher pressures start to merge further north and enabling, little by little, situations of atmospheric stability and higher temperatures.

Increasing temperature, luminosity and lack of rain mark the arrival of summertime. These situations may be interrupted by abrupt convective rainstorms due to high surface temperatures. High pressures remain in the centre of the Peninsula for large periods of time, warming the air with temperatures frequently reaching 40°C in the Alentejo Region, and forcing daily work rhythms concentrated in the early morning and late afternoon. During this time, soils dry and their susceptibility to erosion is higher the more they stay without rain (which is aggravated if there is low organic matter content).

The Mediterranean basin is very susceptible to the negative impacts of climate change, according to the last IPCC reports. This will further enhance the degradation processes that are already common in the region since human action first introduced pressure on the natural resources. The most likely effects will be the increase in frequency and duration of droughts and decrease in number of days of rain. The analysis of trends in the Standard Precipitation Index (SPI) for the Mediterranean region show contrasting trends in Europe, as the north becomes wetter and the south gets drier, especially the Iberian Peninsula, Southern Italy, Greece, Cyprus, Western Turkey; the same will likely happen to Northern Africa.

In the Alentejo region, the analysis of daily rainfall data (1941-present) shows similar trends, with nearly all ETCCDI Indices pointing towards a warmer and drier climate: increase in Consecutive Dry Days (CDD), reduction of total annual precipitation (PRCPTOT), and reduction in days of rain over 10, 20 and 25mm, but with a trend towards maintaining the volume of rain for the most intense day (RX1day). This ensures that soil remains dry for longer, and that organic compounds are more exposed to solar radiation for longer, increasing soil erodibility; all while extreme erosivity remains similar, which means that the susceptibility to soil erosion is higher.

The effects of climate change in soil loss and its regenerative capacities in the Mediterranean context is almost indissociable from Desertification, which the UNEP defines as "soil degradation in arid, semiarid and dry-subhumid areas, resulting from various factors including climate change and human activity". This leads to soil degradation, which is the "reduction or loss of ecological and economical productivity caused by changes in land use, physical and chemical processes or both" (Geeson, Brandt & Thornes, 2002).

## 2. Soil Water Erosion and Land Degradation

### *2.1. Background and Importance*

Soils are "likely the most important resource of the Biosphere and of every population's Natural Heritage, in part due to its non-renewable character at the human timescale: it is easily destroyed by the impact of rainwater, and washed away by surface runoff, giving place to an impoverishment of ecosystems that is shown by a loss in both productivity and biological diversity" (Lopez-Bermudez *et al.*, 1993, 5). Therefore, the need to understand the physical, chemical, and biological processes that act upon this resource has driven numerous studies worldwide, in different scientific domains.

It was, however, in the USA that, in the early 20$^{th}$ century, researchers started to study surface runoff, sediment availability and soil loss. This was partly due to the observed soil degradation when colonies were established in previously natural lands. The Soil Conservation Movement was created between 1890-1920 and it had its foundations in the works of Dawkin and Marsh. Marsh' book "Man and Nature" (1864) concisely formulates the relationship between humans and the natural environment, acknowledging soil as a fundamental part in the global structure of what we today understand as the "ecosystem".

Among the primary authors behind these movement, Pinhot and Roosevelt can be highlighted by having led projects towards a better natural resource management, as well as Spillman's work on the need to apply soil conservation methods in agriculture (1910). Yet, the decisive step towards analysing soil degradation processes was taken in 1915 when the US Forest Service initiates the first quantitative studies following Miller (1917) to be targeting the understanding of soil loss and surface runoff triggered by rainwater. This work would then result in the first published studies of this kind based on field methods and experimental plots.

Still in this context, some studies developed by the USDA's Soil Conservation Service trigger the growth in interest around these subjects. For instance, between 1928 and 1933, ten experimental field sites were implemented by Bennet, which would later be upgraded to a total of 44. It was then in the 1940's that the erosional role of rainwater and the mechanical impact of rain droplets on soils were systematized by Laws (1940) and Ellison (1944), respectively.

The continuously growing database that constituted the results obtained from numerous experimental plots would become the incentive needed to start researching a mathematical equation that could explain soil loss based on the principal intervening factors. According to Wishmeier and Smith (1978), the development of universal equations to directly compute soil loss started in the US Corn Belt around 1940 which culminated in a practical method to estimate soil loss at the slope scale in 1956.

Initially, Zingg (1940) published an equation that related the degree of soil loss with slope length and incline. The following year, Smith added the calculation of factors related to the type of land cover and management practices. In the late 1940s, Browning, et al. built on the previous equations and created a new one that included parameters of soil physical and chemical properties. Later, Musgrave (1947) added the mechanical effect of precipitation and, in 1954, the Universal Soil Loss Equation (USLE) was produced by the National Runoff and Soil Loss Data Centre in cooperation with the University of Purdue. To validate this equation more than 10 000 observations of surface runoff and erosion were used from 49 different locations and, with time, the equation has been consecutively revised and improved as experimental and analytical methods also improve.

In Europe, an ever-growing number of researchers from various fields dedicate their time towards experimental and theoretical work on soil erosion. Agronomists, geographers, engineers, pedologists, and hydrologists share the objective of better understanding mechanisms that lie behind erosion and soil degradation, so farmers can better control them and mitigate their effects. This tendency can also be correlated to the environmental issues that Mediterranean European countries face, especially south-eastern Spain, and southern Italy, Portugal, and Greece, due to high levels of land degradation following overexploitation of natural resources and climate change.

In the 1950's Portugal started a soil conservation programme following the grave consequences of the wheat campaigns promoted by the Estado Novo fascist regime. This programme was based on experimental plots towards the analysis of the processes behind soil water erosion. The Nacional Secretariat for Agriculture then founded two Soil Erosion Experimental Centres in 1961: one dedicated to cereal production in south-eastern Alentejo (Vale Formoso) and one to study vineyards in the high slopes of the Douro valley (Pinhão). The aim was to compare the amount of sediment obtained in different conditions of slope, aspect, vegetation cover and management practices. Both still operate and host some of the longest erosion data series in Europe.

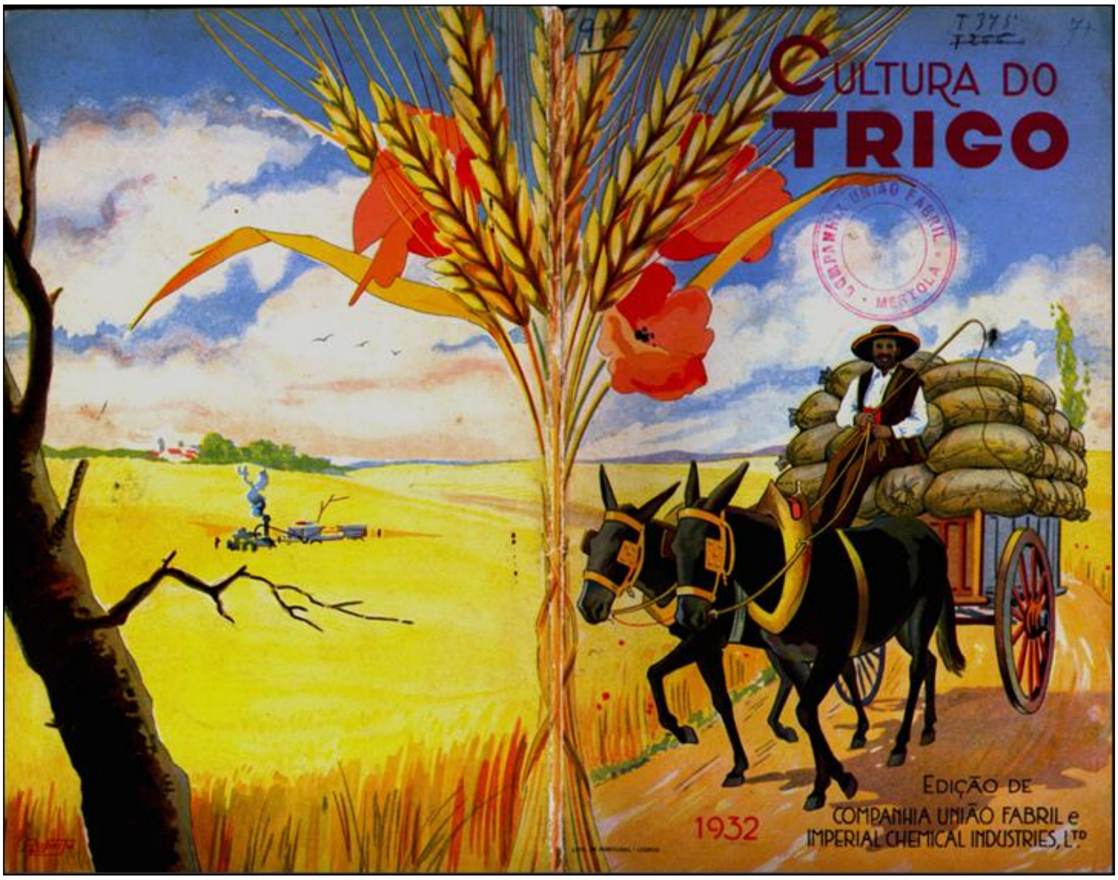


**Figure 1.** Poster from the Estado Novo Wheat Campaigns which led to the over exploitation of poor soils in the Alentejo Region.


**Figure 2.** The Vale Formoso property in 1930, the caption can read "ruins resulting from the excessive usage and lack of erosion protection" (1930)

*2.2. Erosional Processes and their Effects*

Considering the natural characteristics of the Mediterranean, the predominant erosional processes are related to water erosion: since the warm season is simultaneously dry, and the precipitation volume is less important than its temporal and spatial variability (high erosivity), soils in a frequent water stress scenario are highly erodible, especially if they are previously degraded by land management.

Soil Water Erosion is a subject of growing concern due to an ever-growing conscience that soil is a hardly renewable natural resource, especially when high land use intensity is present in the landscape. Soil degradation from both human and natural controlling factors can be observed at both physical (shallowing of the upper horizons from erosion) and chemical (loss of fertility from organic matter and nutrients). Within this context, farmers tend to first increase fertilizer usage to compensate for mineral nutrient loss (for example denitrification) and later, to abandon land due to lower productivity rates and higher production costs. In these conditions, soils show a lower permeability and water retention capacity, which translates to higher surface runoff coefficients and lower root development, restricting plant growth. Soil water erosion carries other environmental issues such as the reduction of total dam volumetric capacity (due to sediment concentration at the bottom) with an associated higher flood risk.

Three distant phases are involved in soil water erosion: 1) particle disaggregation, 2) hillslope transportation, 3) sediment deposition. Rainwater impacts the soil surface and its mass, speed and angle of incidence determine the extent to which it can disaggregate the particles. These particles are then moved in the first place by the effect of the 'splash' itself, and then by the accumulation of more water at the soil surface as in surface runoff (diffuse) or in rills (concentrated). Runoff itself is also responsible for some particle disaggregation, as viscosity and surface characteristics may allow for some of it to happen.

The most widely used method to estimate soil loss is the Universal Soil Loss Equation (USDA, 2017), which considers soil loss as a f(R, K, L, S, C, P), where R is rainfall erosivity, K is soil erodibility, L is the slope length, S is slope incline, C is vegetation cover, and P are the mitigation management practices. Each one of these actions encompasses its own set of driving forces: Erosivity and Erodibility.

Yet, and towards a more descriptive approach, we will separate the Erosivity (exogenous' elements ability to erode soil) and Erodibility (endogenous characteristics that make soil particles degradable) factors. Thornes and Wainwright summarize it as such: "Erosivity is related to the energy of the falling water droplet and its subsequent surface runoff, while Erodibility is related to the physical and chemical properties of the soil".

*Erosivity*

A primordial element of rainfall erosivity is the mass and velocity of the rainwater. The diameter of a droplet (directly related to its mass) may vary between 0,4 and 1,2mm depending on rainfall intensity, with maximum values registered up to 4,6mm (Feignold & Levin, 1986). These values are still variable depending on vegetation cover and its height. For example, small shrubs may be a dissipating agent that decelerates water before their final impact to the ground, either descending through the plant or falling from the leaves. However, trees may have the opposing effect: as water accumulates on the leaves until saturation, when it drops its diameter and mass may be higher than the original event, increasing the erosive effect of the impact.

In a Mediterranean climate, it is also demonstrated that the variability in diameter of rain droplets within a same rainfall event may be very wide (Thornes & Wainwright, 2004). The same was observed in the Lower Alentejo region, where rain gauges registered very different values even though they were relatively close.

It is also important to highlight the role that landscape morphology has over a soil's erodibility. Independently from the energy transferred from the droplet in the moment of impact, higher slopes are more susceptible to water erosion and surface runoff, except for rare cases where slope aspect and gradient associated with wind speed and direction act on attenuating and dissipating said energy.

Apart from this, the temporal distribution of rainfall events is of utmost importance: in the station of Mértola – Vale Formoso, the month with higher daily intensity (< 25mm) was September, when the first rains of the year occur and the soil is at a maximum of water stress. This means that this season is both the highest in erosivity and erodibility, with erosional processes triggered to the maximum, which can be further intensified if management practices are not adequate.

*Precipitation*

Soil particle disaggregation from rainwater is one of the fundamental processes of water erosion. The efficacy of this action is a result of the transfer of kinetic energy from raindrops to soil particles which, depending on the characteristics of both the water and the soil may have variable effects. Three phases arise from the action of this 'splash': 1) the impact, which compresses the soil surface depending on the force of action; 2) the splash, which skips the disaggregated particles from their original place; 3) the formation of a small crater or cavity, convexly centred, in the place where the splashed particles were.

The impact of rainwater over the dry soil triggers the destruction of soil aggregates and subsequent compaction. Transportation will be minimal as it only affects the particles dislodged by splash. If a screen of water is formed over the soil and precipitation continues, then particle disaggregation may also occur from the interaction between water viscosity and soil erodibility.

The efficacy of this process is dependent on various factors, but mostly due to the characteristics of rainfall events. Then, the energy from a precipitation event is dependent on the amount of rain, its distribution over time, and the size of the rain droplets. Studies show that the average diameter of rain droplets is higher in more intense rainfall events, however, as it reaches a certain limit, droplet diameter stabilizes or even slightly decreases.

*Runoff*

Surface runoff or 'Overland flow' occurs in one off two situations: when rainfall intensity is higher than soil infiltration rate (Hortonian Flow), or when soil becomes saturated with moisture (Saturated Flow).

It starts diffusely and then evolves to a laminar flow if rainfall continues. The movement of water along the slope is not uniform, as it tends to accumulate on small rills that form where the surface is more erodible. The complexity of the flow network decreases towards the bottom of the hill: diffusely flowing water will accumulate on rills, which in turn then evolve to gullies as the flow becomes more concentrated. The course of flow is often disturbed by whatever obstacles it finds, from rock fragments, roots, or vegetation cover, which mean a decrease in runoff connectivity.

The effects of surface runoff are different under sheet flow, rills, or gullies, due to the different magnitude of forces in action, inertia, viscosity, and flow turbulence. Runoff erosivity capacity depends, among other factors, on friction, sediment concentration from the inter-rill, and slope. In gullies the processes are similar, but with increasing impact. These channels are important morphological elements and very sensitive in terms of dynamic equilibrium. Even though the main action of surface runoff on soil erosion is to transport sediment, it also influences particle disaggregation, at a rate that depends on factors such as quantity and intensity of rainfall, slope, soil characteristics, vegetation cover, among others.

During runoff, detached sediments are transported. This sediment flow varies in amount and distance travelled depending on the surface characteristics such as soil properties (clay content, aggregate stability, antecedent moisture content), rugosity, terrain (slope, aspect), vegetation, and presence of plant litter. The presence of obstacles has variable effect on surface runoff, as it can both hinder and potentiate flow: vegetation cover reduces runoff by allowing water to infiltrate and reducing connectivity, however, plant litter may create a smoother surface that promotes flow, as well as some hydrophobic effect of organic matter.

*Erodibility*

Soil erodibility is related to parent material – as it influences soil particle size, distribution, and aggregation – as well as to land cover change. Shallow soils, together with fragile vegetation growth and land use intensity all together create the scenarios of high erodibility found in many Mediterranean ecosystems, triggering mechanical erosion processes, which in turn reduce organic matter and water retention capacity, further enhancing the susceptibility to degradation, in a negative feedback loop. In the context of climate change, soil erodibility may become a grave issue: as annual rainfall decreases and becomes more seasonally concentrated and more intense, the dry period and water stress during summer months also increase.

Erodibility – as well as erosivity – may also be influenced by vegetation: plant roots create a structure that mechanically favours soil structural stability as well as chemical reaction and maintenance of soil colloids. On the other hand, the falling leaves and their deposition on the surface may act as a protective layer for the surface horizon, enabling runoff and its soft deposition and infiltration without moving particles.

The rate at which hillslope erosion processes evolve based on vegetation cover is a subject that got very wide results: high values can be found in Wheat (90kg $ha^{-1}$ $yr^{-1}$), while lower values can be found in Spontaneous Vegetation (3 kg $ha^{-1}$ $yr^{-1}$), Quercus (4 kg $ha^{-1}$ $yr^{-1}$), and Pines (7 kg $ha^{-1}$ $yr^{-1}$). In the southern Alentejo, erodibility is derived from soil type and land characteristics: topography, aspect, slope, vegetation, and land use.

Topography has an important factor in the linearity of surface flow: all small irregularities directly affect the velocity of flow and potential for flow accumulation, as well as stream erosivity, transport and deposition potential.

In the Vale Formoso Experimental Centre, abandoned plots are in a regenerative situation where the ecological succession will slowly colonize the slopes with some native Mediterranean species. When the plots were abandoned, erosion rates sharply reduced, until virtually no sediment transport is occurring, and only surface runoff is observed, which shows that vegetation cover, especially native vegetation, has an important role in reducing soil erosion and combatting land degradation.

Erodibility is defined by the ability of soils to endure particle disaggregation and transportation. This resistance depends on various factors such as soil properties (particle size, aggregate stability, and permeability), vegetation (percent and type of cover), topography (slope incline, length, rugosity, and convergence/divergence), and land management (tillage, crop rotations, terracing).

*Vegetation*

The importance of vegetation cover on soil conservation is widely mentioned in research regarding water erosion, as it sharply reduces the amount of sediment to be disaggregated and transported. The erosive action of precipitation exponentially decreases in relation to vegetation growth. It is therefore a reduction in transported sediments since particle disaggregation is also hindered as plants protect soil from direct impact which has a higher erosivity. Also, flow velocity also decreases with the presence of obstacles, which reduces sediment transport. When soil is totally covered by vegetation, only rainfall events of high intensity and duration can still yield sediments to be transported, therefore, in highly vegetated plots there is virtually no erosion, only surface runoff. The degree of influence of vegetation in soil erosion is determined by the phenotypical characteristics of plants (height, diameter, and shape), cover continuity, and density.

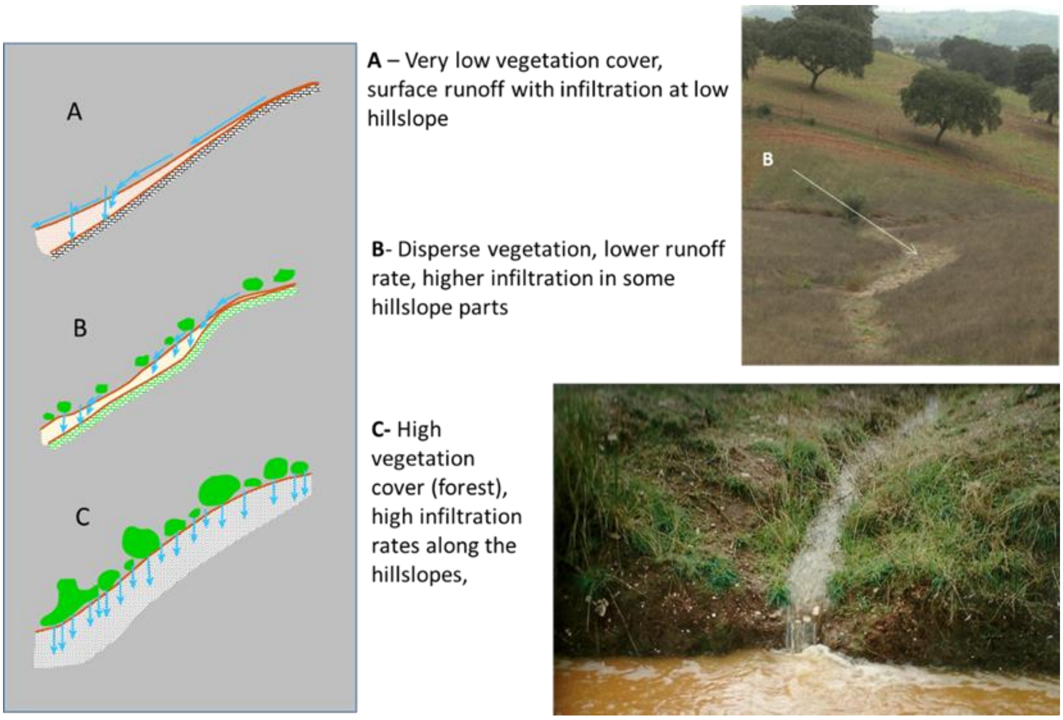


**Figure 3.** The effect of vegetation cover on surface runoff

*Topography*

Topography has an important role as different soil profiles have specific characteristics depending on its slope relative position, being different at the base, middle or top of the hill. This is due to morphogenetic and paedogenetic factors both prior and current. So, as water is flowing down the hillslope, it encounters different conditions which in turn allow for the runoff development to change along the way. Topographical aspect is relevant as it determines how exposed the soil is to the dominant winds and rainfall directions and angles of incidence.

*Slope Gradient*

Slope steepness is also of fundamental importance to surface runoff, as it increases velocity together with slope length. Splash effect is also different in different angles of incidence: a rain droplet falling vertically at a zero percent incline has an initial area of impact equal to its area. However, when it happens on an inclined plane the area is stretched, and the force of impact is reduced. Also, splash effect acts differently on a flat area or at an incline: when terrain is flat, the number of particles to be transported by splash is equal in all directions of the area of impact; however, as the slope inclines, gravity increases the likelihood of a particle to go down rather than up.

*Rugosity*

Other important element to consider when studying soil water erosion is surface rugosity and microtopography and its changes over time. Rills and inter-rills evolve and behave similarly to hillslopes, but at different scale and magnitude. The modification over time of soil surface depends on external factors such as tillage and other management practices, which then are modified by the action of rainwater and surface runoff. Tilled soil then slowly progresses towards compaction and crusting of the surface, with slits of desiccation being common in longer dry periods.

Higher surface rugosity implies a higher surface area, and its configuration may or not enable the action of surface runoff: for example, horizontally ploughing hinders surface runoff, while vertical plough tends to increase it. At the top of a slope, surface rugosity tends to increase as soil erosion progresses, while at the bottom it decreases due to higher sediment deposition. The presence of soil crusts reduces permeability and triggers surface runoff.


**Figure 4.** Rock Fragments, Rills and Sediment accumulation during and after a precipitation event in the Serra de Mértola

*Land Management*

Agricultural land use may heavily contribute to its degradation. For example, de degree of protection cover for cereal production is minimal, as soil is tilled and prepared during late autumn, where most of the heavier rainfall events occur, yielding high soil losses. Some management practices that can both increase and hinder soil erosion are tillage, crop type and rotations, as well as the presence of terraces. Tillage is one of the most important factors defining overland flow and sediment transportation, as plough depth and direction have contrasting effects on both surface runoff and soil erosion. Data from the Vale Formoso Experimental Centre shows that fallow with vertical plough sharply increases sediment transportation when compared to horizontal plough. Crop types and rotations also have contrasting effects: in the plots where wheat was present, sediment transportation was much greater than in  Lupine, Pasture, Quercus, and Pines. In the Serra de Serpa and Mertola area, rotations between fallow, wheat, and lupine are common. As contrasting erosional processes are found in each cover, the gambling between the wetness or dryness of the agricultural year and the cover present will define sediment flow and success of the rotation.

*2.3. Land Degradation Processes in Mediterranean Ecosystems*

As a living organism and basis for much of the systems that human life and civilizational development depend on, soils emerge as an interface system with notable fragility. Even in natural ecosystems without human pressure, sometimes the inherent characteristics of parent material, climate, vegetation cover and morphological features may lend the landscape with innate vulnerability to eventual future degradation gradients. One can say that soil shows both the characteristics of a 'living organism' and a 'natural resource': the biotic features make it both a driver and a vulnerable piece of the natural world and the human interactions it enables; while its finitude – its ability to be explored and exhausted – make it un-renewable to the human scale, turning it into an issue of much concern in scenarios of higher land use intensity, climate change, and enhanced desertification.

Even knowing the accelerating effect that human activity has directly in the depletion of soil quality, one cannot ignore that a simple variation in climate and a higher likelihood of droughts (which are in part enabled by human action) are driving forces for natural geomorphological processes, which is what erosion ultimately is. Going through the processes of land degradation involves understanding driving forces both natural and anthropic, which coexist in both space and time and intertwine themselves at each scale of analysis: the natural setting influences human action and its extent in the same way that human action may trigger and accelerate natural dynamics, while both ultimately represent degradation gradients.

Within this context, land degradation processes may be divided in two main groups: natural causes (weather and climate unpredictability and variability, mechanical erosion and fire), and anthropic causes (when land use dynamics enhance the likelihood and intensity of the previous effects, while human-induced climate change gives it another degree of complexity, uncertainty and intensity).

*Natural Factors*

Evaluating the fragility of terrestrial ecosystems while only considering the natural processes requires a distance from the influence that human activity and pressure may have within these processes. In Mediterranean Ecosystems, the climatic conditions and relatively recent geomorphology have yet the same natural erosivity and erodibility factors prior to human activity. The unpredictability and variability that is already inherent to this region will only be exacerbated by climate change in the coming decades.

The Mediterranean region has the ideal conditions for soil mechanical erosion from both wind and water, while still enabling a favourable environment for fire to take place and have its action in the ecosystem, with some species of plants being dependent on it to open their seeds while others developing a layer of protection in their trunks (for example the Quercus Suber).

*Human Action*

Human activity influence landscape dynamics in a scale and degree that operates under a set of complex sub-systems of the natural environment. As humans tend to enhance or accelerate natural processes such as water erosion or dry period frequency (due to climate change), it is difficult to split between what is and what is not triggered by human activity. However, it is possible to determine where and when did such interactions occur and at what degree they were responsible to degradation gradients: the wheat campaigns of the Estado Novo regime had a clear impact on depleting soil organic matter, increasing sediment availability through successive tillage.

As societies evolved from hunter-gathering to plant domestication, agriculture, and urbanization, degradation gradients also evolved, increased, and became more complex. Hunting and gathering meant that as natural resources such as animals and edible plants became scarcer, populations moved to other places where ecosystems were richer, which allowed for the degraded place to recover. Plant domestication and agriculture meant that the same soi was to be used over and over, while management practices such as tilling exposed soil to the environment, making it more susceptible to degradation. As more resources were needed, animal usage in agricultural activity introduced trampling as an erosional process. As this process of increasing intensification and growth continued, fertile lands were suddenly not enough to meet all the population's demands. This meant that as societies grew in complexity and population, there was a tendency to use ever more marginal lands for agricultural production. These lands are poorer and easily degradable, which poses a challenge to food security. In Portugal, the process of exploiting marginal lands when population increased can be traced back a few centuries at cycles of about 200 years. The last example can be found during the early years of the fascist Estado Novo Regime, where the autarkic policies defended by the government led to the clearance of the very shallow schist soils of the Serra de Serpa e Mértola, leading to massive degradation gradients.

In the Mediterranean region, cereals were the first vegetable species to be domesticated, followed by olives, vines, and legumes, which complete the trilogy of bread, wine and oil that characterizes this region. Sheep and Goat were the predominant cattle due to their adaptative capacity towards the environmental characteristics, followed by cows – more towards heavy work than meat – and later pigs, which were used for meat, even though two out of the three predominant religions of the region forbid it.

**Figure 5.** An example of an overgrazed area in the Serra the Mértola area

The need to clear vegetation to convert land to agriculture and human settlement was satisfied using fire (Thornes & Wainwright, 2004). Not only does fire influence soil erosion (which is not the scope of this chapter), it also represents huge amounts of greenhouse gas emissions as burning biomass releases $CO_2$. Studies show that fire decreases soil organic matter content and aggregate stability with recovery times of about two and three years, respectively. It also influences phosphate, nitrate, magnesium, Ph variability, plant growth and surface runoff.

There are records of great erosional processes related to agricultural activity since the bronze age. These records are related with big leaps in total population which may be explained by two reasons: populations grow due to an increase in agricultural production – as surplus allows for societal complexification – which creates the need for higher production and productivity rates. Increasing production may include extending the area towards less suitable lands which were not preferred earlier (poorer soils, more inclined slopes), while increasing productivity may lead to fewer and shorter fallow periods.

Yet, does population increase due to higher agricultural production or does agricultural production increase to satisfy a growing population, with higher levels of sedentarism and social complexity? Each great erosional process can be historically associated with a short period of population loss, pointing towards the second hypothesis, to which we must include the complex political setting that has developed around the Mediterranean over historical time. These findings can be associated with research carried out in Greece, Macedonia, Sicily, SW France, Spain, Portugal (Algarve), Turkey, Morocco, Algeria and Libya, and the following scheme models the behaviour of soil, vegetation, and human density in Sögüt-Bakboura, Turkey (Thornes & Wainwright, 2004).

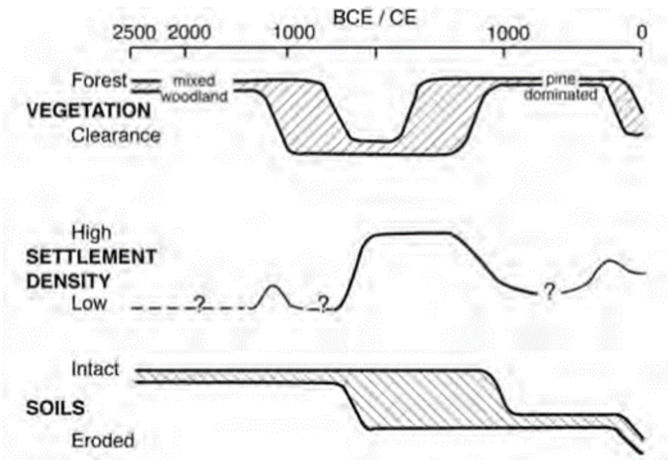


*Figure 10.11* Erosional, vegetation and settlement histories in the region of Söğüt-Balboura, Turkey, demonstrating a close link with a rapid phase of population expansion which coincides with a rapid decline in the juniper–oak–pine woodland around *c.*1050 BCE

Source: After Roberts (1990).

It does seem that the association between population growth and soil and biodiversity loss in ever increasingly complex and stratified societies has accompanied human history. The relationship between territorial carrying capacity and human activity is a strong indicator that ecosystem limitations have far been surpassed by in many regions of the world. With increasing population, consumption patterns of increasing intensity and the same space and natural resources ever, the challenges are growing.

The extent of the human impact on soils can be traced back to population increase, urban encroachment and industrial expansion and their related pressure on natural resources. Soil is the base for sourcing food, feedstock, and energy: whatever humans eat, wear, and how they live are directly dependent on soils.

Changing the structure of landscape production in a scenario of increasing population can mainly lead to one of two situations: intensifying production and closing to the soil's carrying capacity; extensification, with production reaching marginal lands and subsequent land degradation. These can be complemented by the usage of land to produce species to which it is not adapted, as in the previously described example of wheat production in the shallow schist soils near the Mértola Municipality in Portugal.

**Figure 6.** Land Degradation in the Alentejo Region, Portugal

*Climate Change*

The human ability to induce land degradation was until now presented as an issue with very distinct spatial and temporal extents. However, since the industrial revolution, the associated greenhouse gas emissions have been causing a disturbance on the earth's radiative balance. If then the human impact on the natural environment was coincident with the areas of human activity, now it is felt globally, with the more vulnerable and less-responsible regions of the world taking the larger share of the burden.

The impacts of climate change on soil systems is related to two phenomena: soil degradation, due to its effects on the plant-soil feedbacks; and desertification, as in the impacts on land-climate feedbacks. These are two distinct scales both territorial and thematic: the former is related to soil as a resource and the systems that directly interact with it (surface air, vegetation, other biota, water), and the latter with the relation between soil, climate, and societies.

Plant-Soil Feedbacks are defined as "the interactions between soil, plants, and soil abiotic mechanisms that influence the performance, diversity, and structure of biotic communities, and enable ecosystem services (Pugnaire *et al*., 2019). The increase in atmospheric carbon dioxide at first may have the effect of increasing photosynthetic activity which increases biomass and soil organic matter. However, the associated higher surface air temperature is behind increasing organic decomposition rates, fire risk and susceptibility to mechanical erosion.

The higher risk for soil resources is when ecosystems reach the so-called 'tipping points'. The increase in atmospheric GHG alters the radiative balance which increases surface and air temperature, also increasing the rate of organic matter decomposition, permafrost thawing, and extreme weather events, all which contribute to further increase atmospheric GHG values, in a snowball effect. The IPCC reports estimate soil loss to be 10 to 20 times higher than soil formation in conservation agriculture, a value that increases to 100 times under conventional practices and is further increased in bleaker climate scenarios (IPCC, 2019). Degraded and deforested ecosystems are less resilient and with lower adaptive capacity, perpetuating social vulnerability.

Land-Climate Feedbacks are the result of interactions between soil, societies, and present and future climate. These three axes will determine soil properties, crop yields, and water availability issues. Even though it is an essentially human-induced issue, the thin line between how the climate will evolve and how the natural environment will respond is the paramount example of how coupled these issues are. The consequences of enhanced desertification are especially felt when they also impact human life. Beyond the loss in organic matter, it is estimated an annual loss of 42 tons of nitrates and 26 tons of phosphates (Pierzynski *et al*., 2017). Agricultural income (and by extent the food systems) will also be affected, with an estimated decrease in 16% by 2050 in Europe, with its respective regional variations (Brevik, 2013).

The encouragement of community organizations, accelerating the transition towards a more sustainable agriculture, training on desertification and soil degradation in the most affected areas, the establishment of partnerships at the local, regional, and global scales, increasing the public participation and the use of traditional knowledge are some of the measures suggested by the Union for the Mediterranean towards facing desertification, soil degradation and climate change.

## 3. Mitigation and Adaptation

Climate change mitigation and adaptation will be fundamental to tackle land degradation in Mediterranean Ecosystems. As the climate gets warmer and drier, erosional processes will become more intense. Also, plant growth will likely be altered, with earlier germination, water stress and hindered development. In the Southern Alentejo, the tilling that takes place during autumn will likely see the soil drier for longer, enhancing erodibility, while also enabling carbon emissions from organic matter decomposition. Therefore, it is important to understand both how plants will behave and adapt to the changing environmental conditions, as well as to understand how the agricultural sector should act towards mitigating their causes and adapting to their effects.

*3.1. Vegetation and Agriculture*

Mediterranean vegetation will be impacted by climate change both in its primary productivity, structure, and distribution. As atmospheric $CO_2$ levels rise, plant primary productivity would also be expected to rise. However, this is not what empirical evidence has shown in Mediterranean vegetation, as the lack of precipitation leads to increasing water stress, and accelerated erosion leads to nutrient loss, both limiting plant growth and carbon uptake by plant systems. Higher temperatures will also increase susceptibility to fire, which both further releases $CO_2$ and triggers erosional processes. This will happen even though some species are well adapted to warm conditions due to their morphology (leaf area and protection, for example) and adaptation strategies (such as early germination).

As an adaptation mechanism, plants also tend to migrate to the areas that are suited to their characteristics. As the climate gets warmer and drier, original conditions will migrate north, and so will vegetation, tendentially. However, many species' migration rates will not compensate for the velocity of the changing climate, as the climatic changes are due to anthropic processes of GHG emissions for which natural processes are not suited (plants may migrate 100km in 250-1000 years, while warming moves 42km in around 42 years) (Solomon, *et al*. 2017).

These changes will be detrimental to the food sector, especially agriculture. This will require measures that both ensure climate change mitigation and adaptation, while contributing to erosion reduction and combating desertification.

One of such strategies that can achieve all the above-mentioned issues is soil carbon sequestration. This concept encompasses the removal and storage and excess atmospheric $CO_2$, which require an increase in organic matter content, water retention capacity, aggregate stability, and soil protection by vegetation. All of these are ways of combating erosion, increasing water use efficiency, and enhance fertility with positive effects in agricultural yield and energy savings from irrigation. Carbon sequestration will be fundamental in Mediterranean ecosystems, as the poor climatic conditions mean that vegetation will soils that are more resilient to changes in temperature and rainfall. Furthermore, the trends in land use intensity – in the case of the poor lands that were unsuitably managed, such as the SE Alentejo schists – mean that there is not only the need but also the opportunity to capture carbon, as soils are far from the values found in natural vegetation. As an example, preliminary data from the Vale Formoso Experimental Centre estimates that areas of natural vegetation (shrubland) can store more 2,75tC/ha than pastures at the same soil and terrain characteristics (soil type, slope gradient, and aspect), while holding 1.65 times more moisture content.

The measures that can ensure carbon sequestration in the Agriculture, Forestry and Other Land Use sectors are: 1) Tillage (reduced, minimum, no-till, shallow, subterranean), which reduce erosion and allow for increases in organic matter; 2) cover crops, which ensure soil cover protection from erosion, and may help delay germination; 3) residue management (green manure, usage of straws for cover protection); and 4) natural fertilization (such as manure or compost).

**Figure 7.** Machinery for no-till farming, which greatly reduces the erosional processes compared to conventionally tilled soils

**Figure 8.** Post-fire erosion control in the Alcaria Alta, Algarve

*3.2. Land Abandonment*

Land abandonment has been proven to be a way of contributing to climate change mitigation and adaptation, combating desertification and to provide ecosystem services of climate regulation and biodiversity (Novara *et al*., 2017).

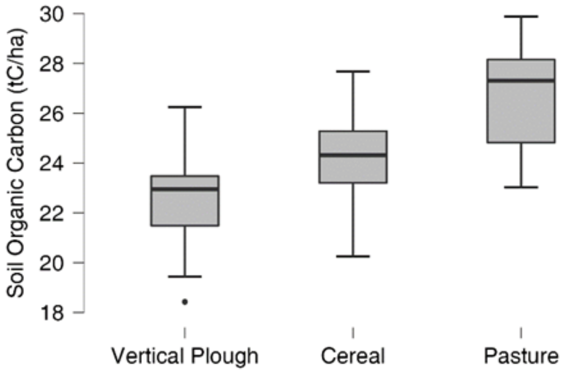


**Figure 9.** Differences in Soil Organic Carbon in plots with the same years of abandonment but different starting points (preliminary data)

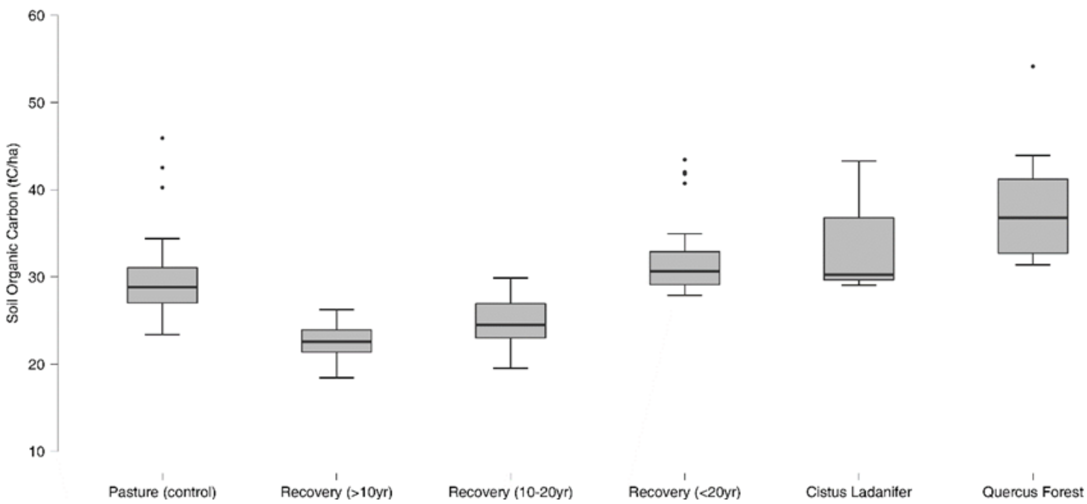


**Figure 10.** Soil Organic Carbon in abandoned plots of the Vale Formoso Soil Erosion Centre, compared to conservation pasture (control), and areas of Cistus Ladanifer and Quercus Forest (preliminary data)

The abandonment of agricultural land has a very quick effect on reducing sediment yield during erosional events, as the new vegetation cover decreases soil erodibility. In some cultures, this effect is especially important, as the absence of ploughing means that soils will no longer be bare when the first autumn rains arrive. Also, eliminating land use intensity from consequent years of agricultural activity and grazing means that the rate of organic matter depletion also decreases. Increased vegetation cover both reduces erosional processes and increases organic matter input to soils, which, combined, lead to an overall increase in organic matter content, water retention capacity and fertility.

This increase in organic matter content is of paramount importance for both mitigation soil erosion and land degradation, but also in combatting climate change: increasing organic matter has a direct effect on soil carbon sequestration which is one promising tool that simultaneously mitigates and adapts to climate change by removing carbon from the atmosphere and increasing fertility and water-use efficiency.

The increase in organic matter and soil organic carbon content is dependent not only on the years since the last disturbance or agricultural year, but also from the type of activity from which the land was abandoned.

## 4. Concluding Remarks

Soil degradation has important implications for agricultural activity and, ultimately, the food sector. The Mediterranean region is considered by the IPCC as a climate change hotspot with increasing drought duration and frequency and reduction of total annual precipitation. However, it is still possible to mitigate soil erosion and land degradation with a set of practices that both mitigate the effects of both erosion, degradation, and climate change, such as the decrease in erodibility, increase in water-use efficiency, and enabling carbon sequestration. Also, there are other co-benefits associated with the provision of ecosystem services such as biodiversity and cultural values of some native species and practices, which ultimately enable a sustainable development of fragile rural areas in the dry Mediterranean region. Finally, global initiatives such as the Soil Carbon 4perMile (Rumpel *et al*., 2020) and Land Degradation Neutrality can be powerful tools towards achieving these goals.

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## Chapter 2. Gully recovery practices in a Central Brazil environment

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### Introduction

The occurrence of accelerated soil erosion is a common phenomenon in Cerrado environments, being found on different lithological foundations and slope formats. In the Triângulo Mineiro region, studies on erosion in the form of gullies have been taking place since the 1970s, through studies by Lepsch (1975), Baccaro (1994; 2007) and Pereira (2021). There are several possibilities of study, whether the specific processes and/or forms resulting from erosion in gullies.

The search for answers about the evolution of this type of erosion seeks to associate processes from different origins, with a common focus on the intensity of precipitation, the shape of the slopes, the typology of the surface materials (soils, regolith, deposits), the conditions surface and subsurface hydrodynamics and soil occupation dynamics, among other elements that can be used in specific types of study (Wischmeier, 1962; Bertoni and Lombard Neto, 1990; Morgan, 2005; Forsyth, Bubb and Cox, 2006).

The approaches to the problem can vary between those that propose to carry out monitoring of specific situations, which implies measurements, such as measurement of sediment production, monitoring with measurement of the retreat of gullies edges, measurement of the variation of humidity conditions of the soil by tensiometry, or the water table level using piezometers. Cartographic techniques can also be used to follow the evolution of the area affected by gullies over time, using images on different dates. Therefore, there is a diversity of approaches that allow.

Therefore, understanding structural and dynamic issues and the results of the evolution of an erosive process implies a set of approaches that require effort in several horizons. One of the biggest difficulties is the monitoring for a long period of time, in which the different processes that occur in the place can be observed in its development, not being necessary to resort to interpretive models coming from other places. In the case of this research, we followed a gully for 15 years without interruption, being able to identify the evolution of the form, as well as the dynamics involved.

The present article intends to present a retrospect of the studies carried out in the gully located at Fazenda Experimental do Glória (Uberlândia/MG) demonstrating aspects

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related to its evolution and dynamics, as well as the responses to experiments to recover the area affected by erosion.

## 1. Study Area

The study area is located on the right side of the Glória Stream, in the county of Uberlândia (State of Minas Gerais), between the geographic coordinates of 18°58'19''S and 48°12'31"W Greenwich, in an altitude between 830 and 860 meters above sea level (Figure 1), with local relief is composed, predominantly, of convex and tabular forms.

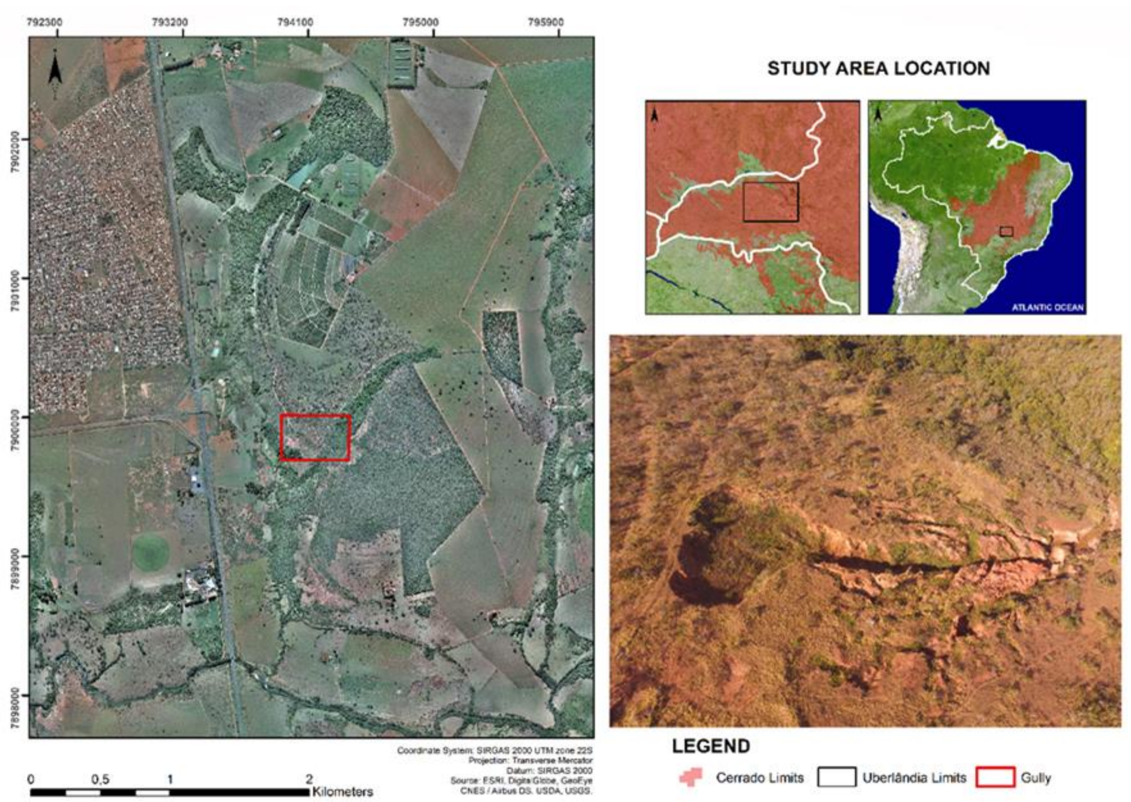


**Figure 1.** Location of the study site. Source: the authors (2022).

The geological sequence of the area is composed by basalt (Serra Geral Formation) under sandstone (Marília Formation) and a Cenozoic sedimentary cover. The superficial material has a sandy-clay-loam to sandy-loam texture, resulting from the alteration of sandstone and alluvial materials (Rodrigues, 2002).

Natural soils in this hydrographic basin have high variation because of their lithological composition and the conservation condition of the site. Around the gully, the soils augmented by the extraction of gravel, was classified by Silva (2010 and 2011) as Oxisol in the upper part of the slope and Inceptisol near the valley bottom. In the area the soil has an exposed Bw horizon with a sandy loam texture of a typical Oxisol.

The climate is characterized by well-defined two seasons with dry autumn/winters from May to September and rainy spring/summer from October to April, with average annual temperature and precipitation of 22.6° and 1507 mm. (Figure 2) These climatic conditions are controlled by the Atlantic air mass or Continental air mass. (Petrucci and Oliveira, 2019; Vrieling et al., 2007).

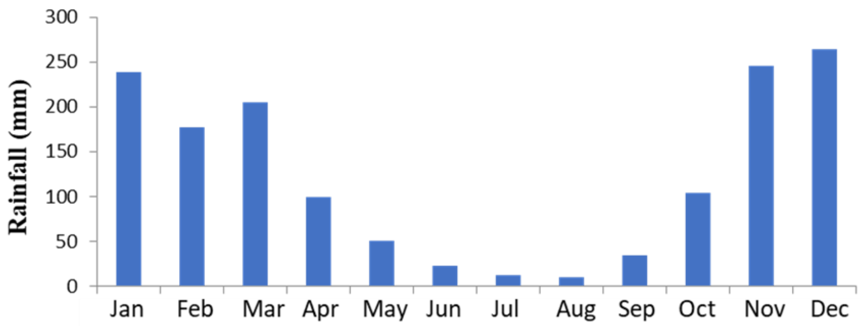


**Figure 2.** Climatogram of the Study Area (2009-2017). Source: Confessor, Carvalho & Rodrigues (2022).

A gully erosion appears on this site in the 1960/1970 decades due to extraction of saprolite levels of gravel, when the natural savanna vegetation was removed, leaving exposed sandy material, compacted, friable, with low levels of aggregation and with few organic matter. The gully grow up to the slope until almost the divide and branches spread to the side slopes. Actually the gully has almost 300 meters long and 80 meters wide at the head. The deepest point reaches at least 10 meters (Abreu et al. 2010).

Bezerra, Guerra and Rodrigues (2012a) reported that when gullies reach down to the regolith sandstones and gravels there are an expansion of side walls of the gully. The occurrence of water exfiltration at the gully walls, also triggered by the layered materials of the regolith, is due to the tunneling process of the confined water table. So, actually the gully has a continuous flow of water at the bottom.

The management practices have been started in the study area in 2006, trying to stabilize the erosion using mechanical, edaphic and vegetative practices as reported by Silva *et al*. (2009); Silva, (2010); Biulchi, (2012); Pereira Júnior, (2013) and replanting: Serato and Rodrigues, (2011); Machado, Confessor and Rodrigues, (2014), Confessor, Machado and Rodrigues (2016), Costa, Barcelos and Rodrigues (2018). The initial signs of stabilization in the study area were visible some months later.

## 2. Methodological Approach

According to Rodrigues (2018) due to environmental variation and huge types of soil degradation a huge group of techniques have been attempted to determine the best possible solution to revert degradation of soil by erosion. In this study case practices used were from edaphic, mechanical and vegetative types. Each one of these practices try to solve a specific part of the situation, that in most cases, we need to use more than one practice. Bertoni and Lombardi Neto (1990).

Mechanical practices were adopted to support the other practices and to produce an environment which conducts the emergence and development of the vegetation. Normally these practices have a higher cost due to the use of machinery. According to Bezerra, Guerra and Rodrigues (2012b), the construction of soil terraces helps in the retention of concentrated rainfall as well as its dispersion. In the upper part of the slope a group of terraces were constructed to decrease the runoff (Figure 3). In our study case it was recommended that terraces be arranged at an average of 30 meters long starting from the head of the gully to the valley bottom (Silva, 2010).


**Figure 3.** Samples of Mechanical practices used on the experimental site: A - lateral branch of the gully. B - palisades built in the lateral branch. C - vertical walls of the lateral brach. D - scarification of vertical walls. E - Terrace built on the lateral slope. F - Trenches built to fill with mulch. Source: the authors (2022).

The retention of the water flow in these terraces reduces the sediment flow enabling fixation of the plants. Retention basins were built at the end of the terraces. Another practice was the construction of trenches were produced and filled with mulch, as additional barriers to the runoff . In the bottom of the lateral gully channels, palisades were built in order to retain the flow of sediments produced by runoff in the lateral slopes. These palisades were built with intertwined bamboo segments and anchored with bags filled with sediment, thus retaining coarse sediments and allowing water to flow.

Steep and unstable slopes can be observed at the edges of the erosive feature, which do not provide ideal conditions necessary for plant fixation, restricting their growth and propagation. Mechanical re-slope practices (scarification) were used as a way to rework these microrelief, smoothing the slope of the gullie's walls until they present the minimum slope necessary for fixing the vegetation (Machado *et al*., 2014).

Edaphic practices are applied for the improvement of soil fertility. In this study case three techniques were used: organic fertilization, chemical fertilization and green manure (Figure 4). Organic fertilization is extremely important because any type of decomposed organic material could aid in the absorption and retention of water and also add minerals into the soil. Chemical fertilization adds macro and micro nutrients to the soil, but do not improve soil conditions quickly, so it must be adopted together with organic fertilization.

According to Confessor, Machado and Rodrigues (2016) ,green manuring incorporates organic matter from plants grown especially for this purpose. These plants are usually short-cycle cultivated only to be incorporated into the soil after cropping, which generates a large amount of biomass in a short period of time. Normally these plants conduct nitrogen fixation in the soil. In this study case a group of *leguminoseae* were selected to do this function.

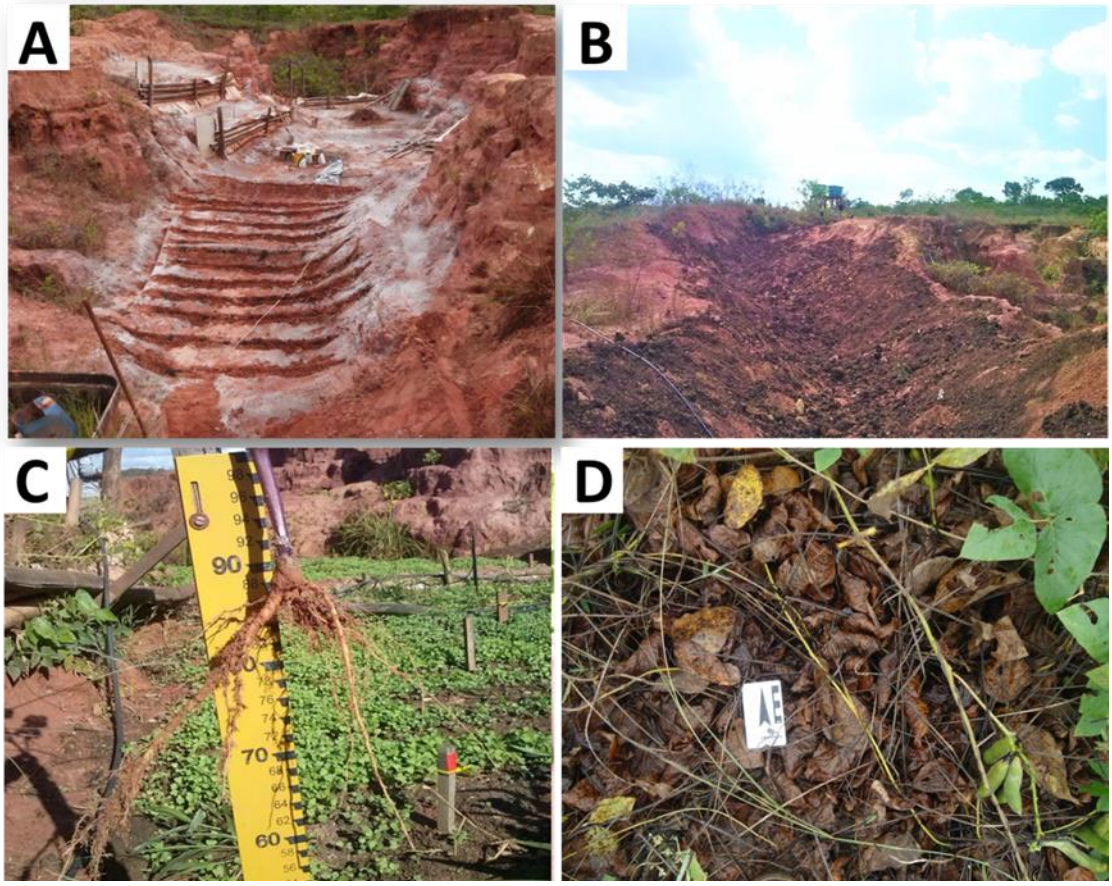

**Figure 4.** Samples of Edaphic practices used on the experimental site: Chemical fertilization and liming (A); Organic fertilization of bovine manure (B); Roots of annual plants (C); Litter cover plants (D). Source: the authors (2022).

Vegetative practices were used to insert a typology of exotic and resistant vegetation (Figure 5), where there were only stony surfaces or bare soil. The main procedure is to provide a base for fixing the roots of the plants. In this sense, an edaphic practice is associated, that is, the mixture of surface sediments with bovine manure, coming from external areas of the same rural property. A set of leguminous and herbaceous plants was selected for this purpose. After experimental tests, the most adapted to the new soil surface were planted.

The revegetation techniques used in the present study also attempted to establish perennial tree cover. Seedlings were planted around the erosion, with the intention of protecting the slopes, reducing the runoff and retaining as much water as possible on the slope. These seedlings try to protect the soil around the gully, fixing the bare soil and providing a vegetal cover of the surface through the production of litter to avoid direct contact with raindrops, minimizing the splash effect.

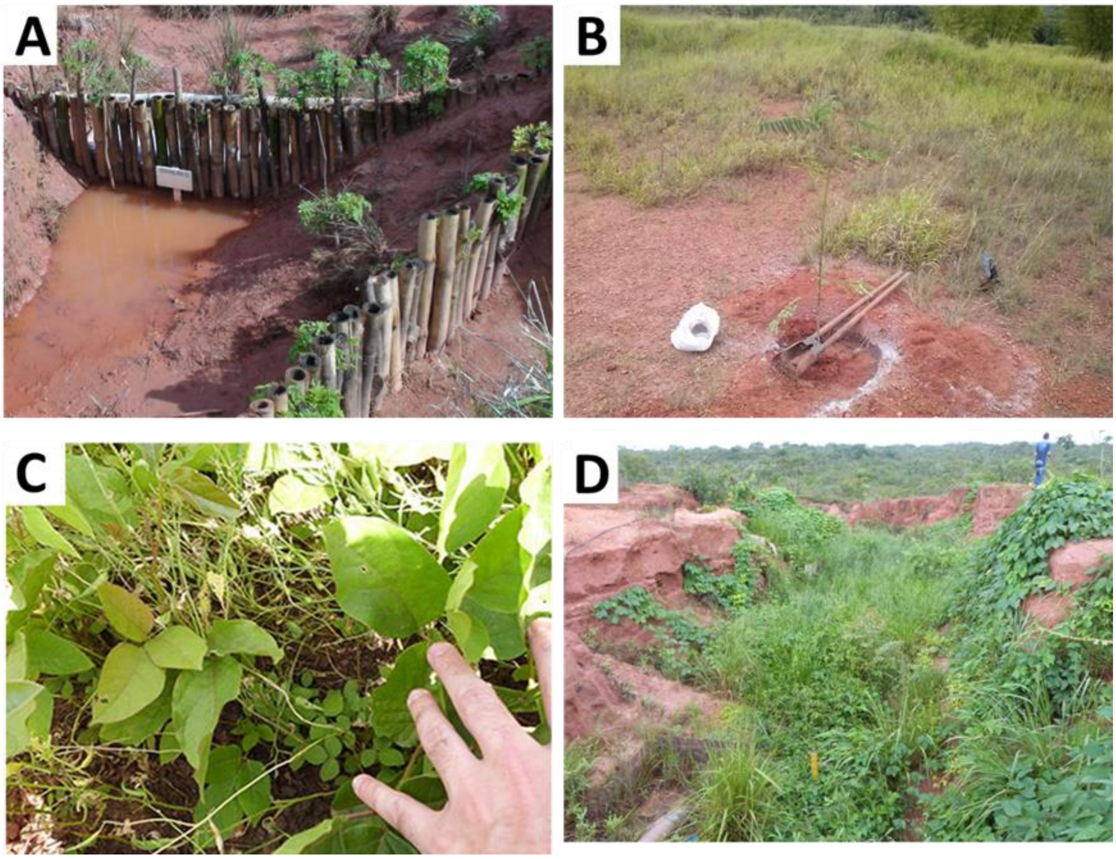


**Figure 5.** Samples of vegetative practices: Planting seedlings in sediment retention barriers (A); Planting of seedlings in areas adjacent to the erosion process (B); Mix of annual plants (C); Result of cover crops (D). Source: the authors (2022).

## 3. Results

After the construction of terraces at the head of the gully, attention was given to the lateral branches. In one of these areas a group of practices was used during 2006. These branches are in constant change, erosive processes are accelerated due to the runoff which contributes to the collapse of the lateral walls of the gully. Barriers to disperse energy from surface flows proved to be efficient, reducing the erosive potential of runoff during rainy events. As an additional effect, barriers can contribute to reducing the loss of clay (and associated nutrients) carried by runoff, and increase the use of water, since retained by the barriers, the water has more time to infiltrate the soil.

The physical characterization and the texture of the soil is presented in Table I. The low fertility at the study area is common in tropical soils and this creates difficulties in the process which try to revegetate and stabilize the surface eroded (Table II).

The construction of palisades inside the side branch of the gully produced excellent results after the implementation of sediment containment techniques. It is noticed that the construction of large palisades at the bottom of the ravines, has the difficulty of accessing the site, as well as the implementation of techniques, since the instability of the bottom and the walls of the gully do not facilitate the installation of experiments because the side walls are affected by landslides.

**Table I.** Soil physical and texture characteristics of the study area. Source: (Silva, 2010).

| Total Density | Particle Density | Porosity | Sand | Silt | Clay |
|---|---|---|---|---|---|
| $g.cm^{-3}$ | | % | | $g.kg^{-1}$ | |
| 1.49 | 2.67 | 44,07 | 886 | 19.5 | 94.5 |

**Table II.** Chemical properties of soil in the study area. SB- Base Saturation; t- Effective cation exchange capability; T- CEC calculation at pH 7.0; V- Base Saturation % (BSP); m-Aluminum Saturation; OM- Organic matter. Source: (Silva, 2010).

| pH | P | K | Ca | Mg | Al | SB | t | T | V | m | OM |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $H_2O$ | $Mg.dm^{-3}$ | | | | $Cmol_c.dm^{-3}$ | | | | % | | $g.kg^{-1}$ |
| 4.9 | 4.2 | 0.02 | 0.25 | 0.1 | 0.5 | 0,37 | 0.87 | 1,5 | 25 | 55 | 5 |

In areas where temporary channels with moist soil for a long time, the implementation of palisades was more productive. Over time, an important volume of sediments accumulated in these areas (Figure 6), demonstrating the effectiveness of the procedure in retaining thin and coarser sediments. With the change in the dynamics in these areas, a recolonization by local species began, in addition to the regrowth of the bamboo used in the construction of the barriers (Figure 7).

The second site chosen for the implementation of the experiments is heavily degraded. The soil was exposed, with sediments at the bottom of erosion and side walls exposed and unprotected due to lack of vegetation. The set of applied practices tried to stabilize the erosive processes in this ravine.

The implementation of edaphic practices included the use of chemical (NPK) and organic (tanned bovine manure) fertilization. Vegetative practices included the selection of 4 species indicated for the initial revegetation, seeking a quick surface coverage and resistance to extreme conditions in the area. In this sense, the following species were selected: Calopogonium (*Calopogonium mucunoides*) and Feijão de Porco (*Canavalia ensiformis*), Mucuna Preta (*Stizolobium aterrimum* ) and Nabo Forageiro (*Brassica rapa*).

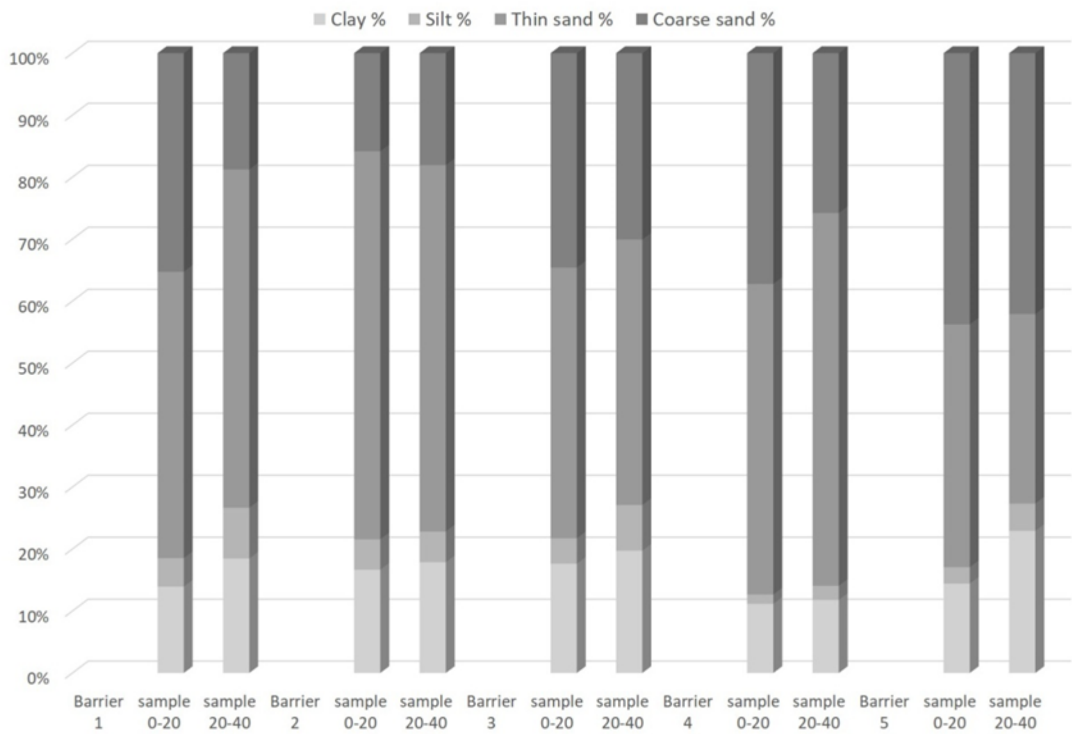


**Figure 6.** Physical characterization of samples of material collected from bamboo palisades in the study area.

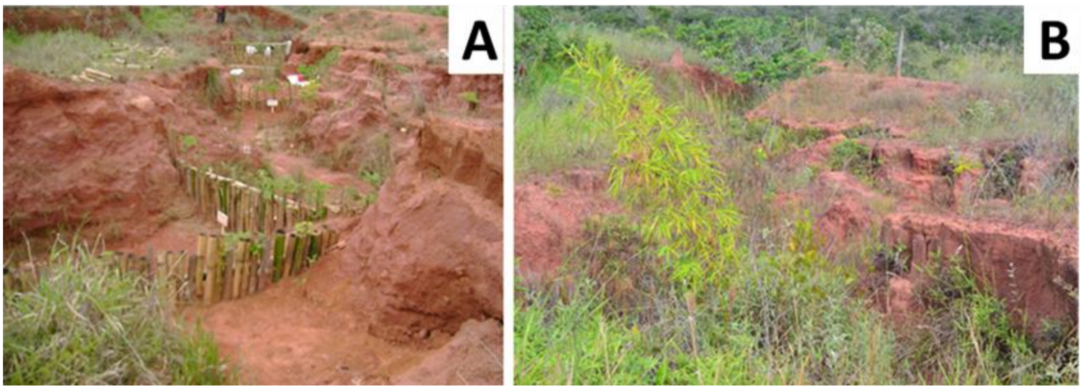


**Figure 7.** Results of Palisade implementation in 2006 (A) and in 2017 (B). Source: Rodrigues (2018).

The revegetation process inside the gully was aided by irrigation. The period of installation of the vegetative practices was carried out in the dry period of the year, avoiding the impact of the storms that characterize the beginning of the rainy period, and that promote strong runoff.

To solve the water deficit and allow the development of vegetation in periods between rains, volumes of water were supplied to the plants through irrigation (Figure 8). The water used in this process was taken from the perennial channel inside the gully. An autonomous hydraulic pump produced enough volume to irrigate the study area in the initial months of revegetation.

The constant supply of water by irrigation helped the vegetative growth within the erosive feature, allowing the development of selected plants as well as invasive species (Figure 8), guaranteeing the total coverage of the soil in a period of 100 days after planting.

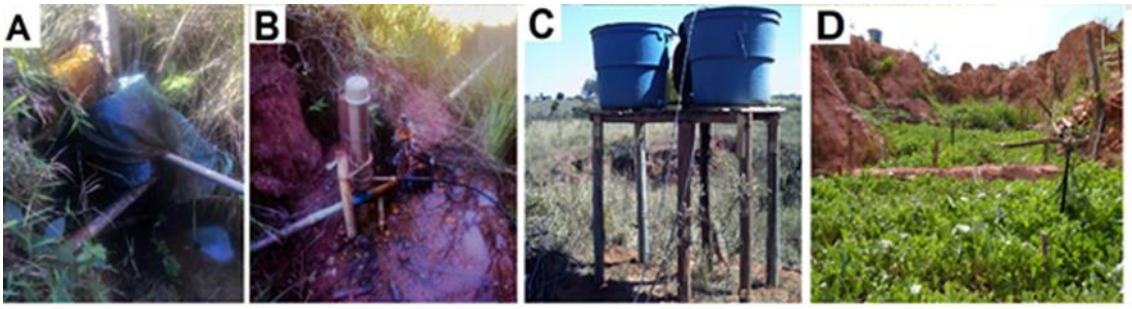


**Figure 8.** Irrigation of the study sites. Water Collection Location (A); Hydraulic Pump (B); Water Storage and Distribution System (C); Initial Irrigation Phase (D). Source: Confessor; Machado e Rodrigues (2016).

The experiment followed the changes that occurred during 280 days, monitoring the evolution of the surface cover, changes in sediment deposition and its textural and chemical composition (Figure 9).

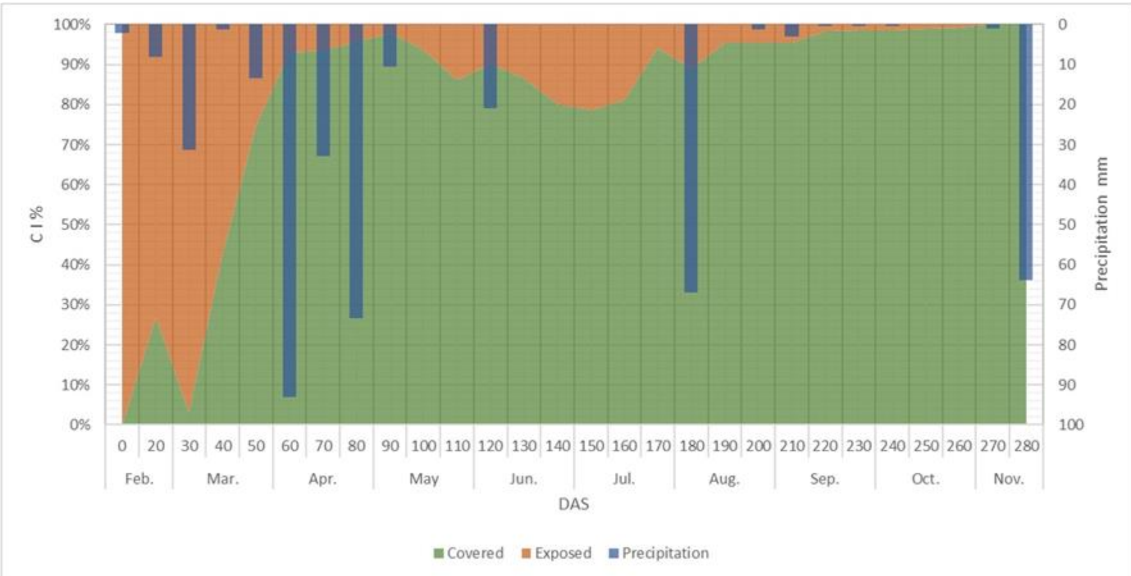


**Figure 9.** Percentage of Land Cover and Ten Days Total Rain in the 280 days of experimental procedures.

The vegetation cover provided by the seed mix showed rapid and continuous growth. The records of fall cover displayed at 30 and 130 days after planting are from ant predation (30 days) and closure of the life cycle of one of the plant species inserted in the site (130 days). After predation, ants were controlled through the use of ant killer during the remaining time of the experiments. In addition to the plants selected for planting, seeds of other species naturally present in cattle manure also became part of the local vegetation. The plant mix produced helped to cover and protect the soil, with values of almost total coverage (98%) being shown at 80 days after planting (Machado, 2015).

In addition to soil protection, edaphic and vegetative practices also contributed to the improvement of the physical and chemical conditions of the soils at the site table III and figure 10. In a comparative study between the pre-experiment and post-experiment degraded area and a non-degraded area with native vegetation, an increase in porosity and Organic Carbon (OC) in the soils after implementation of the practices is noted.

The addition of these attributes contributes to the improvement of soil quality, helping to increase the cation exchange capacity (CEC), infiltration and root growth (Ciotta *et al*., 2003; Andrade and Stone, 2009), generating environments that are more favorable to vegetative propagation.

**Table III.** Bulk Density (Bd), Particle Density (Pd), Total Porosity (Tp) and Organic Carbon (O.C.) of soils.

| | **Bd** | **Pd** | **Tp** | **O.C.** | |
|---|---|---|---|---|---|
| | | | | 0-5 cm | 0-20 cm |
| | g/cm³ | | % | g/kg | |
| Area before the experiments | 1,47 | 2,60 | 43,33 | 3,5 | 3,0 |
| Experiment area | 0,87 | 2,27 | 61,64 | 27,5 | 7,4 |
| Native Cerrado vegetation area | 1,17 | 2,53 | 53,63 | 25,0 | 23,7 |

| Sample | ph (water) | mg dm-3 | | cmolc dm-³ | | | | | | | | V% | m% |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20cm | | P | K | K | Ca | Mg | Al | H+Al | SB | t | T | | |
| before | 4,9 | 4,2 | 6,5 | 0,02 | 0,25 | 0,10 | 0,5 | 1,2 | 0,37 | 0,87 | 1,50 | 25,0 | 55,0 |
| after | 6,1 | 21,4 | 20,50 | 0,06 | 1,25 | 0,25 | 0,0 | 1,1 | 1,56 | 1,56 | 2,66 | 57,3 | 0 |
| very low | | low | | | medium | | | high | | | very high | | |

**Figure 10.** Soil chemical attributes before and after interventions. Parameters for the classification of results adapted from Sousa, Lobato (1994) and Machado (2015).

In addition to allowing the growth of the implanted vegetation, the favorable conditions generated by mechanical, edaphic and vegetative practices provided the establishment of new ecosystem relationships in the place. Plant species present in areas surrounding the erosion process began to occur in places where recovery practices were installed.

This process of vegetative succession occurred spontaneously (Figure 11 A). The new species established themselves in the area through seeds present in cattle manure, eventual seeds present in excrement of animals that defecated in the area (such as birds and small mammals) and/or arising from the action of wind scattering.

With the diversification of vegetation, there was an increase in the supply of food and shelter for the animals. It was possible to observe in the recovery areas, the return of the local fauna, with the presence of insects, birds, reptiles and mammals (Figure 11 B and C). Below the surface, the addition of organic matter to the soil made food available for pedofauna, generating organic residues, reworking the unconsolidated topsoil, generating a layer of aggregates 5 to 10 centimeters thick (Figure 11D).

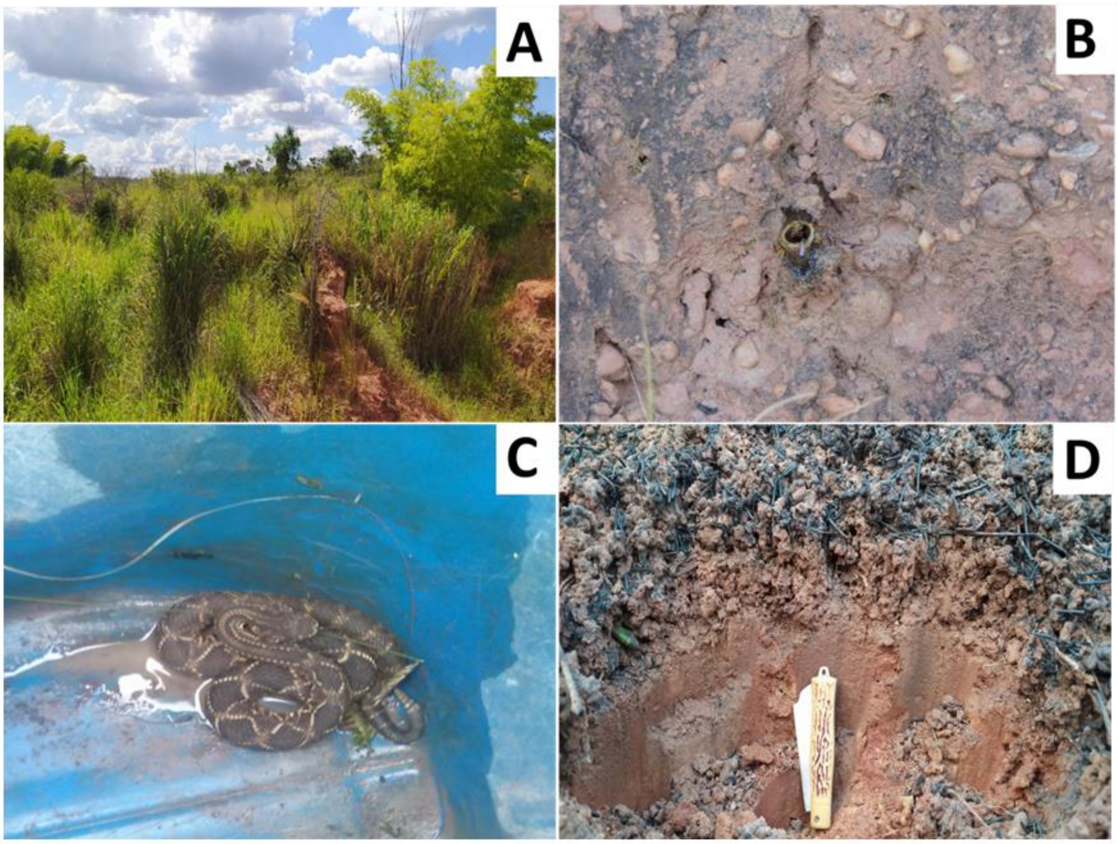


**Figure 11.** Ecological improvement: Vegetative succession of the Experimental Area (A); Endogenous bee hive(B); Rattlesnake Serpent (C); Soil aggregates derived from earthworm(D). Source: the authors (2022).

**4. Conclusions**

It is notable that all the practices adopted to control the advance of the lateral walls and the production of sediments in the gullies were partially successful during its implementation. Notably, it is perceived that the erosive feature must be treated as an integrated set where it receives direct influence from its parts and surrounding areas.

Although some experiments did not have direct success, they provided favorable conditions for the appearance and stabilization of the area, even the barriers that deteriorated over time, were able to provide conditions for the appearance of vegetation, so that it started to fulfill the role of retaining the sediments and protect the soil, replacing barriers in this function. And even if the vegetation that was inserted in the place did not settle or have been replaced by invasive species, these ended up providing better physical-chemical conditions of the soil, the texture of the surface material, retention of moisture in the soil and creation of conditions ecological conditions for ecological succession to occur.

The recovery of degraded areas demands knowledge, involvement, time and money, but the alternative measures pointed out in this research show ways to reduce costs, proving their effectiveness, since they provided favorable conditions for the fixation of native or exotic plants in addition to promoting the gully stabilization.

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**Chapter 3. Forest fires in Portugal**[9]

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**Introduction**

Wildland fires are a generalized and recurrent problem. Although wildland fires are characteristic of certain regions and seasons, vegetation fires occur with varying regularity and severity across almost every biome on Earth (Archibald *et al*., 2013). It has been estimated that more than 30% of the global land surface is subject to a considerable frequency of vegetation fires (Chuvieco *et al*., 2008).

Li *et al*. (2013, 2014) argue that fire is an important Earth system process and the primary terrestrial ecosystem disturbance agent on a global scale. Earth's forests and vegetation provide a vast source of fuel, and fires consume huge quantities of biomass in all ecosystems ranging across all biomes, from tundra to savanna and from boreal to tropical forests, where many of our ecosystems are considered fire dependent (Belcher, 2013).

Fire has been burning ecosystems for hundreds of millions of years, helping to shape global biome distribution and to maintain the structure and function of fire-prone communities. It is clear that for millennia vegetation fires were a natural phenomenon (Pausas *et al*., 2008) and there is unambiguous evidence that wildfires go back to the Famennian Age (Devonian/Carboniferous periods) (Jones and Rowe, 1999).

Fire is also a significant evolutionary force, and is one of the first tools that humans used to re-shape their world (Bond and Keeley, 2005). It is both friend and foe to the human race, having strongly influenced our social development and success as a species, yet it remains a serious threat to human life (Belcher, 2013). Fire is a part of many ecosystems (Bento-Gonçalves *et al*., 2012), and it has served forest thinning throughout time, both for agriculture and grazing, thus taking on the role of crucial "ecological factor" for development or regression of forest systems around the world. While humans have altered fire regimes since their early history, recent decades have been marked by rapid-fire regime changes as a result of significant shifts in human population, particularly with respect to growth, socioeconomic factors, and land management (Pausas and Keeley, 2004).

[9] This text is partially based on the works previously published by the authors and other collaborators, namely Vieira and Bento-Gonçalves (2015; 2020), Bento-Gonçalves et al. (2011; 2015), Ferreira-Leite et al. (2015a; 2015b).

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Even today, in some climates, fires are a natural phenomenon, but most of the fires are caused by human activity and only a minor part is produced by environmental factors (FAO, 2001). Equally, an only relatively small number of forest fires are responsible for the very high proportion of the total damage (Strauss *et al*., 1989).

Due to the high number of natural and human variables directly and indirectly involved and the complex interactions that take place amongst them (Pyne *et al*., 1996), the study of wildland fires is extremely complex and difficult.

The magnitude of a wildfire – which can be measured in terms of physical parameters such as the rate of spread or the fireline intensity or in terms of its direct consequences (e.g., the area burnt) – is also conditioned by factors of diverse origin such as climatological, topographic, social, economic or thermodynamic (Planas and Pastor, 2013).

Pausas & Schwilk (2012) argue that throughout much of the history of ecological science, wildfires were viewed as disasters that destroyed ecosystems. Currently, however, most scientists and managers have overcome this shortsighted view and now consider fires as ecological processes that influence structure and function in many ecosystems worldwide.

Interest in fire research has become global and interdisciplinary due to influences, interactions, and feedbacks among fire, terrestrial, and atmospheric systems in the context of human health (Malilay, 1999; Bowman & Johnston, 2005; Amiro *et al*., 1996; McMahon, 1999; Mott *et al*., 1999), climate dynamics (Bergeron & Flannigan, 1995; Larsen, 1996; Flannigan *et al*., 1998; Behling *et al*., 2004; Flannigan *et al*., 2005; van der Werf *et al*., 2006; Power *et al*., 2008; Lavorel *et al*., 2006), and policy adaptation (Xanthopoulos, 2007; Stephens & Ruth, 2005; Moritz & Stephens 2008).

In fact, fire regimes – and their direct and indirect effects – are influenced by: changes in climate (and concomitant change in natural ignition rates); the spread of naturalized exotic plants (affecting fuels); the changed distributions of native plants and fuels; and changes in human populations (affecting changes in land use, fragmentation and frequency of human caused ignitions). These factors will influence the areas of fires but how they do so will vary widely, increasing the potential for large fires in some places, decreasing it in others (Gill & Allan, 2008).

Recent work has begun to synthesize common trends in environmental influence on fire across broadly different locations, but the comprehension of overarching biophysical controls on global fire activity is still limited. The collection of fire data by remote sensing provides an archive from which to examine global patterns of wildland fire, such as differences between areas of the planet where fire occurs and those where it does not.

Krawchuk *et al*. (2009) characterized the observed global fire occurrence pattern (Figure 1). The results provide a novel multivariate framework to describe where we currently see wildland fire across the planet.

In recent years, extreme fire seasons have resulted in substantial impacts on human lives and properties in Portugal in 2003, 2005 and 2017, Greece in 2007 and 2019, in Australia in 2009 and 2013 and in the USA in 2007 and 2013 (Cary *et al*., 2003; Keeley *et al*., 2004; Maditinos & Vassiliadis, 2011; Cruz *et al*., 2012). The impacts of fires largely depend on the fire's characteristics (e.g., size, heat released, duration and intensity). Larger fires are the result of more extreme conditions (high fuel availability, low humidity, high temperatures and high wind speed) and they are therefore often more intense and have greater impacts than smaller fires.

Hantson et al. (2015) produced a global map of the fire size distribution as estimated by β of the power law (Figure 2), with low β-values indicating distributions with a higher frequency of large fires. The authors showed that both human and natural factors determine the global pattern of the fire size distribution.

Clear spatial variations can be observed, with sometimes rather sharp transitions between different regions. Some clear spatial patterns that coincide with some of the global biomes arise: low β-values are observed in boreal areas and areas with little vegetation cover (e.g., southern Africa, Australia), and the highest values are mainly observed in tropical savanna and woodland areas and temperate agricultural areas.

In a relative sense, the area of fire considered to be 'large' may be linked to the upper range of fire areas that cover a certain large proportion of the area burned by all fires (Gill & Allan, 2008): in the United States, only 1 or 2% of all wildland fires become large incidents, but they account for about 85% of total suppression-related expenditures and upwards of 95% of the total acres burned (Williams & Hyde, 2009).

Similar relationships exist elsewhere. In Canada, only 3% fires reach a final size greater than 200 hectares, but these represent 97% of the area burned'(Stocks *et al*., 2002); in western USA, Strauss *et al*. (1989) reported that 80–96% of the forest area was burned by 1% of the fires, and, also in western USA, large grassland fires burned more than 70% of the total area burned (Knapp, 1998); in Mediterranean basin, large forest fires are becoming more and more frequent and are responsible for most of the overall area burned over the last 20 years as a consequence of global change (Piñol *et al*., 1998; Pausas, 2004), in 2004 mega-fires burned up to 25,899 ha in Portugal and up to 2,500 ha in Spain, each time, by a single fire event, one year later, they burned up to 17,388 ha in Portugal and more than 12,000 ha in Spain, and the number of large fires (>100 ha or >500 ha depending on the works) represented less than 1% of the total number of fires (Moreno *et al*., 1998; Díaz-Delgado *et al*., 2004; Pereira *et al*., 2005; De Zea Bermudez *et al*., 2009, Ferreira-Leite *et al*., 2013).

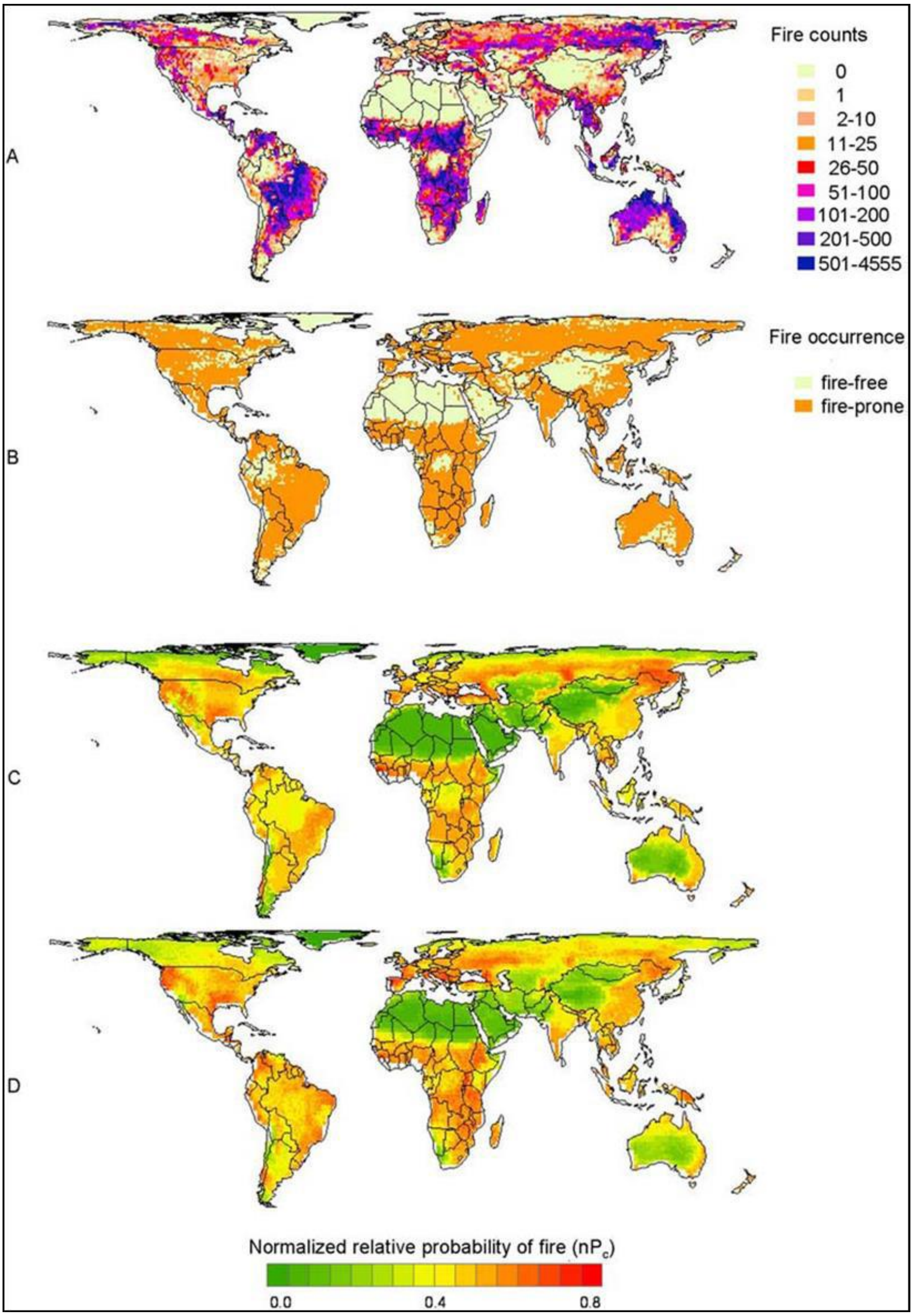


**Figure 1.** The observed and modeled distribution of fire under current conditions. (A) Cumulative counts of fire activity detected by the Along Track Scanning Radiometer (ATSR) around the world at a resolution of 100 km over 10 years. (B) The same fire data classified to represent fireprone (orange) and fire-free (yellow) parts of the world; note that areas of white within terrestrial boundaries were clipped from the analyses to match climate data. (C) Mean of normalized relative probability of fire (nPc) for ten FIRENPP sub-models of fire-prone parts of the world under current conditions. (D) Mean of normalized relative probability of fire (nPc) for ten FIREnoNPP sub-models of fire-prone parts of the world under current conditions (Krawchuk *et al*., 2009).

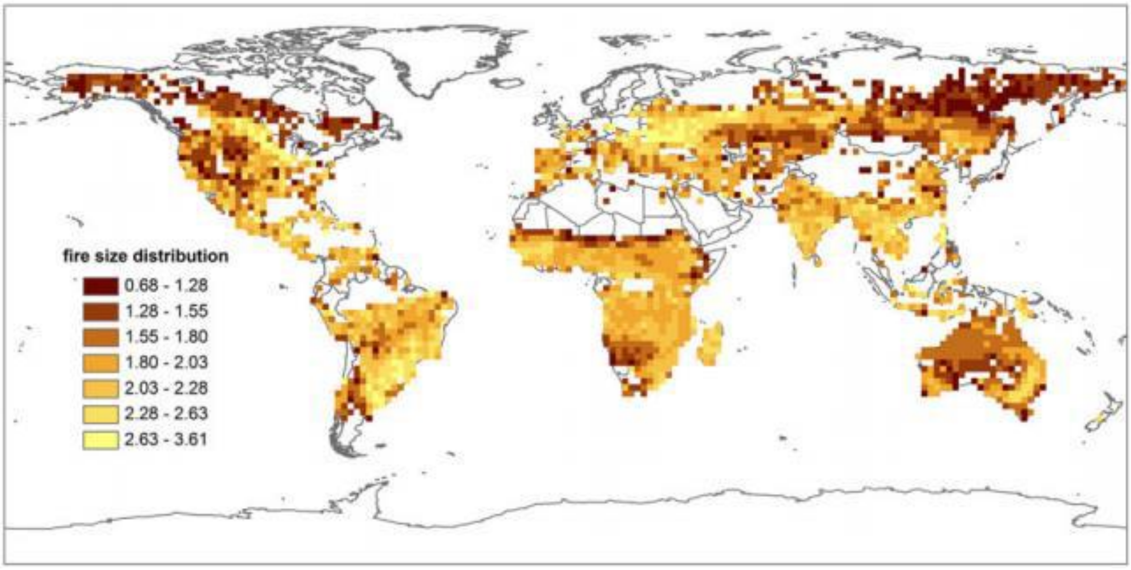


**Figure 2.** Global map of the fire size distribution as estimated by β of the power law, fitted to the fires in each grid cell. Areas with low or absent fire occurrence, where the power law could not be fitted, are marked in white (Hantson *et al*., 2015).

## 1. Wildland fires in Portugal

Over the millennia Portuguese woodlands revealed an evolution pattern typical of the Mediterranean region. It was characterized by the destruction of the original forest species by frequent fires and its subsequent replacement by pastoral fields, the use of the best soils for cereal cultures, and he use of timber for fuel and construction (Rego, 2001). The deep-seated relationship between humans and their vegetation is evident in the Portuguese territory.

Humans have shaped their land cover, particularly through the use of fires, in accordance with their needs (Cordeiro, 1990). Accordingly, the transformation of the land cover by humans has been increasingly discernable. From the mountain peaks to the peripheral lowlands (Daveau, 1988, Devy-Vareta, 1993), archeology has reconstituted the establishment and organization of society in the bronze and iron ages and demonstrated societies diverse economic activities throughout the ages (Jorge, 1982). The general tendency of dislocation was accentuated after the Middle Ages. The principal causes identified for the destruction of the Portuguese forests was "the growing populations' increasing requirements of wood for housing and cooking" and the "greater need for arable land for agriculture" (Andrada and Silva, 1815). The first written references on forest fires in Portugal are from the end of the Twelfth Century and they identify the disparaging effects that fires had in transforming the majority of the Portuguese land cover.

### *1.1. Evolution of Wildland fires in Portugal during the 20th century*

The increase of forest fires in mainland Portugal (in public woodlands) has been particularly flagrant since the 1970s. From a yearly average of 72 outbreaks and 1,205 ha of burned area, occurred in the period between 1943 and 1970, we witnessed an huge change during the decade of 1971 to 1980 (Table I, Figure 3), when fires consumed 26,764 ha (annual average), resulting from 726 outbreaks (annual average).

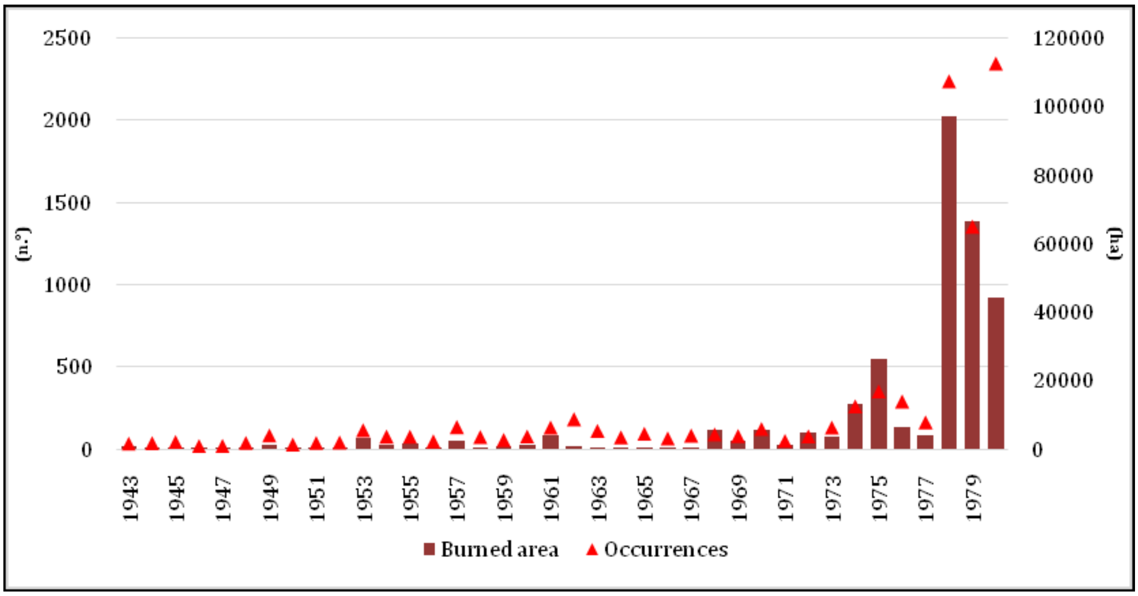


**Figure 3.** Evolution of the number of annual occurrences of forests fires and burned area in mainland Portugal between 1943 and 1980. Source: Natário, 1997; ICNF, 2013.

This marked increase in the number of forest fires and burned area resulted from a plethora of factors, many of which are the result of the profound social and economic changes in the Portuguese population, particularly in those living in forest areas.

In fact, beginning in the 1970s, many of these changes were verified in several southern European countries, particularly in the Mediterranean region. The rural exodus initiated in the 1960s led to a decrease in grazing and pastoral activities and the subsequent accumulation of fuels in the Portuguese woodlands (Lourenço, 1991; Vélez, 1993; Moreno *et al*., 1998; Rego, 2001). The transformations in the traditional land use patterns and lifestyles of the local populations led to a significant increase of abandoned agricultural areas. On one hand, this resulted in the recovery of the natural vegetation and the increase in the accumulated fuel in the traditional forest areas (Lourenço, 1991; Rego, 1992; García-Ruiz *et al*., 1996; Roxo *et al*., 1996). On the other hand, it naturally increased the area of woodlands. Many of these areas were transformed into spaces that were prone to large fires during the summer months due to the high levels of biomass that had accumulated throughout the years.

**Table I.** Evolution of the number of annual occurrences of forests fires and burned area in mainland Portugal between 1943 and 1980. Source: Natário, 1997; ICNF, 2014.

| | Occurrences (total) | Burned Area (total) |
|---|---|---|
| | Number | Hectares |
| 1943 | 32 | 868 |
| 1944 | 35 | 95 |
| 1945 | 42 | 422 |
| 1946 | 17 | 109 |
| 1947 | 18 | 151 |
| 1948 | 36 | 297 |
| 1949 | 82 | 1,258 |
| 1950 | 26 | 73 |
| 1951 | 36 | 176 |
| 1952 | 38 | 170 |
| 1953 | 113 | 3,024 |
| 1954 | 75 | 1,176 |
| 1955 | 74 | 1,438 |
| 1956 | 46 | 272 |
| 1957 | 133 | 2,220 |
| 1958 | 73 | 472 |
| 1959 | 54 | 892 |
| 1960 | 76 | 1,318 |
| 1961 | 130 | 3,932 |
| 1962 | 181 | 868 |
| 1963 | 110 | 95 |
| 1964 | 70 | 422 |
| 1965 | 92 | 109 |
| 1966 | 63 | 151 |
| 1967 | 81 | 297 |
| 1968 | 88 | 5,581 |
| 1969 | 79 | 2,375 |
| 1970 | 121 | 5,490 |
| 1971 | 49 | 1,014 |
| 1972 | 76 | 4,978 |
| 1973 | 130 | 3,679 |
| 1974 | 258 | 13,133 |
| 1975 | 350 | 26,417 |
| 1976 | 289 | 6,514 |
| 1977 | 162 | 3,983 |
| 1978 | 2,241 | 97,344 |
| 1979 | 1,355 | 66,330 |
| 1980 | 2,349 | 44,251 |

### *1.2. Evolution of Wildland fires in Portugal: the recent reality*

Since more systematic and rigorous statistical information became available in the 1980s, data on the number of fires and burned area have registered very diverse results (Figure 4).

A significant and continued increase in the number of fires has been registered since the early 1980s. This increase is not due only to the greater generalization of quality of the statistical information. We highlight the years 1995, 1998, 2000, and 2005 due to their unusually high values (above 30,000 occurrences). These values result not from favorable meteorological conditions to ignition. In fact, when analyzing the number of occurrences, we can verify that while in 1991 there were significantly less occurrences than 1989, prior to 2003, it registered the greatest amount of burnt area – in part explained, but not justified, by meteorological phenomena (Lourenço, 2011). Similar comparison we can make between 2003 and 2004, with an identical number of occurrences but very different values of burned area.

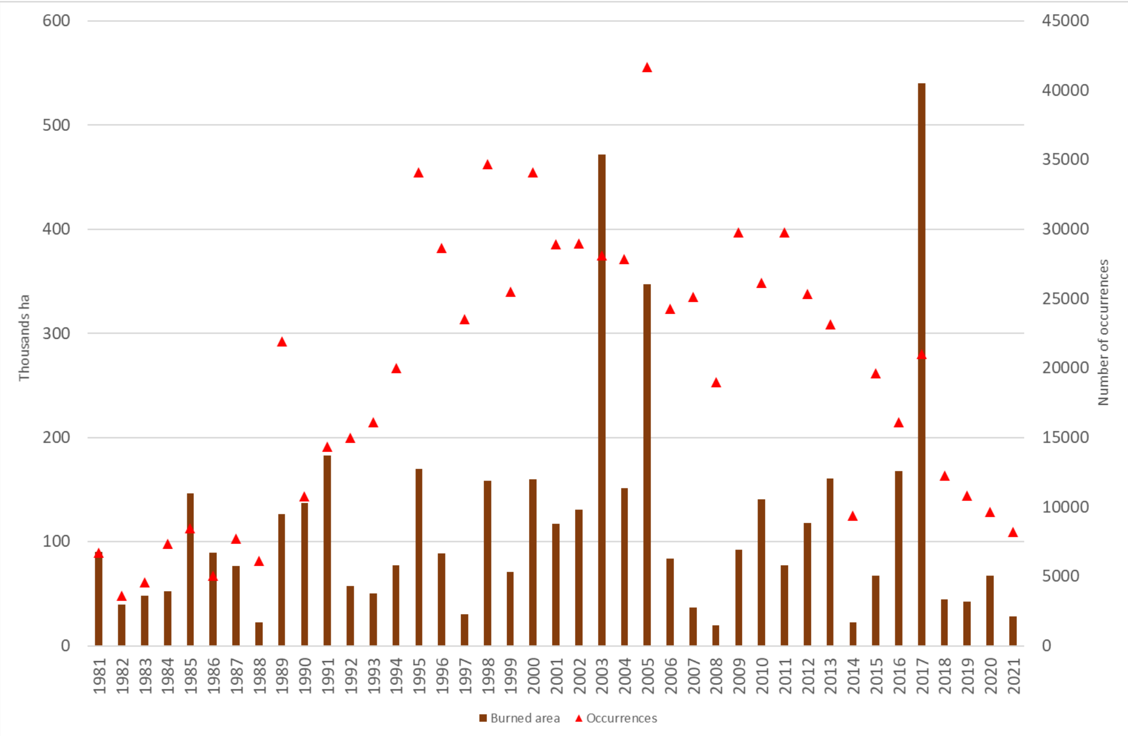


**Figure 4.** Total number of occurrences and burned area in mainland Portugal between 1981 and 2021. Source: ICNF, 2022.

In the beginning of the twenty-first century there was a substantial reduction in the pattern of the growing number of fires – if we consider that 2005 was an anomaly, just as 1989, 1995, 1998, and 2000 were. The year 2005 stood out due the fact that it countered the tendency for a reduction in the number of occurrences verified in Portugal since 2001. After 2011 this tendency became even more evident.

However, regardless of that decrease, since 1995 the yearly number of fires in Portugal has continued to be over 20,000. In the years following 2005, the number of fires decreased to 14,930 (in 2008), the lowest value since 1991 (14,327). The most recent years analyzed, corresponding to the second decade of the current century, seem to confirm the recent pattern of reduction in the number of fires. As a matter of fact, since 2018 the number of fires has progressively been falling below the 15.000.

In the long run, and considering 2021 as the upper limit, a tendency towards the increase in the number of fires is apparent, although not very marked. The regression analysis shows a correlation ($R^2$) of 08.83% between the number of occurrences and the temporal evolution (Figure 5).

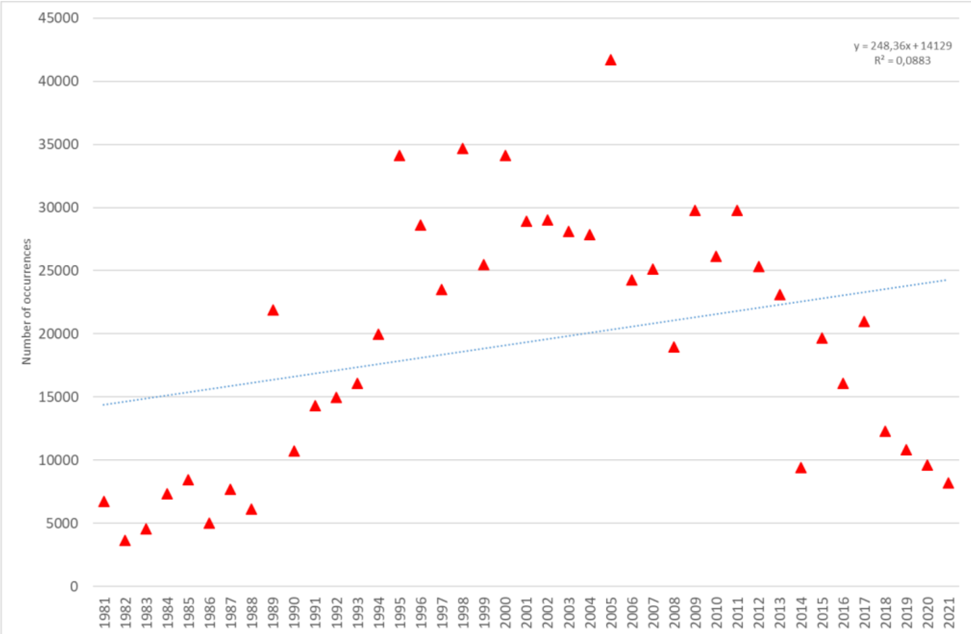


**Figure 5.** Evolution of the number of forest fires in mainland Portugal between 1981 and 2021 and the coefficient of determination ($R^2$). Source: ICNF, 2022.

Regarding the burned areas, the regression analysis ($R^2$=2.03%) confirms a tendency towards the consolidation of the values of burned area throughout the previous years. This can be explained by the large variations registered during this period (Figure 5).

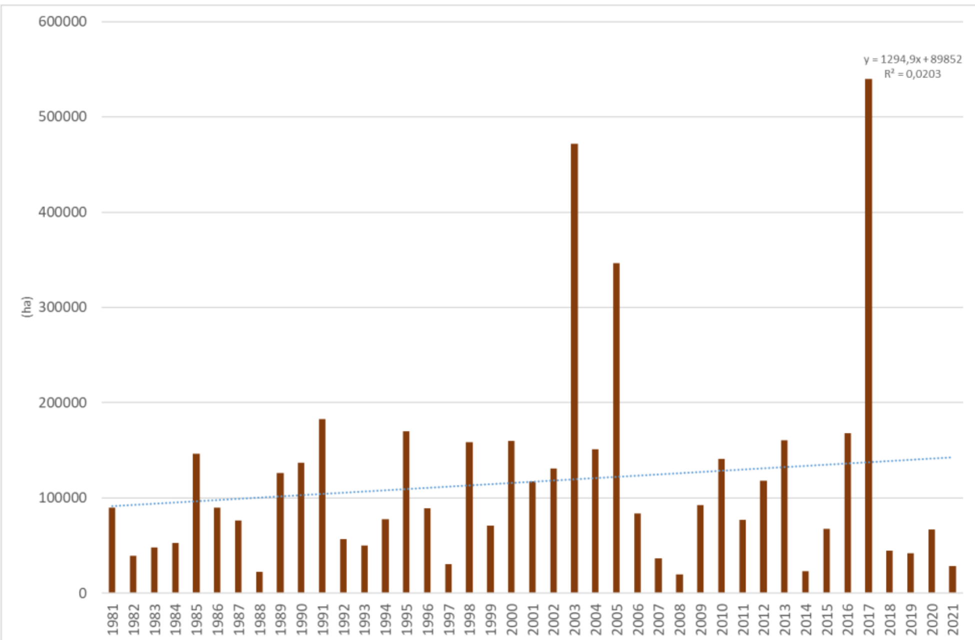


**Figure 5.** Evolution of burned area in mainland Portugal between 1981 and 2021 and the coefficient of determination ($R^2$). Source: ICNF, 2022.

The minimal values registered in the years 1988, 1997, 2007, 2008, 2014, and 2021 (below 33,000 hectares), which are attributed to less favorable meteorological conditions for the propagation of fires rather than other factors, should be emphasized. On the other hand, the extreme values registered in 2003, 2005, and 2017 which cannot be explained solely due to meteorological conditions, should also be highlighted (Lourenço, 1988).

In reality, in 2003, in certain regions of mainland Portugal the meteorological conditions were highly favorable to the occurrence of forest fires. In that year there were two very intense heat waves in late July and early August that registered very high temperature minimums and maximums and very low relative humidity. As we have verified in the recent years, these conditions are for the most part susceptible to the development of critical situations which favor the outbreak of forest fires (Pinto Gomes, 2001; Pereira & Santos, 2003; Santos *et al*., 2003; Lourenço, 2007). Accordingly, 2003 marks a watershed in terms of forest in fires in Portugal, particularly regarding large forest fires.

Moreover, 2005, which had an extended period of drought (from the beginning of the year until November), also presented much higher values than the previous years. Together, these two years, registered over 300,000 hectares of burned area (425,839.1 hectares in 2003 and 339,088.9 in 2005). Whilst the 2003 and 2005 have been considered "anomalies," the fact is that 2005 marked the sixth consecutive years in which burned areas covered over 100,000 hectares, as well as the sixth time since 1968 that burned areas covered over 150,000 hectares and the second time areas over 300,000 hectares were scorched.

The year of 2017 was equally marked by two periods of extreme heat, one of them throughout the month of October, resulting in several large forest fires, an accumulated burned area of 539,921 hectares (the worst year ever in terms of total burned area), aggravated by an unprecedented number of fatalities (115 victims).

Following the same pattern associated with the number of occurrences, there was also a steady reduction of burned areas in 2006, 2007, and 2008. This phenomenon was in large part due to the meteorological conditions which were not propitious to the outbreak of fires.

In the following years, a large variation in the size of the burned areas was verified. The years of 2009, 2011, 2014, 2015, and 2018-2021, with values of burned area below 100,000 ha, intercalated by 2010, 2012, 2013, 2016 and 2017, with burned areas above 100,00 ha (value largely overpassed in 2017).

*1.3. Some considerations on the Portuguese wildfire reality*

The main factors conditioning forest fires in mainland Portugal are meteorological (Rebelo, 1980; Bradstock, 2010; Carvalho *et al*., 2008) because, to a greater or lesser extent, they influence all the other physical variables, in particular, the condition of the fuels.

However, in Portugal, forest fires have also long been associated with cultural and social and economic factors which, due to action or inaction, have abetted the ignition and especially the spreading of fires throughout the landscape (Moreno, Vázquez & Vélez, 1998; Romero-Calcerrada, 2008; Vélez, 1993).

These factors result, first of all, from the profound transformations in the populations residing in forest areas. This transformation has been particularly acute since the beginning of the industrial development in the 1960s (Cravidão, 1990). This makeover led to a considerable decrease in the populations living in forest areas. Moreover, besides demographic changes regarding age, social, and economic structure, economic activities also were transformed. The primary sector witnessed a significant reduction, particularly the agropastoral activities directly related to interventions in the woodlands. In contrast, the industry and service sectors had a significant increase, following a trend common to southern Europe.

Consequently, there was a significant change in the traditional social practices associated with the rural economy. More precisely, the traditional relationship between agriculture and woodlands was deeply transformed. Practices such as cleaning forest areas, gathering of firewood and other forest products, small-scale herding in the woodlands, and the removal of weeds and other material had, by tradition, eliminated the accumulation of highly flammable biomass from the forest spaces (Lourenço, 2006).

Besides the factors above, it is worth highlighting the property structure in Portugal. The bulk of the national forests are divided into small-size properties which significantly hinders the management of theses spaces. Above all, the small size of the properties decreases the potential revenues obtained from the land and, consequently, lead to their neglect and abandonment (Baptista & Santos, 2006). The lack of an associative tradition in Portugal, where 90% of the forest space is privately owned, also obstructs the centralized management of these areas and their respective development. This fact, associated with an incorrect management of forest areas, also has contributed to hampering successful firefighting initiatives and devaluing the social, economic, and environmental utility of these spaces.

Another factor hindering the implementation and efficacy of forest fire mitigation measures is the composition of Portuguese woodlands (principally Pinus pinaster and Eucalyptus globulus) which have a high degree of combustion and a dense land cover.

In conclusion, the population exodus from rural areas has greatly contributed to the abandonment of agricultural lands and woodlands and, therefore, created the necessary conditions for the outbreak and dissemination of forest fires (Vélez, 2006). Over the last few decades, we have witnessed several important transformations which have homogenized the Portuguese landscape, namely changes in land use and the reorganization of rural areas through the conversion of traditional agricultural activities which had compartmentalized and structured the national woodlands into dense, continuous, and mono-specific forest areas (Guiomar *et al*., 2006).

The increasing "urbanization" of rural areas, i.e., the growing sprawl of urban areas into forest spaces, also increase the risk of fires (Caballero, 2007; Lampim, 2009).

All these changes had profound social, economic, and environmental consequences (Lourenço, 1991; Alves *et al*., 2003). Moreover, they were also complemented by a transformation in the rural population's attitude towards fires.

## 2. Wildland Fires in the Portuguese northwest

Forest fires have been a plague that has indelibly affected the national territory. Every year thousands of hectares of forest and scrubland are consumed by fire, destroying the vegetation cover and exposing the soil, making it vulnerable to erosive processes. The impacts they suffer result not only from the direct effects of fire, but also from the erosive processes that occur afterwards.

Year after year, Portugal has been witness to this reality, for if until 1986 we had never been plagued by a fire larger than 10,000 hectares, 2003 saw the 20,000 hectares mark pass, and 2017, twice, the 38,000 hectares mark.

The geographical distribution of the number of forest fire occurrences in Northwest Portugal is not uniform, with the total number of occurrences being higher in the more urban municipalities, and there is a positive correlation between the number of occurrences and the number of inhabitants (APIF/ISA, 2005).

The distribution of burned areas in the Northwest is also characterized by the existence of a marked difference between the most and least mountainous counties.

Considering the last two decades, and regarding the evolution of the number of fires in the Portuguese Northwest, we can see a high number of occurrences, which translates into a total of 165,390 occurrences in the period from 2001 to 2020, which represents 40.40% of the total national number of occurrences. As for the total burned area recorded in the Northwest from 2001 to 2020, 449,293 hectares were recorded, corresponding only to 15.6% of the total burned area recorded for the country in the same period (Figure 6 and 7).

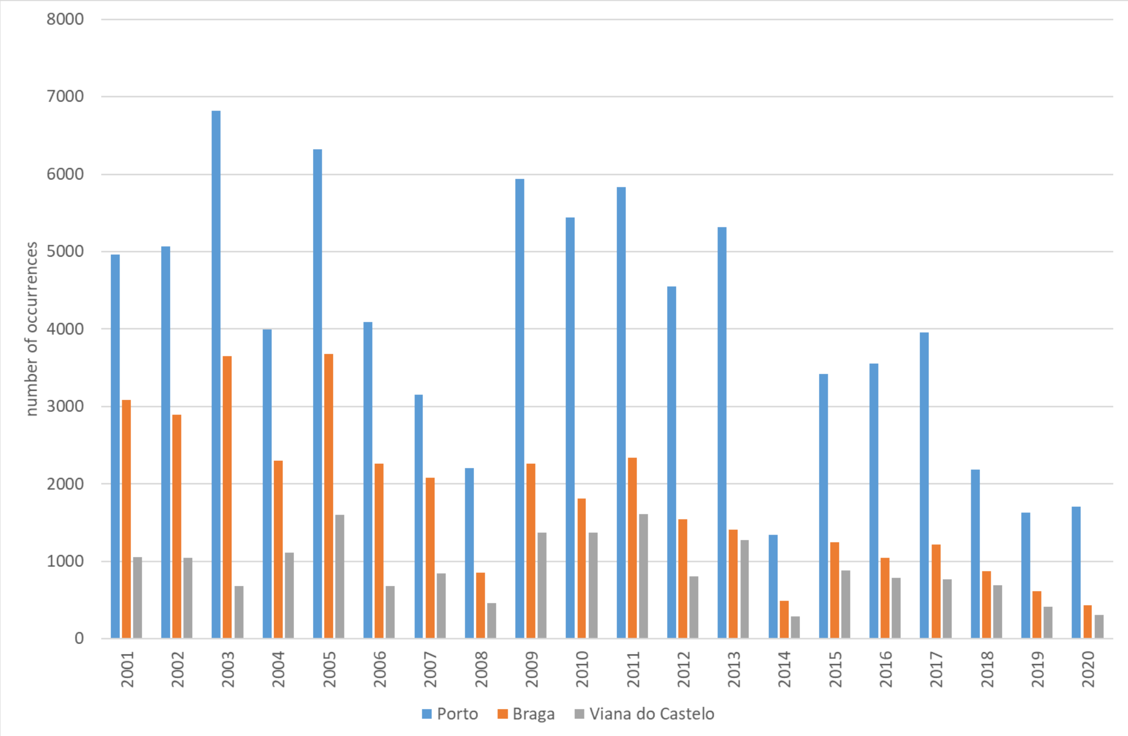


**Figure 6.** Evolution of the number of occurrences in the Northwest, from 2001 to 2020. Source: ICNF, 2020.

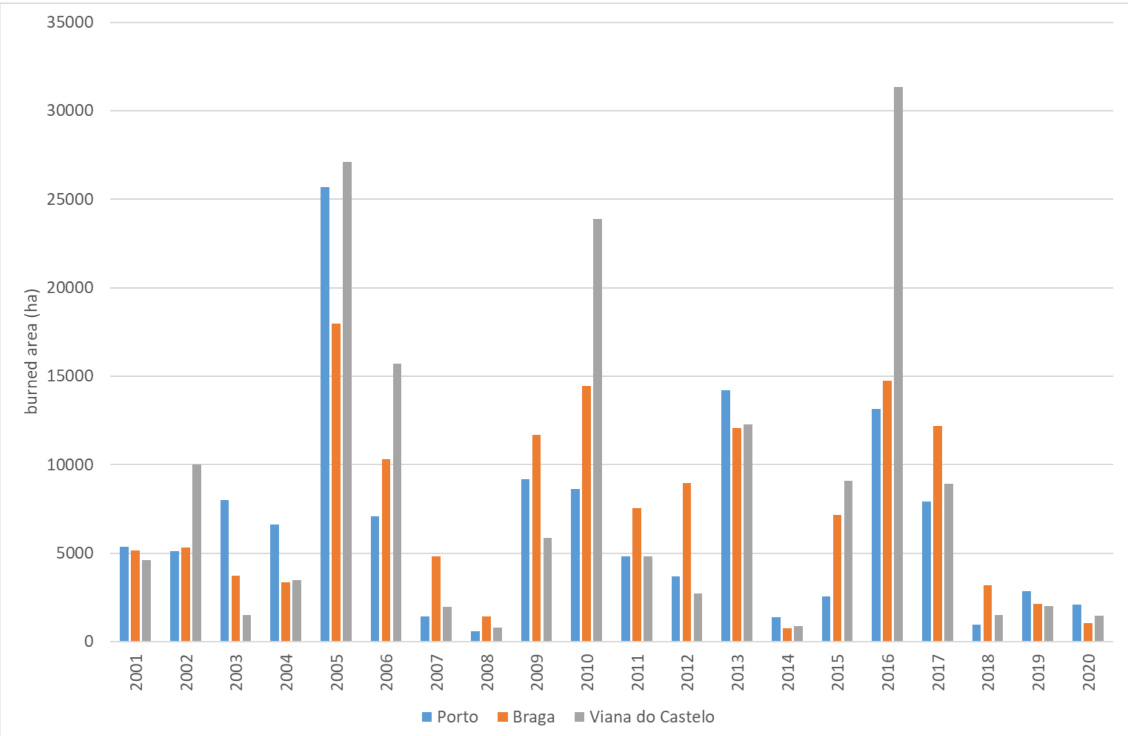


**Figure 7.** Evolution of the burned area in the Northwest, from 2001 to 2020. Source: ICNF, 2020.

When we analyze the number of occurrences for mainland Portugal, and although some differences can be observed in each of the districts, it can be seen that the Northwest generally follows the pace of the rest of the country, with 2003 and 2005 standing out as the years with the highest number of occurrences recorded between 2001 and 2020. Thus, in mainland Portugal, 20,896 occurrences were recorded in 2003 and 27,631 in 2005, while in the Northwest there were 11,149 and 11,598 occurrences, respectively. However, we can state that for this period there is a tendency for the number of occurrences to decrease over the years (Figure 6).

Regarding the burnt areas in the Portuguese Northwest (2001-2020), the years 2005, 2010 and 2016 have the highest values, above 45,000 ha, and it is interesting to note that unlike what happens for the whole country, where the years 2017 and 2003 have the highest values of the series (with more than 540. 000 ha and more than 470,000 ha, respectively), the Northwest presents relatively low values (29,033 ha and 13,233 ha, respectively) and it is in 2005 that the maximum value of burnt area is reached (70,746.36 ha) (Figure 7).

The evolution of the area of burnt forest stands is marked by annual variations, between 2835.04 ha (recorded in 2008), which is the minimum value of the series, and 70,746.36 ha (in 2005), the maximum value of the series. There is, however, a very slight tendency for the decrease of burnt areas in this period in the Northwest of Portugal.

In conclusion, in Northwest Portugal there is an annual variability of the burnt areas, as well as of the forest fire occurrences, although there is a trend, in the last two decades, towards a reduction, albeit not significant, of the burnt areas and occurrences. The values of burnt area and number of occurrences in a given year do not seem to influence the values of the following year. This stochastic behavior can be partly explained by the variability of meteorological characteristics of the summer season.

The climate also has a very important influence on the amount and type of vegetation in each region and the seasonal dynamics of its moisture content, directly and indirectly influencing the occurrence of forest fires and their propagation (Pyne *et al.*, 1996). The high rainfall recorded in the Northwest, with average annual totals exceeding 2000 mm, allows for high biomass productivity (Table II).

**Table II.** Rain stations located in the Cabreira Mountain (NW Portugal), in the municipality of Vieira do Minho (1961-1990). Source: IMNG.

| Rain station | Average annual rainfall R (mm) | Station altitude (meters) |
|---|---|---|
| Brancelhe | 2118,7 | 380 |
| Guilhofrei | 2705,7 | 350 |
| Salamonde | 2281,9 | 550 |
| Zebral | 3071,1 | 775 |

High precipitation is, unquestionably, the most outstanding climatic characteristic of the Northwest, and will provide a high biomass productivity, making the counties where the wild spaces have greater territorial expression, usually the most mountainous, more vulnerable to fire progression.

The demographic reality of the Northwest unquestionably has a direct influence on "forest protection", insofar as the aging population in rural areas and the concentration of the population around the main urban centres creates spatial imbalances, with the direct consequence of the abandonment of agricultural and forestry areas in the interior, often causing an incipient management of these areas and, consequently, an increase in the fuel load (APIF/ISA, 2005). Due to this reality, and favored by a climate conducive to the production of biomass, the shrub stratum has advanced over agricultural fields converting them into scrub area, which subsequently, as the species develop, is being dominated by the tree stratum, making these areas more susceptible to the occurrence of forest fires, leaving them much more vulnerable, in the event of the manifestation of this risk (Lourenço, 2006).

Thus, the high production of biomass, the abandonment of the rural world, and in particular of mountainous areas, associated with the problems of these mountainous areas, considered disadvantaged areas due to permanent natural handicaps and the resulting socio-economic constraints (Bento-Gonçalves, 2006), which have to do with the fact that these areas are subject to a wide range of conflicts that result from a range of interests, often antagonistic, derived from land use, such as coexistence between the rural world and city visitors, free range cattle raising and some common land holders, hunting, etc. (Bento-Gonçalves *et al.*, 2009), create favorable conditions for the rapid spread/progression of forest fires and hinder detection and combat resulting in extensive burned areas.

The consequence of this phenomenon, which depletes forests and, in general, the vegetation cover of our territory, is subsequent soil erosion and degradation.

The direct impacts are observed in terms of loss of nutrients (Úbeda & Sala, 2001; Coelho et al., 2004), translating into a reduction of its fertility and, consequently, in the subsequent difficulty of forest recovery (Thomas *et al*., 2000).

In terms of the mineral component, by removing the vegetation, the superficial layers of the soil will be unprotected and exposed, becoming vulnerable to erosive action, namely from rain, which normally occurs in the fall/winter months that follow the fire season.

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## Chapter 4. Soil erosion assessment approaches: overview and specificities under post-fire conditions

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### Introduction

Soil erosion by water addresses natural phenomena integrating in a complex way several physical processes, involving energy and mass transfer from the atmosphere to the soil surface along actual topographical gradients. This complexity generates complexity in both selection of assessment methods and interpretation of assessment results. It is therefore important to clearly identify the object under assessment in order to reduce such fundamental constraints, which is not always a simple matter.

Time and spatial scales very much affect erosional processes occurrence and rates. In fact, erosion is a spatially distributed phenomenon, involving sediment transfer along hill-slopes and from slope plans to the linear structures of the natural drainage network. As well, erosion is a time discontinuous, episodic, phenomenon, following the lack in time continuity of the erosive agent, the rainfall. Moreover, erosion phenomena combine continuous and threshold type of mechanisms, meaning that erosional responses may vary from nil to very high magnitude. This range is determined by changes in erosion processes contribution to total loss, from splash everywhere in a field or catchment in virtually all rainfalls (negligible to low loss), to interrill erosion in some events with Hortonian overland flow generation (low to severe loss), to gully incision in very few heavy and prolonged rainfall episodes, with topographically concentrated overland flow running over saturated soil (severe to very severe loss).

Assessing runoff erosion encompasses these wide ranges of processes time and space occurrence and continuity. Therefore, no such thing as a normalized erosion measurement methodology exists, and a wide set of methods historically developed, according to research needs and progresses in specific technology and instrumentation. The principles to be followed when assessing erosion are:

- to set the basic time and space measurement unit according to information requirements and practical feasibility;

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- to accept the black box approach for those units and ensure that it is experimentally respected (known inputs and outputs through system boundaries);
- to withdraw any wish to extrapolate measurement results to other time spans and spatial scales.

The present text aims at providing an overview on methods for measuring water erosion. In this sense, modelling, mapping and estimation techniques are not explicitly mentioned in this overview. The structure of the text is based in a general classification scheme of methods to assess water erosion, basically reflecting the commonly accepted categories of erosion research approaches. The fundamentals of each category of methods is presented in each section, together with the methods scope, description, discussion, including application conditions. Furthermore, the specificities inherent to the context of post-fire erosion measurement is also addressed when applicable.

**1. Field surveys**

Field surveys are currently performed to obtain a direct insight on actual erosion processes occurring and their spatial distribution within the survey area, to derive estimates of past or actual rates and trends of soil loss, to assess and eventually classify land degradation status (Hudson, 1981; Morgan, 2005). Field surveys may be also performed under specific conditions, as those following an extreme and evidently damaging rainfall erosive event, providing therefore a timed picture (Vandekerckhove *et al*., 1998; Figueiredo, 2009). Furthermore, they may be performed in sample areas as part of a cartographic approach to wide regions where erosion or land degradation has to be assessed, this way, contributing to draw the regional picture of the problem or status (LADA, 2009).

Field surveys are basically an organized way to collect the necessary information for the survey purpose, which, normally, may not be obtained with similar detail and quality by other means, as existing map or remote sensing techniques. As so, it is important to clearly define the specific objectives of the survey for the area selected for observations, which may be more geomorphic process-oriented or degradation assessment-oriented. Also, as costly, time and labour consuming operation, surveys should be carefully prepared, assembling prior to field work, all information needed to draw an anticipated picture of the area and limit the information that might be redundantly collected there. Scheduling of the survey is a matter of operation management.

A field survey comprises visual observation of erosion features and signs in the field as, for instance, runoff flow paths, crusts, surface rock fragments, rills and gullies. Observations are appropriately recorded together with notes on impressions or perceptions built on-site, that may provide interpretations helpful to data treatment. Some involve extensive data collection, others are much simpler; some add field measurements of soil properties or erosion features, others simple record their occurrence. Data collection has to be geo-referenced either locating sites in a sufficiently detailed map or by means of a GPS device; forms might be prepared in hardcopies or in a portable electronic device as a PDA, tablet or laptop (Eicher, 2005; Fleskens and Strosnijder, 2007; LADA, 2009; Zanden, 2011). Examples of recording sheets are found, for instance in Zanden (2011), and in LADA (2009). Hurni (1988) published a form specifically focused on agricultural land. Other less oriented forms are provided in Goudie *et al*.cols. (1990).

Results obtained with this approach are limited in quantitative terms, although in cases information collected might provide the basis for quantifications on soil loss rates or amounts. On the contrary, these methods are very valuable to identify active processes and their spatial distribution, as well as damage determined by those processes during erosive events, on-site or off-site. They are also helpful for locally calibrating models or indirect quantitative assessments via soil properties and ground features.

## 2. Field measurements

Research methods to quantify erosion rates in the field, under actual conditions, evolved through time towards a short number of types, specific to processes measured, which may be setup with more or less instrumental sophistication. Besides, according to measured object, they can be grouped as: (i) methods materially measuring soil export from a known area by runoff erosion (splash collectors, sediment traps, runoff plots); (ii) methods measuring topographic changes associated to runoff erosion (erosion pins, benchmark-based micro-relief surveys, and rill and gully volumes). These methods are described in the following sub-sections.

### *2.1. Splash measuring devices*

Splash is measured with cups or boards (Figure 1). Splash cups may be of two types: source-cups (soil containers) and sink-cups (splash collectors) (Morgan, 2005). In the first case, a container (metal, PVC or glass cylinder), filled with the testing soil, is exposed to rains and the mass loss due to splash removal of soil particles is measured after each rainfall or a period of precipitation. Early studies of the erosive characteristics of rainfalls, by Ellison cited by Hudson (1981), applied this method with sand as test material.

The second type is more commonly used and consists of a PVC cylinder, inserted into the soil with its top rim at a similar slope gradient as that of the surrounding ground, that should outcrop a few millimeters to avoid incoming runoff washed particles (Poesen, 1986,; Morgan, 2005; Fonseca, 2005) (Figure 1). Inside the cup, a filter paper traps incoming particles splashed from the surrounding area. Drainage of precipitation water has to be ensured, and can be obtained with a hole deeper than the cup itself.

After each rainfall or group of rainfalls, the filter paper cone is replaced by a clean one and the mass of trapped particles is measured in lab.

**Figure 1.** Splash cup, 5.5 cm diameter installed in a field experiment (Fonseca, 2005; Figueiredo *et al*., 2012) (left), splash boards installed in outdoor micro-plot experiment with simulated rock fragments (Figueiredo and Posen, 1998) (centre), and board capturing splashed particles during a rainfall simulation micro-plot experiment using burnt soil samples (Alves, 2018 and Royer, 2019) (right).

Splash boards, are rectangular plates (metal, plastic), placed vertically besides the area under assessment, that receives particles splashed and collects them in a container at its foot (Morgan, 2005) (Figure 1). Mass of these particles is measured in lab. Splash boards have problems in windy areas and their height cannot be shortened because trapping efficiency declines (Figueiredo and Poesen, 1998).

The mass loss from soil containers or the mass of particles trapped in cups or by board requires corrections before being taken as splash loss. Correction procedures to account for the size of cups are provided by Poesen and Torri (1988). As well, Figueiredo *et al*. (2004) adds correction procedures to account for the presence of rock fragments in soil surface. Furthermore, splash measurements are sometimes taken as a surrogate of soil detachability. However, in sloping areas, there is an actual net splash transport downhill which can be assessed with a model developed by Poesen (1986).

*2.2. Sediment traps*

Sediment traps collect soil particles washed by runoff along hill-slopes (Dunne, 1977). A common model is named Gerlach trough and consists on a buried metallic box with a gutter upslope, to drive in washed material, and an exit pipe to drain the box of excess runoff water (Morgan, 2005). Gerlach trough is covered to avoid collecting precipitation and normally has an internal grid to separate large (organic) washed material from sediment (Coelho *et al*., 1990). This is deposited in the box bed, or in a removable container, which is pull-out ad cleaned in every sediment collection, therefore facilitating this operation. Sediment trapped is oven-dried and weighted and referred to runoff contributing area to express results in soil loss mass per unit area.

The system is commonly installed down-slope unbounded areas, where the contributing drainage area is fairly defined by natural ground topography (Coelho *et al*., 1990). However, it can be applied for bounded areas, therefore becoming a special case of erosion plots. Nevertheless, they are designed to collect runoff but simply washed soil particles, unless additional or alternative design elements allow runoff storage or sampling, as it is the case of bottles to where runoff water and suspended sediment are conveyed through a pipe, after reaching a certain level inside the box.

A series of stakes inserted into soil normal to surface, along contour lines, holding a plastic sheet adequately fixed into soil, can trap washed particles by upstream runoff (Dunne, 1977). These devices are currently named silt fences or erosion fences (Figure 2), they are also used to measure post-fire erosion rates (Prats *et al*., 2012) and Robichaud and Brown (2002) provide details on installation and operation of these devices. As water is diverted laterally or surpasses the trap, sediment accumulates upslope and. Erosion rate estimates may be based on measurement of the deposited oven-dry mass removed in each collection operation, or on deposition volume changes, assessed via changes in relative height of deposition surface during the observation period.

**Figure 2.** A silt fence (unbounded drainage area) installed in forest land, NW Portugal.

### *2.3. Runoff plots*

Runoff or erosion plots are the most commonly applied method to measure runoff and soil loss from areas affected by interril and, eventually, also rill erosion (Hudson, 1993; Roose, 1994; Lal; 1994; Morgan, 2005). They are bounded areas with size, shape and boundaries adequate to purpose and means available to perform measurements, which correspond to runoff water and washed soil collected in devices installed down-slope, normally preceded by a gutter on their front edge. Such devices vary in instrumental or structural sophistication depending also on means and purpose of measurements, and have to account on plot size and characteristics, that determine potential runoff and sediment yields (Figure 3 to Figure 6).

Plot boundaries may be earth ridges, wood or metal plates inserted in soil (both repaired every time leaks are detected), or concrete walls, in the case of well-designed and funded long term monitoring programmes (Fleskens and Stroosnider, 2007; Fonseca, 2005, Figueiredo *et al*., 2012; Figueiredo and Ferreira, 1993, Tomás, 1997, respectively) (Figure 3 to Figure 6). Plots may vary in shape but are normally rectangular, although microplots installed in semi-arid matorral by Bochet *et al*. (1998) had a shape fitting shrub plant canopy ground projection. Plot size varies sharply, indicative surface area and slope length being: (i) micro-plots, smaller than 5m2 (less than 4-5m long); (ii) meso-plots, from 10 to 500m2 (5 to 50m long); (iii) macro-plots, larger than 500m2 (longer than 30m). Plot size has to be adjusted according to the local land use and management practices being monitored for assessing their erosional response. For example, micro-plots can be installed in a heterogeneous land cover area, if they are intended to assess the independent erosional response of land cover patches. However, large plots have to be installed in the same area if the assessment is focused on the global response that results from the connectivity of such patches.

**Figure 3.** Erosion micro-plot (1 m wide, 4 m long) installed in a burnt area at Aveleda, NE Portugal (left), with collection of washed soil particles and ashes (top right), and runoff water and suspended sediment (bottom right) (study area described in Fonseca et al, 2017).

Measured soil loss in each case should be the outcome of actually active erosion processes occurring in the plot area, even though, in some cases this is not a simple design problem, because of temporal changes in vegetation cover and ground condition, and because of the episodic pattern of precipitation and the threshold pattern of runoff and erosion processes. In very large plots, most of the recorded soil loss events do not outcome from the entire plot area, whereas small plots cannot represent the most significant erosion events, issued from a runoff concentration virtually impossible to occur in such small size. Runoff and sediment collection devices can be as simple as tanks connected to the upstream gutter, installed at plot front edge, by means of a conveyor, in which total washed material (soil and water) yielded in an erosive event is stored. Gutter may be concrete, PVC or metal half-pipe or a metal plate onto the ground. Conveyors may be part of the gutters (concrete) or independently installed (half-pipe, rigid or flexible pipe). Both elements are selected according to purposes and conditions of the monitoring system installed, but, in any case, they have to ensure fast conveyance and no loss of material from plot to tank (Figures 4 and Figure 5).

**Figure 4.** Erosion meso-scale plots (7.5 m wide, 15 m long) in an olive grove, with earthen boundaries and open runoff and sediment collecting pond, NE Portugal (study site described in Fleskens and Stroosnijder, 2007).

The system may apply from small plastic tanks or bottles (5 or 10l, for example), to large plastic or metal tanks (50, 100 or 200l, for example), or even trenches open in the soil at plot front edge, covered with a plastic sheet, that also collect rainfall (Figure 4 and Figure 5). The collection procedure normally comprises: (i) water volume measurement (or estimate from a calibration height-volume curve for each container); (ii) suspended sediment sampling, e.g. with a beaker, after thorough stirring of tank contents, and sample oven-dry mass determination; (iii) if present, removal of bed load after draining most runoff water, oven-dry mass determination of total bed load or, when too large, wet-weighing of total bed load and sampling it for water content. Total soil loss in each event is the sum of suspended sediment oven-dry mass (the product of runoff volume by sediment concentration) with bed load oven-dry mass (if present), referred to plot area. It should be noted that, sediment resting on gutter, actually exported from plot but not able to reach the container, is accounted for as bed load. Runoff may be also converted to equivalent height (volume collected divided by plot area, expressed in mm).

In large plots, where large runoff volumes can be expected, the problem of storage volume of tanks is overcome by setting small tanks in series (not more than 3 in total), connected with pipes and runoff divisors. In this case, the first tank collects water and the soil washed from plots, but the remainders receive only a part (e.g. 1/11) of the incoming clear runoff water, the rest being spilled out (Tomás, 1997; Figueiredo, 2001) (Figure 4).

**Figure 5.** Erosion meso-plots (5.2 m wide, 32.1 m long) in a vineyard of the Dourio region (study site described in Figueiredo et al, 2021, and Figueiredo, 2001; photo by Jean Poesen).

Recording systems allow a detailed insight on runoff water and soil loss evolution during an erosive event and this is especially useful when studying erosion processes or modelling. Recording devices for measuring runoff are connected to a data-logger, from which the data can be directly or remotely retrieved or accessed. They may be: (i)inspired in limnigraphs (river stage recorders), in which a sensor (e.g. a pressure transducer) measures runoff water level conveyed through a stable section in the flow circuit (channel segment or a spillway, metal, plastic or concrete); (ii) inspired in rain gauges, in which a runoff convey pipe drips on a tipping-bucket device, or a multiple bucket tilted metal wheel, that rotates when a bucket is filling in with runoff (Morgan, 2005) (Figure 6).

**Figure 6.** Runoff tipping-bucket recorder (Haute Normandie, France).

Runoff recorders may be coupled with mentioned above systems, so as tanks collect total sediment exported during the erosive event, while runoff evolution is is recorded in detail. However, sediment concentration evolution may also be monitored installing sampling bottles filled in during the erosive event water diversion scheme, collected afterwards and oven-dried for sediment mass determination. More sophisticated systems use turbidity sensors to record sediment concentration evolution during runoff event. Both allow coupled analysis of sedigrphs and hydrographs for each event recorded.

*2.4. Ground level monitoring*

Measuring height differences relative to reference surfaces or points, and repeat them through time, provides estimates of soil loss amounts and rates, associated with erosion processes taking place in a given observation area. Methods for measuring runoff erosion considered under this heading include erosion pins, benchmarks for micro-relief surveys and root exposure surveys (Dunne, 1977).

An erosion pin comprises a metal rings resting over the soil surface, fixed there by a nail. Distance from nail top to ring is repeatedly measured through time. Pedestals may form as the ring protects the soil underneath from raindrop impact, and they have to be removed prior to measurement. Nails are taken as local benchmarks and changes in ring position are attributed to soil loss due to runoff erosion. A large number of pins is required for a fair representation of surface evolution, because wash and deposition occur in the same area of observation as sediment is transferred along the hill-slope, and because preferable flow paths and ridges have clearly different pattern of surface evolution.

Benchmarks of any kind, installed, as concrete pillars, or naturally set in place, as embedded rocks, serve as references for micro-elevation surveys at neighbouring areas affected by runoff erosion. Repeated surveys help assessing wash rates from eroded volumes estimate. Tree root exposure is an indicator of land degradation by severe runoff erosion (e. g., Rubio-Delgado *et al*., 2018). Assessment of eroded volumes requires micro-elevation surveys as in the above indicated cases, however with increased practical difficulties. A particular case of benchmark based measurements is the erosion bridge developed by Shakesby *et al*. (2002). The device is perforated metal bridges kept leveled during measurements, as its 2 supporting fixed length legs step over 2 benchmarks. The surface soil profile between the 2 legs (or rods) is obtained measuring vertical distances to ground surface taken from bridge with c. 50 metal sticks sliding through the bridge holes down to the soil surface. Time changes in average elevation are estimates of erosion rates of soil between benchmarks.

Removal of soil particles by runoff erosion in interrill areas also lowers ground surface, actually corresponding to the geomorphological concept of denudation rate (Ahnert, 1998). Due to ground surface roughness it is hardly possible to describe it as sheet removal, but such approach has been adopted for long. It is a useful approach to assess local erosion rates, provided extrapolations are performed very carefully. In fact, the heterogeneity of surface ground features makes them simply point assessments that may not represent larger land tracts. If land lowering rates are converted in equivalent soil loss rates (mass per unit area and time), then a critical conversion factor has to be estimated – soil bulk density – that is normally taken as equal to the actual one, locally measured, assessed or assumed. Bulk density changes during erosive rainfall events (van Wesemael *et al*., 1995), introducing an additional conversion constraint.

Surface micro-topography is generally required for improving accuracy in ground level assessments and monitoring. Developments in micro-topographical surveys, however, were driven far more on account of surface roughness assessment than on account of erosion rates assessment, despite their common basic data requirements. In fact, results from such surveys may serve either the computation of roughness indexes or of mean or local ground level changes following rainfall events, which may aloe the quantification of net erosion rates or those of gross erosion and deposition, and their spatial distribution. This justifies a specific subsection on dedicated to surface roughness in the context of ground level monitoring approaches to measure soil erosion rates.

Methods for measuring surface roughness aim at providing a description of soil surface micro-topography, from which parameters or indexes may be extracted and used for runoff erosion interpretations or as input in erosion models. As detail in description of micro-topography increases, so increases sophistication of methods and equipment, and so increases complexity in data treatment and outcoming results. Full descriptions are 3D, while the simpler approaches provide a 2D description of soil micro-topography, meaning that a direction must be selected for the measurements performed along a straight line.

The simplest method is the chain method, consisting in a chain with a certain length that is placed along a line onto the soil surface, after adequate selection of measurement direction (Morgan *et al.*, 1998). This is generally taken that of actual or expected overland flow paths. Once placed onto the ground, the straight line distance between the two edges of the chain is shorter the higher is surface roughness. An index is derived from the two lengths: that of the chain (normally between 50cm to 1m) and that of the straight line distance between chain edges when resting over ground, named roughness index.

The profilemeter method provides a longitudinal profile of miro-relief, as a result of measurement of vertical distances from a reference level to ground surface, taken at regular horizontal distances. In the 3D approach the reference level is a plan and measurements are taken in two orthogonal directions in the plan. Reference plan or line are not necessarily leveled if their slopes are precisely known. The number of measurements taken depends on the required detail of assessment and it is limited by practical feasibility combined with instrumental capabilities.

In a needle profilemeter, a set of sticks, pins or needles, supported by a frame at regular short distances from each other (e. g. 5cm), are slide down to the ground and the heights to the reference frame measured or represented in a chart draw on the opposite edge of the sticks, pins or needles, to be later measured indoor. A very simple and straight forward variation of the method consists in a ruler along which, at regular intervals, the distanced to the soil surface is measured with a tape (Fonseca, 2005). Either frame or ruler are fixed by two legs and leveled with a bubble level (Figure 7).

**Figure 7.** Assessing surface micro-relief with: home-made device on a micro-plot in NE Portugal (description in Fonseca, 2005) (left); laser profilemeter (centre) and camera capturing images for surface photogrammetric reconstruction (right) on soil samples in NW Spain (centre and right photos by Douglas Bandeira, description in Bandeira, 2019).

Data treatment consists in determining total length of ground surface and use it, together with ruler length, to compute the index above. Alternatively, random roughness, a second index is derived from data, which corresponds to the de-trended standard deviation of surface heights, meaning that a trend of data is obtained by regression, measured data subtracted from the trend line, and the standard deviation of the residuals around the trend line computed (van Wesemael *et al*., 1996).

The procedures and instruments described above do not allow a very much detailed representation of soil micro-topography, as shortening distance between point measurements rises the number of measurements so as they become practically unfeasible. Besides, shortening distances is limited by instrumental capabilities. Laser profilemeters overcome these limitations and provide non-contact measurements (van Wesemael *et al*., 1994; van Wesemael *et al*., 1996). They are sophisticated equipment, commonly placed in lab to work on simulated surfaces, but models exist to work in the field. Also models exist that allow working to output 3D results. The equipment consists in a frame supporting a laser source running over it at constant velocity by means of a motorized system. The laser beam is oriented to the soil surface and according to programmed operation, yet limited by equipment capabilities, measurements can be taken at very short distances along a line (0.1mm). Data is stored during runs and later transferred to perform data treatment and from which indexes may be derived. Due to the highly detailed data provided, complex approaches to deriving indexes are possible, as it is the case of using fractal analysis (van Wesemael *et al*., 1996).

In the case of 3D ground micro-relief surveys, more complexity of data treatment requires spatial analysis and GIS based methodologies. They can be applied with data sets issued form laser profilemeter measurements. However, approaches to this topic include also taking paired ortho-photos of surface ground, later treated with methods typical of aerial photo based surveys (Merel and Farres, 1998). More recently, the increase in performance of image treatment tools allows obtaining very detailed photogrammetric reconstruction of surface micro-topography with non-orthogonal photos and with no height reference requirement (Bandeira, 2019). Also, unmanned aerial vehicles (drones), equipped with cameras capturing high resolution images provide data to obtain a very detailed representation of the surface ground (Barroso, *et al*., 2021). In both cases, robust approaches to data treatment are required and, again, fractal analysis is applied to comprehensively represent the complexity of micro-relief and its changes due to soil erosion processes.

*2.5. Gully erosion assessment*

Linear erosion features primarily result from the incision of ground surface, and further scouring of the soil profile, by concentrated overland flow, to which might be added effects of other processes as splash, sheet flow and mass movements at micro to meso-scale (Govers and Poesen, 1988). They are normally classified according to size and stability, rills referring to short-living structures lower than 900 $cm^2$ crosssection area (1 $ft^2$) (Morgan, 2005). Large stable incisions are called gullies, in spite that these are labeled ephemeral when they meet size requirements but are fresh incisions that may be erased by regular tillage operations as it is the case of rills.

The basic principle in gully erosion assessment is to estimate gully volume and refer it the estimated catchment area draining to the gully system (Vandekerckhove *et al*., 1998; Vandekerckhove *et al*., 2000). This is based on the assumptions that actual gully volume is simply due to linear erosion) meaning that sedimentation and other processes occurring in gully walls are not considered), and that topographically defined catchment area contributed with erosive overland flow to gully incision and development. For most cases, these assumptions are practically acceptable, taking into account either the constraints associated with assessing the contribution of process other than concentrated overland flow to gully actual configuration, and with actual runoff contributing area determination, or the accuracy of estimation procedures applied to outcome gully volume.

Approaches to estimate gully volume may be based in: (i) direct measurements (ruler based or geodetical); (ii) remote sensing techniques (low and high altitude aerial photos) (Vandekerckhove *et al*., 1998, Figueiredo, 2009; Dunne, 1977; Vandaele *et al*., 1997, respectively). In the first case, at selected points along the gully measures are taken to estimate the respective cross-section area, which are integrated over the length of the gully segment they represent to output gully segment volume, the sum being total gully volume. Number of sample sections, measurements performed to estimate crosssection area and integration procedures, depend on gully size on one hand, and required accuracy of estimates on the other hand. In fact, very large gullies (several meters deep and several hundreds of meters long) require geodetically performed measurements. Smaller gullies may be approached with direct measurements with a ruler for gully cross-sections and and a tape for gully segment length (Figure 8). Area of complex cross-sections may be accurately assessed with a needle profilemeter but it is a rather time consuming technique. A much simpler approach consists in assuming a certain regular cross-section shape (triangular, rectangular, trapezoidal, and parabolic) and performing the measurements required determining its area (normally top width and average depth). For a more accurate integration, sections should be selected so as to define gully segments with regularly changing crosssection area, therefore avoiding abrupt changes in size and shape within the segment length.

Remote sensing techniques for gully erosion assessment are applied when the scale of assessment, the extent of the area under assessment, and the expected or required detail of assessment results. Accordingly, the range in resolution of the aerial photos used in this approach is quite large, depending on purposes and practical conditions to perform the assessment. These include available time, consistency and quality of the available information (photos), quality of ground references for photo-interpretation. Ries & Marzoff (2003) used photos taken from a blimp to study gullies in Spain, whereas Vandaele *et al*. (1997) made use of aerial photos in Alentejo, Portugal.

Gully erosion rates can be calculated if a temporal reference exists. Normally this means repeated observations through time, in a monitoring scheme. However, in fully installed permanent structures as large gullies dating techniques may be used to obtain a temporal reference for calculating rates. This is the case of dendro-chronology of plant roots exposed in gully walls. It should be noted that rates calculated are averages that do not, and could never be, representing the actual changes in process rates over time, as erosion sensu lato is an episodical phenomenon.

An extensive recent review on gully erosion assessment methodologies can be found on Vanmaercke *et al.* (2021), covering a wide set of contexts, including burnt areas.

**Figure 8.** Gully formed following heavy rainfalls over a recently burnt scrubland and measuring a rill in a forest road in NE Portugal (top left) (study area described in Figueiredo *et al*., 2012).

### 3. Experimental simulations

#### *3.1. About simulations*

Due to the very high time and space variability of erosion factors, experimental simulation is quite often the approach adopted to study and assess erosion (Hudson, 1091; Morgan, 2005). This approach by-passes some of the difficulties associated with installing and monitoring field experiments and with performing field surveys. Simulations allow triggering rainfall erosion events and controlling their precipitation characteristics and ground or soil conditions, according to convenience. These advantages shorten time required for obtaining research results.

However, the main advantage of simulations is the possibility they provide to control factors and processes, bounding systems to be studied with control of their boundaries. Such conditions are not possible to obtain in the field, considering the large set of interactions between factors and the chaining of processes that are commonly found outdoors, which are the main constraint to scientifically grounded interpretation of assessment results.

Simulations face the problem of reliability in representing the real world, even though it is a fragmented real world. This is a key issue when comparing simulation with field results in erosion experiments. In fact, natural rainfall is hardly replicated by simulators, due to technical limitations, and soil samples used in simulations hardly replicate natural soils, due to disturbance or scale. Scale is often a limitation in simulation experiments, as size of the experimental setup is upper limited by actual instrumental conditions, meaning that those experiments are normally small scale.

All advantages and constraints considered, experimental simulations were and are, undoubtly, a very valuable approach for the advancement of knowledge of runoff erosion processes.

### *3.2. Rainfall simulators: general*

Addressing simulation in erosion experimental research commonly means focusing in rainfall simulation and simulators. As the agent, without which no process occurs, emulating a rain shower has been since long a core research concern. Steps towards this goal were grounded in the deep insight on natural rainfall characteristics that are required to set a reference to be replicated. Drawing the full picture of precipitation characteristics and of how they relate either to easy measurable rainfall parameters, or to synoptic conditions or climatic features is still a hard task. However, since Ellison and with later definite contributions by Laws & Parsons, Ghadiri & Payne, Sfalanga & Torri (cited by Hudson, 1981), natural rainfalls were experimental studied and described with the existing technologies and results obtained are the basis for actual rainfall erosivity estimates. An important advancement was provided by disdrometers, an equipment used for the refined measurement of rainfall characteristics (Tomás, 1997; António, 2010).

To summarize, it is possible to set a reference for natural precipitation characteristics, namely rain drop size distribution and its variation with rainfall intensity, for certain geographical regions, normally accepted as reliable even for other regions. The relationship between rainfall kinetic energy per unit rainfall height and rainfall intensity expresses that variation in useful form, since kinetic energy of raindrops provides the work necessary to breakdown exposed soil aggregates and start erosion processes. On the other hand, such relationship changes geographically, the data sets for deriving it being compiled in the USA, South Central Africa and with a much shorter record length in Italy (Wischmeier and Smith, 1978; Hudson, 1981; Raglione *et al*., 1980).

The simulated rainfall should match natural rainfalls with certain frequency and duration, or, inversely, selected for the specific experiment. This means that a frequency analysis of rainfalls for the area to be emulated in experiments should exist. The most practical result of the mentioned analysis is the Intensity-Duration-Frequency (IDF) curves for the selected weather station. IDF curves provide a tool for setting or knowing the frequency (expressed in terms of return period) of the precipitation being simulated with a certain duration and intensity. Although a relevant approach, this should be complemented with natural rainfall kinetic energy frequency analysis, which is a much more difficult task because it requires performing the frequency analysis itself with basic rainfall data records whilst IDF curves may be published or available and can be used without a prior analysis (Tomás, 1997; Figueiredo, 2001).

Rainfall simulation characteristics are duration, intensity (normally kept constant during the experiment), and kinetic energy of the dropping water at ground or other reference level (e. g., canopy) and spatial uniformity within the target area. Additionally, if technical constraints do not ensure a steady water flow in the simulator, temporal changes should be known as well. As duration is arbitrarily selected (preferably with a sound justification given the natural and experimental conditions), all other characteristics need to be measured, assumed or neglected, according to accuracy required for the experiment. Full calibrating runs with the simulator should include sampling the shower with cups placed in the target area at the required level (normally ground level). Cups may be of various materials (plastic, metal, glass), sizes (accommodating target area size, number of cups and sampling intensity accepted), and shapes (simple cups or funneltopped where funnels are the actual interception device). The longer the run the large the amount of water intercepted by cups, the smaller the relative experimental error. Volume or mass of water captured in the cups averaged and adequately converted to mm h-1 allows assessment of simulated rainfall intensity. Uniformity of water distribution in the target area is assessed via statistical dispersion of water amounts collected in cups (Tomás, 1997; Bompastor *et al*., 2009).

Assessment of simulated rainfall kinetic energy requires additional measurements, namely fall height, initial drop velocity and water drop size distribution. The latter is assumed zero for drippers but has to be assed in the case of sprinklers, the two simulator types described later. To do so, discharge from the simulator nozzles is measured conveying sprinkled water to a bucket and measuring time to fill it or to reach a defined volume. The nozzle diameter is normally given by the commercial provider, otherwise it is measured. Velocity is computed with discharge and crosssectional area of flow in the nozzles (Bompastor *et al*., 2009). If the simulator is multi-nozzle, uniformity should be assessed too, with data dispersion analysis. Height is measured from dripper or nozzle to ground surface or other upper reference level and it is normally fixed according to experimental convenience. Water drop size distribution can be assessed in several ways according to instrumentation available. The most reliable device is the disdrometer, which has a sensor plate hit by falling water drops and the detected signal is converted in drop size distribution, allowing the computations of kinetic enegy and intensity (Tomás, 1997). Acoustic sensors, stroboscopic photos, high time resolution image capture are other means of reaching the same goal, with or without measurement of the falling velocity (Tomás, 1997; Morgan, 2005). The most traditional and low-technology input methods is the flour pellet method, that consists in exposing a pan filled with a thick uniform layer of flour to the water shower at the required level, for a short time span so as to allow pellet formation and limit flour soaking. Pellets formed represent drop hitting flour but a calibration procedure is required to adequately assess water drop size from pellet size (Hudson, 1981). A set of sieves screens pellets by size and a drop size distribution curve can be drawn from the mass pellets trapped in each sieve and the size limits defined by each pair of sieves (Bompastor *et al*., 2009) (Figure 9). The larger the set of sieve the more accurate is the curve. The curve allows derivation of D50 of the simulated rain shower, meaning the median diameter of water drops that halves the total precipitation (the mass of water drops) (Hudson, 1981). Kinetic energy can be computed with this data. If the height of simulation is to be change, the measurements have to be repeated for several heights (Bompastor *et al*., 2009). Operational parameters of the simulator that affect or better control simulated rainfall conditions, should be tested during calibration procedures, and be the actual simulation parameters during experimental runs. They include for instance water pressure at outlet in the case of sprinklers (Figure 9). Simulations should only start when steady state at the defined simulation conditions is reached, normally a short time after starting operating the simulator. To limit water loss, a closed circuit water flow should be possible. Water saving is a crucial issue for simulations, especially under outdoor conditions in remote areas, where water availability is seriously limited.

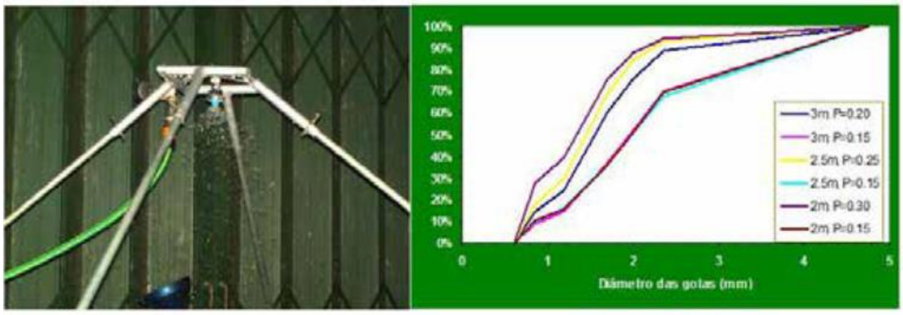


**Figure 9.** Portable single nozzle sprinkler-type rainfall simulator: calibration indoor and drop size distribution curves according to height and pressure (description in Ramos, 2009).

### *3.3. Rainfall simulators: types*

Simulators can be classified by several criteria (Hudson, 1981; Morgan, 2005). They may be portable or fixed structures. The latter work indoor, meaning in a hangar or laboratory and may heavier or lighter structures according to purposes and material conditions to install them. They generally allow larger target areas, more accurate control of simulation conditions, eventually with extended capabilities that may comprise simultaneous rainfall, runoff and subsurface flow simulation and control, wind and moving storms effects, water quality regulation (Zheng *et al*., 2004; de Lima and Singh, 2003; Shainberg *et al*., 1991, respectively). Conversely, portable simulators are normally designed for field conditions, working over smaller target areas, generally with light structure, straight-forward operation, a short set of operational parameters or simple fixed ones, more concerned with water saving design and operation (Figure 10).

Besides, the main criterion for splitting simulators in two main types – drippers and sprinklers – is the drop forming process that sharply differs in the two cases and has important consequences for the characteristics of the simulated rainfall, as well as to operational conditions (Hudson, 1981; De Ploey, 1983; Morgan, 2005).

**Figure 10.** Portable single nozzle sprinkler-type rainfall simulator at work in NE Portugal: in a scrubland (left; description in Ramos, 2009, and Bompastor *et al*., 2009) and in micro-scale experiments using burnt soil samples (right, Alves, 2018 and Royer, 2019).

In drippers, drops form under low pressure (few centimeters equivalent water height), flowing out from a tank at kept at constant water head through narrow tubes (syringe needles, glass or plastic quasi capillary pipes, larger pipes with an axial wire or string fixed centrally). Water drops initial velocity is taken as zero and dropping frequency (mean total discharge from the tank) increases with water head, whereas drop size in determined by the drip device characteristics, namely the narrow tubes internal diameter. In drippers, water drops are very uniform and so the simulated rain shower represents only the D50 of the natural rainfall being simulated and not the range of sizes observed in nature. Furthermore, drops fall from each dripping device onto the ground always in the same position, meaning that some points are severely impacted while others are not at all impacted. To overcome this limitation, drippers should be moved during rainfall simulation runs, in a determined or random pattern, or the trajectory of the falling drops have to be disturbed, for instance by means of fans, or even the drops pass an intercepting mesh after leaving the dripping devices and are reworked to produce the actual simulated rain shower with a totally new drop size distribution (Alexandre, 1989; Bryand and De Ploey, 1983, respectively).

In sprinklers, drops are the result of rapid water flow under hydraulic pressure passing a nozzle where it is under atmospheric pressure. The spray produced includes a large range of drop sizes, therefore approaching natural rains drop size distribution. Nozzle characteristics, namely internal diameter and spray angle determine maximum discharge and the size of target area (also affected by simulation height). However, in sprinklers the set of operational parameters, and their interactions, affecting simulated rainfall characteristics is quite large. For example, besides nozzle characteristics, discharge is positively affected by pressure, meaning that intensity increases as pressure increases, but this induces a finer spray, meaning a decrease in the D50 of water drops. As so, sprinklers normally yield a low D50 of the water drops when compared with that of natural rainfalls with similar intensity, or, stated differently, when compared with natural rainfalls, rains simulated by sprinklers with a similar D50 of water drops have a much higher rainfall intensity than the natural ones (Tomás, 1997; Morgan, 2005; Bompastor *et al*., 2009). To overcome this limitation, typical of sprinklers, some models incorporate a rotating metal disk, with and an open window that intermittently allows the free jet flow, while during part of each rotation cycle the et is intercepted. This way, the intensity is lowered but the water drop characteristics are not changed (Hudson, 1981; Tomás, 1997). Multiple-nozzle sprinklers allow larger target areas but the problem of uniformity of drop distribution within the target area, normal in sprinklers, persists or it is even enhanced due spray cone interception (Hudson, 1981; Morgan, 2005).

In both types, kinetic energy of simulated rainfalls depends on water drops falling height, even though in sprinklers flow pressure in the hydraulic circuit promotes higher drop velocity than in the case of drippers. Only under laboratory fixed structures falling heights can allow approaching water drop terminal velocity, as so approaching natural rainfall conditions. Therefore, in most cases, simulated rainfalls have a lower kinetic energy than natural rainfalls for the same duration and intensity. In the most common cases both types of simulators perform similarly to this respect (De Ploey, 1983).

Outdoor simulations impose special concern about power supply to work pumps and ensure steady pressure in the hydraulic conditions (meaning the need of a fuel motorized power generator), water availability (water tanks) have to be transported to the field), feasible simulator height and appropriate positioning (to ensure a vertical water jet) and wind (the spray cone has to be protected in windy areas by means of a plastic curtain around the simulation area) (Bompastor *et al*., 2009).

## 4. Concluding remark

This overview on methods for assessing runoff erosion is expected to provide a consistent and comprehensive approach to the topic. However, in spite of the wish to cover the most essential cases that contributed to the development of erosion research, it was not meant to be a full review. As so, intentional or not intentional gaps may be found in this overview. Moreover, due the complexity of the object and of its dynamics, assessment methods require sometimes site specific solution to tackle with real world problems. Research innovative procedures are, therefore, ever present in erosion studies, while traditional methods keep their place in this field of knowledge, refining and consolidating protocols as well as adjusting their focus in terms of application conditions.

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## Chapter 5. Fire as a geomorphic agent in rock weathering

Lea Wittenberg[15]

### Introduction: Fire in the earth system

Fire is a principal eco-geomorphic change agent of many terrestrial ecosystems that have shaped the Earth's landscape for millennia (Belcher et al., 2013; Bowman et al., 2009, 2011). According to charcoal findings in fossil records, the global conditions that enabled prevalent fires matured in the Devonian period (≈420 Myr) (Belcher et al., 2013). Once established, fires shaped vegetation distribution and structure, regulated organismal traits and population, affected nutrient cycles and energy flow, and became a critical factor in regulating and modifying the global climate (Bowman et al., 2009).

As a prime and prolonged geomorphic agent, fire can alter the soil and bedrock, provoking immediate geomorphic processes different from those occurring between burns. In addition to the direct effects of the fire, various geomorphic processes are often invoked following the event. The magnitude of these postfire processes and temporal variations in fire occurrence dictate how fires affect rock weathering, sediment production, and landscape evolution.

Fire effect on landscape evolution involves its impact on weathering rates, soil formation and properties, and sediment production and delivery (Buckman et al., 2021; Fernandez-Anez et al., 2021; R. Shakesby & Doerr, 2006; Nurit Shtober-Zisu & Wittenberg, 2021b; Wittenberg, 2012) Given the enhanced nature of the fire-induced responses and the generally low background rates in non-burnt environments, there is a growing understanding that fires have long played a central role in landscape evolution (Mountain et al., 2001; Roering & Gerber, 2005), soil formation (Certini, 2005, 2014) and sediment production and distribution (R. A. Shakesby, 2011; R. Shakesby & Doerr, 2006). However, while most of the scientific effort has focused on fire effects on vegetation and soils, the role of fire as an essential weathering agent has been largely overlooked.

### 1. Fire as a weathering agent

The importance of fires in rock and mineral weathering has long been reported (e.g., (Blackwelder, 1927; Dorn, 2003; Emery, 1944; Goudie et al., 1992). Nevertheless, the literature on fires as rock-decay/weathering agents is relatively limited. Most current theories are based on sporadic field observations (Garty & Binyamini, 1990; Zimmerman et al., 1994), archeological findings, and laboratory experiments (mainly for engineering

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purposes) (Zhao, 2017); however, consistent empirical data is still lacking (N. Shtober-Zisu et al., 2015).

The direct impact of high temperatures produced by fires is evident in the weathering of bedrock surfaces via shattering, spalling, and exfoliation (Fig. 1). Summary of previous studies and relevant references is available (N. Shtober-Zisu et al., 2015, 2018; Nurit Shtober-Zisu & Wittenberg, 2021b). In contrast to the typical spalling and exfoliation caused by thermal stress fatigue and recurring thermal expansion and contraction ('insolation weathering'), the rocks are exposed to a sudden 'thermal shock' during a wildfire. This is because the surface temperature changes faster than the underlying rock, producing a steep thermal gradient. Consequently, the outer parts of a rock mass expand such that the tensile strength of the stone increases radially, causing fractures that are often parallel to the surface (Shtober-Zisu et al., 2015a).


**Figure 1.** Severe exfoliation of the partially buried rock surfaces: a series of expansion cracks and joints develop roughly parallel to the rock surface, evolving into a series of onion-skin-like sheets or slabs of rock separated by crudely curved, subparallel cracks. Source: (Shtober-Zisu & Wittenberg, 2021)

The effect of heating on rock's mechanical properties induces weakening of the rocks and generates weathering. Rock structure and the length and intensity of heat have the most control over thermal weathering. Essential rock structure characteristics associated with fire-induced weathering are: (a) strength of the bond between grains/crystals, (b) degree of porosity, (c) grain/crystal mineralogy, (d) presence of discontinuities, and (e) grain size. In broad terms, experimental tests indicate that igneous rock types endure thermal weathering better than metamorphic or sedimentary rock types.

Fire-induced weathering takes place via four main processes:

(a) High thermal gradient - under the influence of high temperatures, microcracks form in the transition between the hot and cold material, gradually weakening the rock's strength. Under rapid heating and extreme temperature (>2000oC), thin flakes usually form, while deep cracks are formed in the rock material under lower temperatures and longer heating duration. Consequently, the direct impact of the high temperatures produced by the fire is evident in the form of shattering, spalling, and exfoliation (Fig. 1). In addition, rapid cooling has extra effects on the damage evolution of rock, which is induced by the high-temperature gradient generated when temperature changes occur in a short time (Li et al., 2020, 2021).

(b) Expansion of minerals - different minerals have varying coefficients of thermal expansion; it is typically irreversible after heating above room temperature, and a rock's thermal expansion coefficient is usually much more significant than the average coefficients for the minerals in the rock. The "extra" expansion is attributed to the formation of cracks by all differential expansion of mineral grains. The total thermal expansion coefficient in rocks is a function of several parameters, including the rate of heating, crack porosity, thermal cycling, mineral composition, and grain orientation. Thermal cracking occurs above a threshold temperature. In granite rocks, for example, the coefficients of thermal expansion increase with increasing quartz content while decreasing with increasing apparent porosity (de Castro Lima & Paraguassú, 2004). Therefore, rocks composed of several minerals experience inner stress from the differential response to heating and cooling cycles.

(c) Vaporization of pore fluids - rocks may contain trapped water in their pores. When wet rocks heat up, the trapped air and water expand very quickly and forcefully break the rock apart, sometimes causing it to explode. Although rock heating will expel free water, certain temperature thresholds must be crossed relative to thermal diffusivity and coefficient of thermal expansion to release water locked within the mineral structure (Allison & Bristow, 1999).

(d) Breaks down of minerals - Apart from fissuring, fracturing, and spalling, fires may induce discoloration and mineralogical changes in some of the components of the rock, modifying their physical properties. For example, the oxidation of iron minerals with the formation of hematite, the dehydration of clays, the decomposition of calcite or dolomite and the sudden contraction of quartz when temperatures increase to > 573◦C. The occurrences of partial melting and sintering have also been observed (Steiger et al., 2014).

Accordingly, the mineral composition of rocks, their structure, volume of pores and pore fluids, and conductivity are important factors controlling the impact of heating. When the size of the pores is large enough compared with grain size, the mineral expansion will cause only intra- and intergranular cracking, and the rock will suffer granular disintegration rather than splitting. On the other hand, a non-porous rock will respond by severe mesoscopic cracking since there is a lack of space for any increase in volume internally in the rock (Heldal & Storemyr, 2015).

These mechanisms acting (mostly together) during fires often increase the rock material's susceptibility to fire-induced weathering and breakdown. The destruction can be further enhanced during the attempts to extinguish the fire with water that may rapidly cool the heated rock surface and increase the spalling by the resulting thermal shock.

**2. Heating effects on rock disintegration**

Heating can produce two types of micro-cracks in the rock matrix: cycling and thermal gradient-induced cracks. The first form is due to varying thermal expansion coefficients of adjacent minerals in a homogeneous temperature field—the latter results from the thermal stresses caused by the temperature gradients exceeding the local grain strength. Fire-induced cracks appear in nearly all rock types (Zhao, 2017). Early laboratory experiments conducted by Tarr (Tarr, 1915) indicated that all granitoid exhibit a severe loss of strength when heated to temperatures exceeding 500 oC. However, the impact of heat was exceedingly variable, subjected to the rocks' texture, micro-cracks, and porosity. Additional studies on the mechanical behavior of granite (Takarli & Prince-Agbodjan, 2008) revealed that the modulus of elasticity decreased with increasing temperatures, and the reduction rate was most significant when the temperature increased from 500 °C to 600 °C; the modulus of elasticity for the samples heated to 600 °C was 0.37 times of the samples heated to 105 °C.

Furthermore, the crack network expanded with the temperature rise, causing increased porosity and permeability, decreased longitudinal wave velocity, uniaxial compressive strength, and modulus of elasticity. At temperatures higher than 500 °C, the rock samples exhibited more significant damage, probably due to the transformation of quartz at 573 °C (Yavuz et al., 2010). In contrast to polymictic rocks, carbonate rocks are mainly monomineralic and composed of calcite ($CaCO_3$), aragonite ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$) minerals. In addition, it can contain a small amount of quartz, feldspar , and clay minerals, usually less than 5%. Rocks where calcite is the main mineral are called limestone, and those containing the mineral dolomite are called dolomite or dolostone. Limestones are particularly susceptible to fire-induced weathering due to the thermal degradation of organics, the expulsion of water in inclusions (which can occur at 100 °C – 105 °C), and the conversion of aragonite to calcite. Due to the mineral composition, thermal cracking in carbonate rocks develops primarily due to internal stress concentrations, resulting from anisotropic thermal expansion of the calcite (Homand-Etienne & Troalen, 1984).

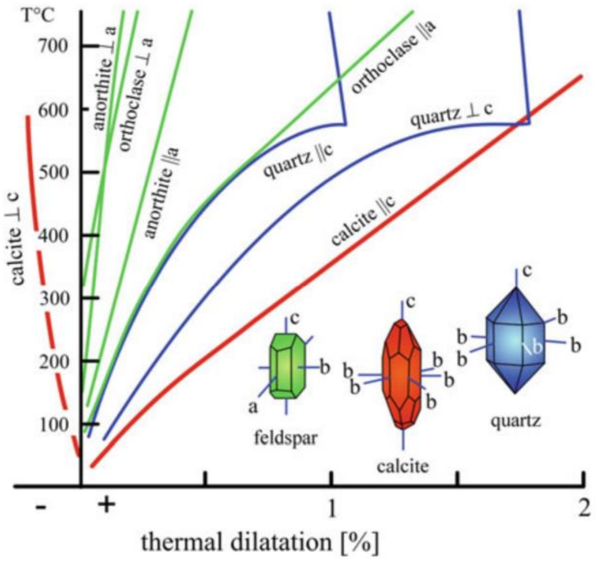


**Figure 2.** Linear expansion changes for some minerals as a function of temperature. Adapted from (Steiger et al., 2014)

Calcite is the only mineral that, upon heating, expands in one direction while contracting in the other. Upon cooling, it will contract along the c axis while expanding along the other ones. (Fig. 2). This trait makes the calcite the most susceptible to thermal cycling, leading to granular decohesion of the stone matrix. In crystalline limestones, A temperature of 200°C was sufficient to produce inter-crystalline cracks (Gaffey et al., 1991).

*Open fire experiment*

To better understand the fire effects on rock disintegration, we conducted an experimental open fire to determine the temperature and gradients responsible for boulder shattering (Nurit Shtober-Zisu & Wittenberg, 2021b). The experiment was set on a small prescribed fire. Fifteen boulders weighing between 1.5–3 kg, representing the carbonate formations abundant in Mt. Carmel, were placed on leaf and twigs fuel beds; the fire was ignited using a flamethrower, and surface temperatures were measured during the first 18 min until the boulders cracked or shattered. We used a portable infrared thermometer to measure and record the searing temperatures (Minolta LAND; CYCLOPS 300bAF).

The results show that ground temperatures reached 700 °C within 5 min from the ignition, and the peak temperature (880 °C) was measured after 9 min. After 12 min, all boulders of all formations were cracked or completely shattered.

The results indicate two distinctive fire-related weathering patterns given the rock's position: spalling and exfoliating over the exposed bedrock, which is typically partly covered and protected by soil, while disintegration and breakdown occur in the case of scattered boulders. Notwithstanding, for all studied cases, a single peak temperature of 880 °C, which lasted for no more than 2 min, was sufficient to trigger prominent rock disintegration. Detailed examination of photomicrographs of the burned rocks (Fig. 3) demonstrated the impact of organic material covering the rock surface. Charred microbiotic crusts covered the surface or passed through micro-fissures, populating pores, voids, and fissures that developed parallel to the surface at a depth of >0.5–1 mm. These fissures and micro-cracks further accelerate the weathering process post-fire for extended periods.

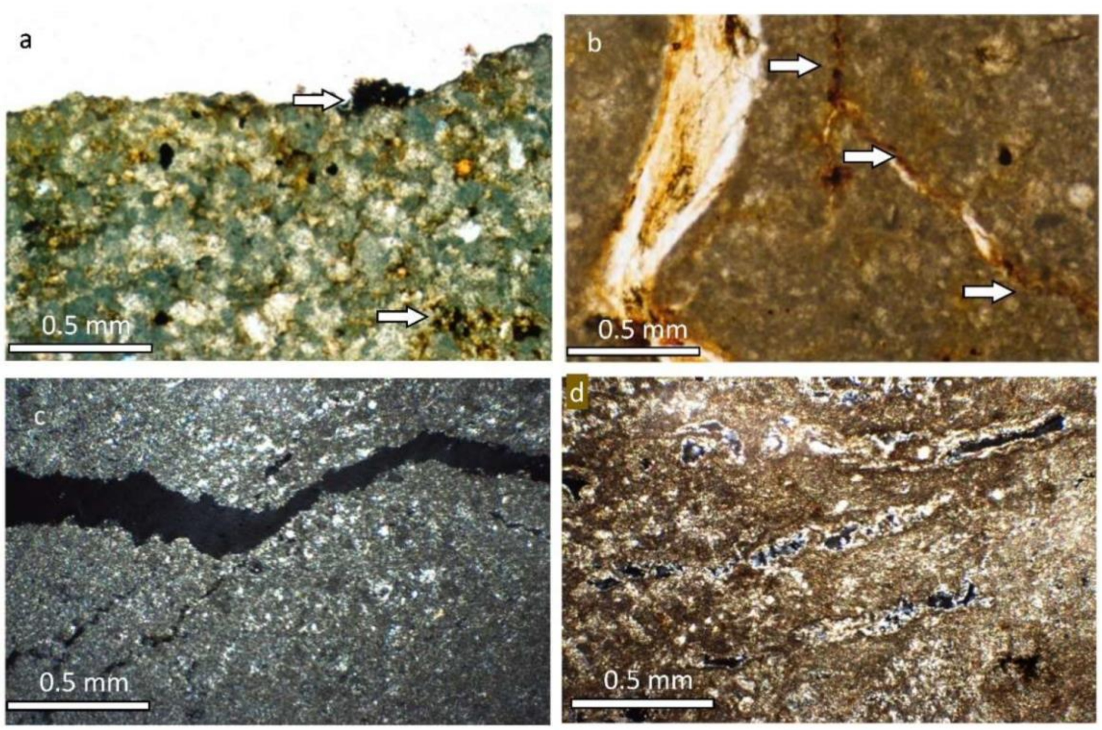


**Figure 3.** Thin sections of severely burned spalls. (a) Weathered chalk surface with charcoal particles attached to the surface and colonies of endolithic green algae at a depth of 0.5 mm (white arrow); (b) weathered chalk with charcoal particles penetrating micro-cracks and roots (white arrows); (c,d) fissures in chalk, enlarged by the heat, parallel, and subparallel to the rock surface. Source:(Nurit Shtober-Zisu & Wittenberg, 2021b)

**3. Fire-induced rock spalling**

Fire spalling affects nearly all rigid and coherent rocks, especially hard, brittle igneous rocks, quartzite, flints, and limestone (N. Shtober-Zisu et al., 2015). Fire accelerates the rock flaking process resulting in rock spalling and shattering of various shapes and sizes, depending upon rock type and fire intensity. However, there are few measurements of the amount of rock so removed.

Granitic rocks are exposed to rapid heating spall at temperatures of 300–375 °C, but they are unaffected by fast heating up to 200 °C and by slow heating up to 800 °C (Blackwelder, 1927). Granitic rocks containing >20% quartz are particularly susceptible to spalling. Quartz expands four times more than feldspar and twice as much as hornblendeas quartz and, when heated to 573 °C, undergoes volume expansion of 3.76% (Kendrick et al., 2016). Thorough measurements of fire-induced rock spalling after the chaparral fire in southern California revealed that 7–55% of the granodiorite boulder surfaces were spalled in a single fire event. When normalized across the entire surface area, the spalled material's volume represents a mean surface lowering of 0.7–12.3 mm. This ratio suggests that, on average, the entire surface of these rocks might be removed in the time represented by 2–14 fires (Kendrick et al., 2016). Other studies report an average lowering of 0.39 mm in wildfire occurred in a sagebrush ecosystem (Zimmerman et al., 1994); Dorn (2003) reports on > 42 mm of erosion from the diorite boulders in his study sites, located in the temperate woodland in Sierra Ancha Mountains, Arizona (Dorn, 2003).

A series of studies were conducted on the carbonate slopes of Mt. Carmel following the 2010 fire. The first study was set up for two research periods: in the first four months after the fire; and three years after. Results indicated severe exfoliation of the carbonate outcrops wherever fire severity was high to extreme (Fig. 4). The bedrock surfaces were extensively covered with flakes and spalls, encompassing as much as 80–100% of the exposed rocks; in some places, boulders were fractured or disintegrated. The most exfoliated surfaces were the chalk outcrops and boulders, while the response of the limestone and dolomite outcrops was less pronounced. These two hard carbonate rocks were spalled to a lesser extent and generated thinner and smaller flakes. A similar trend for the maximum thickness of spalls was observed; the highest exfoliation values characterized the chalk formations with a lowering depth of 7.7 to 9.6 cm. The average values obtained for the maximum thickness of spalls in the limestone yand dolomite formations were lower - 2.6-5.4, respectively (Fig. 5). The effect of the fire is evident not only on the surface of the rocks but also at the near subsurface, to a depth of several centimeters. Substantial alteration of the chalks was found in the thin sections of a severely burned flake. The rocks were completely burned to a depth of 2–3 cm. Fine sediments, roots, colonies of cyanobacteria, and other organic material found in the interspace between the Nari laminae were also burned at this depth.

Three years after the fire, the flakes that disintegrated and detached have fallen, and a new, fresh rock face has been exposed to atmospheric processes and weathering. New surficial cracks have developed in the rock, allowing dust, organisms, and seeds to penetrate. The abundant flakes, so prevalent during the first year after the fire, have nearly disappeared. They have been removed by gravity and runoff, covered by new sediments or vegetation or incorporated into the topsoil.


**Figure 4.** The day after the fire ceased (8 December 2010). (a) Exfoliation of a large boulder of Arqan (chalk) Formation (Fm) surrounded by burned pines and oaks; (b) typical chalk outcrop of Arqan (chalk) Fm, shattered and exfoliated at surface in a layeredlike structure of flakes lying atop one another. Note the brownish colour of the lowermost flakes; (c) 100% exfoliated surface of chalk; (d) isolated flakes on Bet-Oren (limestone) Fm; (e) isolated flakes on Yagur (dolomite) Fm; ( f ) shattered boulder of Arqan (chalk). (online version of this paper available at http://www.publish.csiro.au/paper/WF14221.htm.(N. Shtober-Zisu et al., 2015)

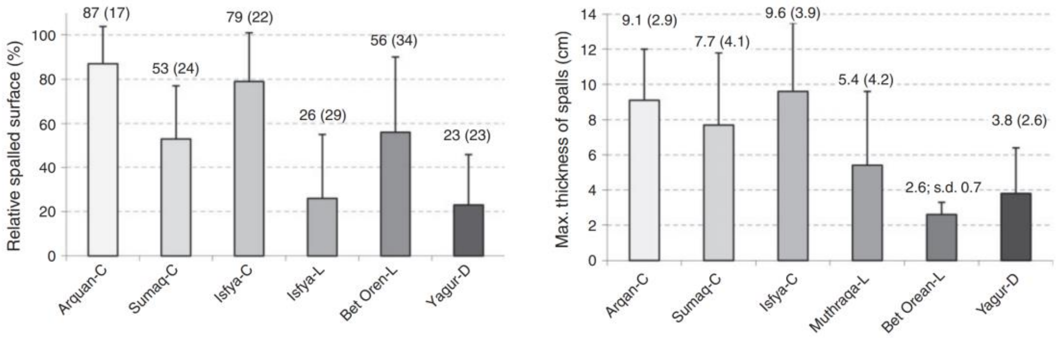


**Figure 5.** left: Percentage of spalled surface, distributed by geological formation. (Labels: average values and standard deviation values (in parentheses). C, chalk; L, limestone; D, dolomite). Right: Maximum thickness of the spalled surface, distributed by geological formation. (Labels: average values and standard deviation values (in parentheses). C, chalk; L, limestone; D, dolomite.) source: (N. Shtober-Zisu et al., 2015).

Buckman et al. (2021) developed a simple fire-spalling erosion formula that estimates the long-term rate of fire-induced spalling in terms of the thickness of the flakes produced by a single fire, the total surface area as a percentage of the exposed rock face affected by a single fire, and the average fire recurrence interval for a given region (Buckman et al., 2021).

$$E = \frac{W\ x\ A}{t}$$

E = rate of erosion due to fire-spalling (mm $yr^{-1}$),

W= average width (thickness) of spalled sheets (mm) for a single fire event.

A = area of rock surface affected by fire-spalling as a percentage (%) of total surface area.

t = average fire recurrence interval (years).

Based on the data acquired from mt. Carmel fire experiments denudation rates equal 0.06-0.9 mm $y^{-1}$. The chalks exhibit the highest rates, while the dolomites are less susceptible to fire-induced erosion (Table I).

**Table I.** Geological formation, the average width of the spalls, and the calculated erosion rates, given the 100-year recurrence interval of the 2010 fire

| | A (%) | W max (mm) | E mm/yr |
|---|---|---|---|
| Arqan (chalk) | 0.87 | 103 | 0.896 |
| Isfya (chalk) | 0.79 | 107 | 0.845 |
| Sumaq (chalk/Limestone) | 0.53 | 82 | 0.435 |
| Muhraqa (Limestone) | 0.26 | 58 | 0.151 |
| Bet Oren (Limestone) | 0.56 | 46 | 0.258 |
| Yagur (Dolomite) | 0.17 | 35 | 0.060 |

## 4. The implication to denudation rates

If fires can erode boulders in a single wildfire event, it follows that wildfires may serve as limiting agents in the geomorphic evolution of slopes. For example, Humphreys et al. (2003) estimated that burning 1% of the rock surface in the sandstone of south-eastern Australia every 20 years corresponds to a denudation rate of 6 m per million years (Humphreys et al., 2003).

Adamson et al. (1983) estimated nearly 6 kg of flakes per square meter of exposed sandstone in the sandstone landscape of the Sydney Basin (Adamson et al. 1983). In case 1% of the area was affected every 20 years, resulting in a spalling rate of 3 g $m^2$ $y^{-1}$, a total denudation rate of about 6 m $My^{-1}$ (assuming a rock density of 2 g $cm^{-3}$) would be the result. This estimate is probably a conservative approximation that does not consider other fire-related erosive processes. Following rainfall events, wind and water flow might further dislodge the weakened crust, resulting in the removal of a 1-2 mm layer (Adamson et al., 1983), equating to another 5-10 m $My^{-1}$. Such conservative estimates are of high geomorphological importance since they equal rates of landscape lowering estimated by other methods in which erosional processes are subsumed under different terms such as valley widening, cliff retreat, and plateau lowering (Humphreys et al., 2003).

Previous studies estimated the rate of denudation of the Mediterranean region in Israel at 10–20 m $My^{-1}$. Rock outcrop may lose as much as 20 cm of its thickness in a single fire. If applied over a long term, this value can be responsible for a high percentage of the total denudation rate. Therefore, wildland fires may serve as significant factors in landscape evolution in the mountainous carbonate slopes of the Mediterranean region.

## 5. The implication to soil stoniness and soil formation

Stoniness (i.e., rock fragment content) is the volume of rock particles larger than 2 mm; stony soils contain over 35% or 40% of the volume of soil particles (Soil Survey Staff, 2010). In Mediterranean areas, stoniness can reach 60%. Rock fragments within and on top of the soil surface affect key hydrological processes including water repellency, thermal properties, physical degradation, erosion, and productivity (Cerdà, 2001; J. W. Poesen et al., 1994; Yang et al., 2021). Poesen et al. (2014) described three main effects of rock fragments on soil erosion: (a) protection against raindrops and splash impacts, (b) reduction of physical degradation of the eroding surface, and (c) retardation of overland flow velocity. Fragments on the soil surface reduce erosion by moderating the splash effect, postponing runoff generation, and preventing sealing processes (Zavala et al., 2009). While rock fragments incorporated into the soil matrix might increase runoff rates (J. Poesen & Lavee, 1994). Thus, the direct impact of fire on soil properties may also depend on the position of rock fragments: rock fragment cover reduces the highest maximum temperature of the soil surface, decreases the depth of lethal heating

(60 °C), and increases the duration of heating. However, rock fragments embedded in the soil only have minor effects on soil thermal behavior (Stoof et al., 2011). Despite the multitude of studies addressing the geomorphic role of rock fragments in various soils, few have considered their formation, especially concerning wildfires and heating (Bierman & Gillespie, 1991; Humphreys et al., 2003; N. Shtober-Zisu et al., 2018) (Fig. 8).

**Figure 6.** Fire-induced increased Stoniness (N. Shtober-Zisu et al., 2015)

To investigate the fate of the detached spall and the effects of fire on rock fragments, we analyzed the soil stoniness ten years after the Mt. Carmel fire (2010). Rock fragments cover was assessed in 75 micro-plot (10*10 cm), at both burned (10 years after the fire) and unburned control sites, using two methods: (a) area, the ratio of surface area covered by rock fragments vs. bare soil area; (b) volume percentage of rock fragments of the total volume of material collected up to a depth of 2 cm.

The fire triggered a severe exfoliation of the carbonate outcrops; consequently, the bedrock surfaces were extensively covered with flakes and spalls, comprising up to 80–100% of the exposed rocks. Ten years after the fire, almost all the burned fractures from the rock surfaces were gone, probably by erosion processes. The previously burned rock surfaces were light-colored, similar to their counterparts in unburned locations. Only a few spalls (1–2 per m$^2$ ) remain firmly attached to the bedrock. Occasionally, fissures and fractures are visible on the rock surface. Pioneering microorganisms such as microcolonial fungi and lichens were observed on denuded and insulated rocks (N. Shtober-Zisu et al., 2015; Nurit Shtober-Zisu & Wittenberg, 2021b).

Surface stoniness and rock fragment sizes were more significant at the burned sites than at the control sites. The fire had a prominent effect on the surface stoniness of the chalks, whereas its impact on the dolomite and limestone was less evident. The stoniness of the control non-burned chalk micro-plots was 23–39%. However, following (10 years), fire stoniness was significantly higher and covered 69–86% of the soil surface (Table II).

**Table II.** Surface stoniness before and after the fire. 1Wilcoxon Two-Sample Test results for each geological formation

| Area | Group | N | Mean | Stdv | Median | Minimum | Maximum | p. value[1] |
|---|---|---|---|---|---|---|---|---|
| Sumaq | Control | 5 | 25.63 | 15.96 | 20.57 | 8.20 | 47.47 | 0.005 |
| | Burned | 10 | 69.56 | 17.96 | 72.05 | 35.03 | 89.66 | |
| Arqan | Control | 5 | 39.34 | 12.34 | 42.08 | 25.61 | 56.40 | 0.008 |
| | Burned | 10 | 77.60 | 15.66 | 81.44 | 40.27 | 91.64 | |
| Isfye | Control | 5 | 23.30 | 14.34 | 16.80 | 11.02 | 45.99 | 0.002 |
| | Burned | 10 | 85.39 | 9.36 | 84.60 | 70.63 | 98.78 | |
| Yagur | Control | 5 | 31.04 | 16.74 | 33.25 | 13.56 | 50.79 | 0.112 |
| | Burned | 10 | 45.23 | 16.19 | 51.71 | 18.78 | 67.72 | |
| Muhraqa | Control | 5 | 42.81 | 25.17 | 53.04 | 5.99 | 69.18 | 0.854 |
| | Burned | 10 | 46.41 | 26.49 | 43.88 | 7.38 | 80.59 | |

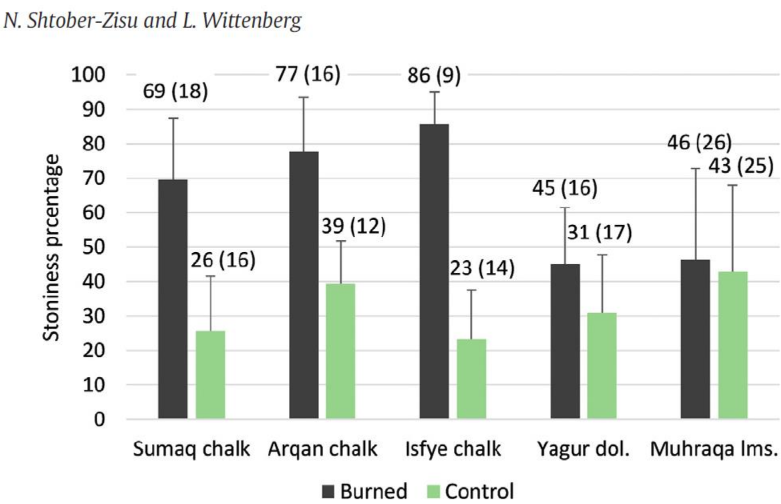


**Figure 7.** Surface stoniness by weight [%]. Average values labeled; std labeled in parentheses source: (Nurit Shtober-Zisu & Wittenberg, 2021a)

Fires have short and long-term contributions of various elements to the environment: initially, as fine materials in the form of ash, burned organic and inorganic substances, and progressively, with the addition of pulverized spall and rock fragments. Thus, fires not only increase the susceptibility of burned areas to enhanced post-fire erosion and land degradation but can also accelerate rock weathering, increase soil organic carbon content, and facilitate soil formation. In the long term, fires play a vital role in the evolution of mountainous landscapes at rates and forms that are not fully understood.

Fire can directly affect soil properties through heating and combustion processes and indirectly via rock weathering and the contribution of spalls and rock fragments. When exposed to high temperatures, rocks tend to disintegrate and exfoliate; chalk exposures are more susceptible to the effects of fires than hard dolomite and limestone.

The exfoliation was nearly completed a decade after burning. Flakes and spalls almost wholly detached from the rock outcrop and exposed a fresh rock face with hardness, similar to the control-unburned rocks. The formerly separated spalls and flakes broke down to form small rock fragments, enriching the soil, increasing stoniness and roughness, and altering the post-fire soil structure  and properties (Fig. 8)

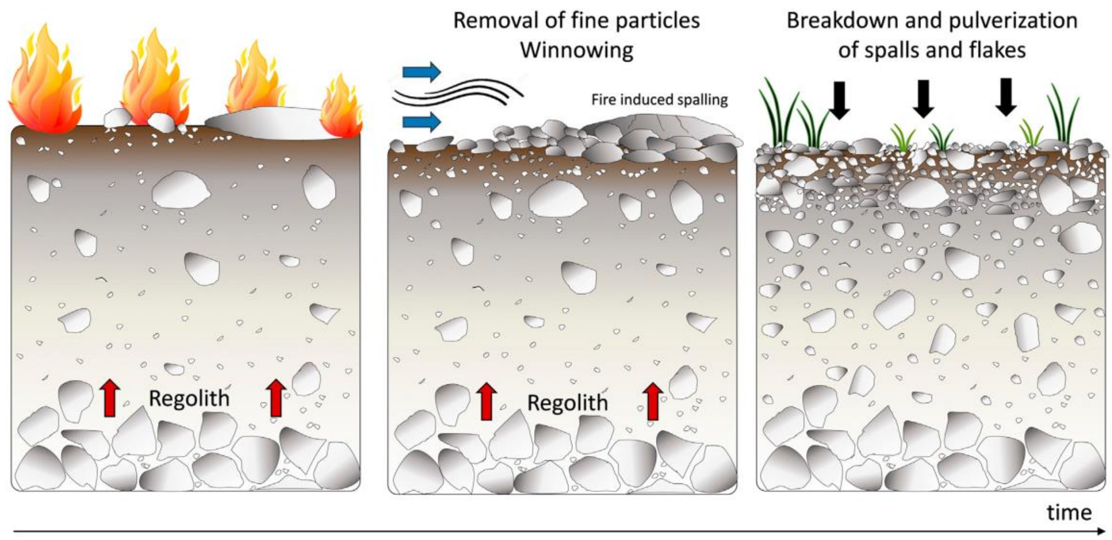


**Figure 8.** Long-term effects of fire on stoniness and pedogenesis: breakdown and pulverization of burned spalls contribute to the increase in soil stoniness source:(Nurit Shtober-Zisu & Wittenberg, 2021a)

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## Chapter 6. Post-fire soil erosion and Mitigation measures applied in the northwest of Portugal[16]

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### Introduction

It is generally accepted that fire is one of the most ancient tools for cleaning areas in order for them to be cultivated and their pasture renewed, among other activities (Sá *et al*., 2007).

Nevertheless, wildfires are becoming increasingly frequent as a result of climate change and poor forest planning, with deleterious impacts on vegetation and soils. Fire drastically reduces or eliminates the vegetation cover, thus exposing the surface to rainfalls that easily erode the top soil layer, which is the major nutrient pool in most soils, in particular the shallow soils affected by wildfires in Portugal. Higher sediment wash rate by runoff erosion typically occurs during the first autumn rainfall events, roughly meaning that the first 6 months after a wildfire are the most critical for nutrient mobilization in eroded soil particles and runoff water.

The destruction of vegetation by fires makes soils vulnerable to erosion, by promoting the removal of nutrients together with organic and mineral components. This significant and continuous degradation of soil, especially visible in Mediterranean areas, makes the implementation of slope protection measures urgent in order to mitigate the effects of wildfires and reduce the loss of soil and nutrients (Shakesby *et al*., 1993; Bento-Gonçalves & Coelho, 1995; Walsh *et al*., 1998; Bento-Gonçalves & Lourenço, 2010; Vega *et al*., 2010; Shakesby, 2011; Bento-Gonçalves *et al*., 2012; Vieira *et al*., 2018).

Nevertheless, this process is closely dependent on fire recurrence, intensity, severity, and spatial variability of soil hydrophobicity (Jungerius & Dejong, 1989; Ritsema & Dekker, 1994; Coelho *et al*., 2004; Bento-Gonçalves *et al*., 2012; Ferreira-Leite *et al*., 2011), as well as the physical characteristics of the affected area (for instance slope gradient and aspect, climate, geological composition) as some pioneering studies conducted in Portugal have demonstrated (Bento-Gonçalves & Lourenço, 2010). Therefore, is important to take all these factors into consideration and adapt the different mitigation measures and techniques to each specific context.

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[16] This text is partially based on the works previously published by the authors and other collaborators, namely: Vieira and Bento-Gonçalves (2016, 2020, 2021a, 2021b), Bento-Gonçalves et al. (2019), Vieira et al. (2018, 2019).

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Science can help solve these problems, by increasing and strengthening present knowledge on actual risks, so as to provide solutions for those posed by future fire regimes and their impact on land degradation.

The effects of wildfires in the ecosystems, in all their different dimensions, have been the subject of extensive research (Neary & Leonard, 2015), especially related to soil erosion and degradation (Bento-Gonçalves *et al*., 2012). In this work we will show some case studies in the northwest of Portugal, where fire affected areas were intervened and monitored regarding the occurrence of soil erosion and the implementation of mitigation measures.

**1. Research on soil erosion**

Soil erosion is a severe environmental problem that has become widespread on almost the entirety of the planet's land surface, with direct and indirect effects on soil productivity and, consequently, human survival.

This degradation of soil, as a resource, typically takes place as a result of a diverse set of erosive processes that have varying effects on the earth's surface, causing problems not only in eroded areas, but also in locations where sediment is deposited. One of these processes is silting, which can be detected in rivers, reservoirs, lakes and even in farmland, as well as other areas subjected to various human activities.

Following work developed essentially during the first half of the 20$^{th}$ century, in 1960, the United States Department of Agriculture established the threshold of soil loss within American territory as a maximum of 5 tons per hectare, per year (t/ha/year)(Guerra, 2016). Ashman and Puri (2002, quoted by Guerra, 2016) consider that, according to estimates, 80% of the world's agricultural soils are subject to some form of erosion. Likewise, the values presented by Pimentel *et al*., (1995, quoted by Vásquez-Méndez et al., 2011) indicate that approximately 80% of agricultural soils in the world suffer from moderate to severe erosion, while 10% suffer from mild to moderate erosion.

The consequences of this phenomenon are especially notable if we take into account that the average rate of soil formation is around 1 t/ha/year. In agricultural areas, vineyards or soils without vegetation, soil loss values are above 15 t/ha/year in China, at 6 to 7 t/ha/year in the United States (Nearing *et al*., 2017) and are greater than 14 t/ha/year in Europe (Boardman and Poesen, 2006).

In addition, soil erosion can lead to the loss of 75 to 80% of its carbon content, causing carbon emissions to be released into the atmosphere (Morgan, 2005). Erosion caused by water adversely affects soil quality and productivity by reducing infiltration rates, water retention capacity, nutrients, organic matter, soil biota and soil depth.

Consequently, soil erosion is a problem that has generated significant concern among the scientific community and has prompted numerous studies over several decades, all over the world (Morgan, 1995; Laflen and Flanagan, 2013).

Soil erosion is a global problem and, although it is more severe in developing countries, it has now become more of a concern in more technologically advanced countries (Guerra, 1996). Soil erosion corresponds to the detachment of individual particles, their transport and subsequent deposition by one or more erosive agents, whether natural or anthropic (Boardman and Poesen, 2006). According to Selby (1993), soil water erosion corresponds to a geomorphological process that takes place on slopes, resulting from the impact of raindrops (splash erosion) and the flow of precipitated water. Other authors also refer to the slope erosion process, reinforcing the role of these two agents (Guerra, 2016).

However, soil erosion, considered herein essentially as water erosion, is also a product of weathering (in its various forms, whether chemical or physical), of living beings and, especially, of anthropic actions. Indeed, weathering and erosion are not only intrinsically linked but are also two fundamental processes within the lithological cycle. Soil erosion is a phenomenon that takes place on practically the entire land surface of our planet, and in some areas, erosion and the consequent deposition of sediment are essential in order to maintain the soil's natural fertility.

However, the erosion of slopes also promotes the removal of the superficial part of the soil, which is precisely where the highest concentration of nutrients can be found (Bento-Gonçalves *et al*., 2008a). When this process takes place at rates higher than those of weathering and those necessary for soil formation, its loss is irreversible. Erosive processes, facilitated by the development of rills and gullies, which have a significant impact on agricultural land, also produce adverse effects downstream, namely sedimentation and the clogging of the bottoms of valleys, which can result in the obstruction of communication routes and destruction of other infrastructure and properties (Van Beek *et al*., 2008).

Soil erosion produces significant effects, both on-site and off-site. The on-site effects consist mainly of the loss of soil materials (the soil itself), plant residues, soil organic matter, and nutrients, as well as a reduction in soil fertility, productivity, biodiversity and biological activity (Osman, 2018). Regarding the off-site effects, they take place as a consequence of the movement of sediments and nutrients. One of the effects is reflected in water contamination, which can come about as a result of the excessive accumulation of nitrogen and phosphorus, causing eutrophication, or of toxic metals and organic compounds (such as pesticides), producing biomagnification. The other off-site effect results in damage produced by sediments: sedimentation of watercourses and dams, damage of roads and destruction of houses and other infrastructures, among many others.

These effects impact significantly on human activities, which, in turn, produce enormous economic losses. Pimentel *et al*. (1995) referred that the total on-site and off-site costs of the damage caused by wind and water erosion and the cost of erosion prevention each year totals 44,399,000,000 US$ in the USA.

Soil erosion and degradation pose a significant threat to global food security, compromising the well-being of at least 3.2 billion people around the world (IPBES, 2018). Soil is responsible for 99% of the world's food production (Hatfield *et al*., 2017), which is why it is so critical that soil erosion mitigation strategies and measures for protecting our soil are developed and implemented in order to ensure we are able to continue to live in a sustainable and food-secure world.

## 2. Wildland Fires, impacts on soils and mitigation measures

One of the primary environmental disturbances contributing to the increase of soil erosion and degradation, which often require the application of restoration measures, is wildland fires (Bento-Gonçalves *et al*., 2012).

Indeed, they are one of the main drivers of land degradation, producing several effects on soil, water and vegetation, in addition to their socialeconomic impact:

- Changes in soil properties (infiltration rates, porosity, conductivity and storage capacity);
- Changes in soil structure;
- Increase in runoff and overland flow;
- Increase in soil losses;
- Increase in water erosion;
- Reduction of organic matter content;
- Destruction of vegetation cover;
- Loss of habitats;
- Mass movements, gullies etc.

These impacts have been strongly demonstrated (Certini, 2005; Neary *et al*., 2005; Cerdà and Robichaud, 2009; Mataix-Solera and Cerdà, 2009; Massman *et al*., 2010; Zavala *et al*., 2014; Neary and Leonard, 2015), as well as their contribution to the overall erosion and degradation of soil (Moody and Martin, 2009; Shakesby and Doerr, 2006).

In order to reduce and prevent soil erosion after a fire it is fundamental that adequate measures be implemented, and a strategy for forest and soil defence and recovery structured, taking into account the continuous growth in the number of fires and burnt areas witnessed (Robichaud, 2009; Bento-Gonçalves *et al*., 2012), especially in Mediterranean areas (Bento-Gonçalves *et al*., 2019).

The main intervention measures applied to areas affected by wildland fires can be grouped according to the following three categories (Robichaud, 2009; U.S. General Accounting Office, 2006; Bento-Gonçalves *et al*., 2012, 2013):

1. Intervention measures applied immediately after fires (sometimes even before the fire is entirely under control), which fall under "emergency stabilisation," seek to control erosion and are often based on mulching, log barriers along contour lines or check-dams in water lines, and seeding. The main objective is to promote soil protection, increasing infiltration and hydrological regulation;
2. The second category encompasses "rehabilitation" techniques, corresponding to interventions carried out between 1 and 3 years after the fire, including a set of actions used to repair facilities or mitigate damage to lands unable to repair themselves;
3. The last category ("restoration" strategies) focus on implementing long-term actions geared towards restoring and improving habitat quality and productivity, and increasing resilience.

Independently of the measures to be applied, it is essential that the areas in need of soil protection measures be decided upon (Robichaud, 2010).

Moreover, medium- and long-term strategies must be developed to increase the heterogeneity and fragmentation of the structural diversity of vegetation, which may contribute to increasing the landscapes' resistance to fire (Moreira *et al*., 2009).

Thus, in most cases, a minimum set of priority objectives can be defined to reduce the impacts of forest fires (Vallejo, 2006):

1. Soil protection and hydrological regulation;
2. Reduction of fire risk, increasing the resistance and resilience of ecosystems and landscapes to forest fires;
3. Development of adult, diverse and productive forests.

In the short term, several mitigation and restoration strategies can be applied, depending on the risk of soil degradation and management objectives. Consequently, scientific and technical bases of intervention geared towards managing burnt areas must be developed and disseminated.

These strategies must be applied immediately after fires have taken place to minimise erosion and, at the same time, contribute to the conservation of ecosystems.

According to Vallejo and Alloza (2018), who analysed the application of these measures in the Iberian Peninsula, post-fire intervention must preferentially be conducted on steep slopes and in drainage channels in order to protect the soil more effectively.

One of the appropriate options for steep slopes with scarce vegetation cover and high risk of erosion is "mulching" (deposition of a covering of woody debris on the surface of the unprotected soil), accompanied by seeding, in areas with low regeneration capacities. When the main objective of this restoration is not solely to protect the soil, but also to improve biological diversity and the resistance and functionality of the affected areas, it is advisable that arboreal and shrub species with high growth rates be planted.

However, depending on the position in the burnt area, soil recovery techniques can be grouped into different types (Table I), as follows: i) hillslope treatments, ii) channel treatments and iii) roads and trails treatments. These treatments can be combined for use in burnt areas (Robichaud *et al*., 2000; Neary *et al*., 2005).

Despite the importance and valuable contribution of these treatments to soil protection and vegetation recovery, certain authors argue that in some cases it may be preferable not to apply any measures whatsoever (Bautista *et al*., 2009; Robichaud, 2009), whilst also clearly stating that the efficiency of any measure must be monitored and evaluated continuously, as well as its impact on the soil, water and plants in the short and long term (Kruse *et al*., 2004; Neary, 2009; Robichaud, 2009).

**Table I.** Burnt area emergency rehabilitation (BAER) treatments (Neary *et al*., 2005, based in Robichaud *et al*., 2000)

| **Hillslope** | **Channel** | **Road and Trail** |
|---|---|---|
| Broadcast seeding | Strawbale check dams | Rolling dips |
| Seeding plus fertiliser | Log grade stabilisers | Water bars |
| Mulching | Rock grade stabilisers | Cross drains |
| Contour-felled logs | Channel debris clearing | Culvert overflows |
| Contour trenching | Bank/channel armouring | Culvert upgrades |
| Scarification and ripping | In-channel tree felling | Culvert armouring |
| Temporary fencing | Log dams | Culvert removal |
| Erosion fabric | Debris basins | Trash racks |
| Straw wattles | Straw wattle dams | Storm patrols |
| Slash scattering | Rock gabion dams | Ditch improvements |
| Silt fences | | Armoured fords |
| Geotextiles | | Outsloping |
| Sand or soil bags | | Signing |

### *2.1. The research develod in the University of Minho on post-fire soil erosion and mitigation techniques*

During the last two decades researchers from the Department of Geography of the University of Minho (coordinated by the authors of the present chapter) have developed work on post-fire soil erosion and mitigation techniques. Among other initiatives we can highlight the participation in the *RECOVER* project (PTDC/AGR-AAM/73350/2006), that took place between 2007 and 2010, in collaboration with the University of Aveiro and the Coimbra Agriculture School, which aimed to develop mitigation techniques and strategies for reducing soil and water degradation immediately after forest fires. Thus, a set of feasible solutions was tested in order to reduce ash washing. It also included the proposal of methodologies for three-dimensional modeling and modeling of flow/flow surfaces, and their integration in an Integrated Information System (IIS) and in the modeling of morphological processes in a GIS (Geographic Information System) environment (Bento-Gonçalves *et al*., 2008a, 2008b; Vieira *et al*., 2009, 2010, 2011).

Since 2010 we have been developing the project *SoilProtec* (Emergency measures for soil protection after forest fires), whose main objectives are to develop mitigation measures for soil erosion affected by forest fires. In this sense, we have implemented an experimental field in the Peneda-Gerês National Park (with the support of the Institute for Nature Conservation and Forests and the Peneda-Gerês National Park), developing emergency measures applied to processes triggered on slopes and in channels, as well as evaluating the effectiveness of these implemented erosion mitigation measures and their cost/benefit ratio.

In 2013 we started a second phase of the *SoilProtec* project, which was developed with the support of the Municipality of Santo Tirso, in order to implement experimental areas for the evaluation of fuel reduction techniques in forested areas of the county, seeking to assess their effectiveness and the impacts caused on soil and forest (Rocha *et al*., 2016).

In 2017, following the major fire that hit the urban-forest interface of the city of Braga, in partnership with the Civil Protection Service of Braga City Hall, we implemented erosion plots for monitoring erosion processes, taking into account different erosion mitigation methods (different types of mulching), and we implemented erosion mitigation measures in canals.

We are currently developing 3 research projects related to the occurrence of forest fires: one related to the economic quantification of the impacts of forest fires (Ecofire; https://eco-fire.pt/eng/); another aiming at conceiving and implementing an optimization framework (including mathematical programming, meta-heuristics, and GIS and visual interfaces) for Fire-aware forest management and Resources management for wildfire prevention and suppression (O3F; http://o3f.dps.uminho.pt/); and the third whose main objectives are to establish a post-fire performance model based on the risk of soil loss and soil quality, and the development of a tool to monitor soil recovery (Erofire; https://www.cecs.uminho.pt/en/projetos/erofire-avaliacao-do-risco-de-erosao-pos-incendio-usando-marcadores-moleculares/).

From the research that has been developed by the team from the University of Minho regarding the study of forest fires, their impact on soil (erosion and degradation), and measures for the mitigation of erosion in burned areas, we will present in the next sections two case studies, which illustrate the erosive phenomenon that occurs in the slopes of northwestern Portugal and the measures tested for its mitigation.

## 4. Soil erosion monitoring and evaluation of mitigation techniques on fire affected areas in the Peneda-Gerês National Park

### *4.1. The study area and fire characteristics*

The occurrence of two major forest fires in 2010 in the Peneda-Gerês National Park produced an extensive area vulnerable to soil erosion within a Protected Area of very high value.

The natural characteristics of the burned areas, with steep slopes and poor soils, reveal a high risk of soil erosion. These characteristics lead us to implement different techniques for erosion mitigation in the experimental area, in order to evaluate not only their effectiveness, but also their cost/benefit relation.

The area identified for implementing the techniques was affected by the fires that broke out on August 2010 in the municipality of Terras do Bouro (Fig. 1), in the heart of the Peneda-Geres National Park (NW Portugal). These fires produced a continuous burnt area with 3500ha which was subject to different fire intensities and severity. It is a large area, occupied by scrublands and stands of Pinus pinaster. The lithology is mainly granite and the soils (cambisols) are generally thin and stony. The land cover in the last 50 years has been essentially composed of woodlands that are favored by the climate, which is characterized by high amounts of precipitation.

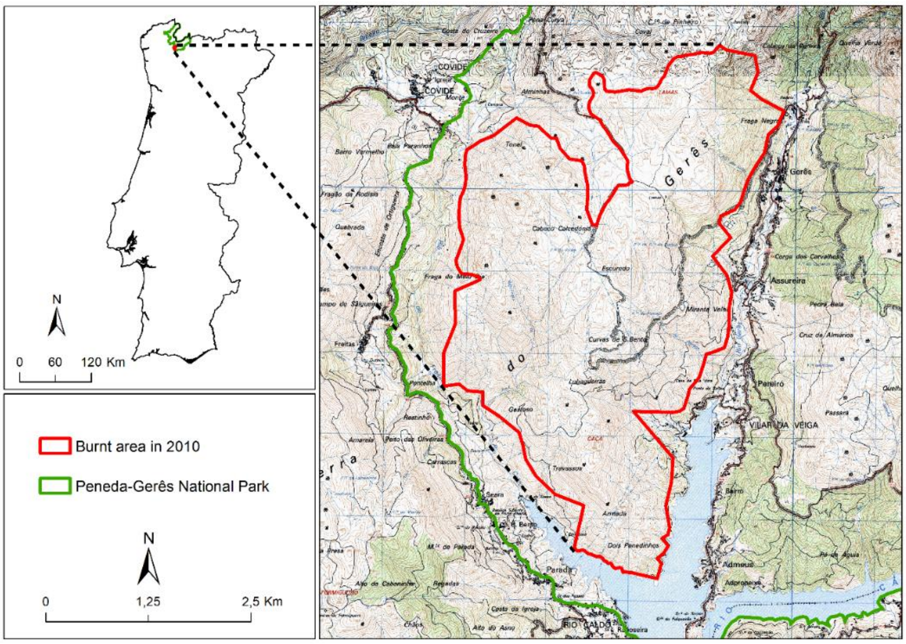



**Figure 1.** Limits of the burnt area in the two large forest fires that occurred in 2010 in the municipality of Terras de Bouro.

In order to evaluate the severity of the fire on the affected area, we analyzed the satellite images from before and after the forest fires. Based on Landsat 5, images of July 30, 2010, and April 28, 2011, a NBR algorithm (normalized burnt ratio) was implemented with the definition of five classes of severity: very high, high, moderate, low severity, and not burned (Fig. 2).

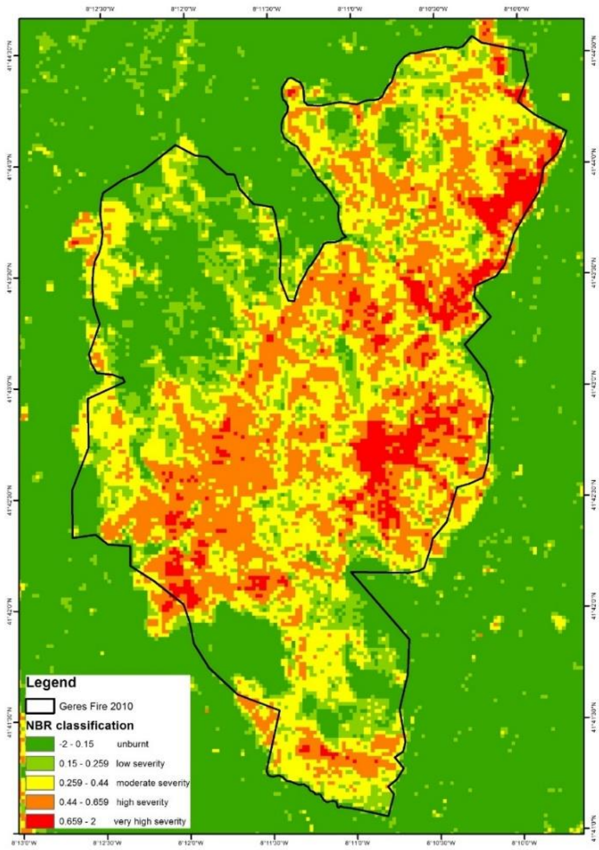



**Figure 2.** Severity map of the burnt area in the forest fires of August 2010. Created by Chris Schafer (Sydney Catchment Authority – Australia).

The result was validated in the field (Fig. 3), where fire severity was evaluated using the BAER methodology presented by Parsons *et al*. (2010) and the methodology proposed by Lampin et al. (2003).

Based on the distribution of the severity of fire and on the erosion risks identified in the field and topographic conditions, two experimental areas were defined, in order to implement the erosion mitigation techniques. Through the "Soil Protec" project (Emergency measures for post-fire soil protection), different low cost emergency measures were tested. The techniques were implemented in slopes and in channels immediately after the fires in areas of low to medium fire severity.

These areas were essentially composed of Pinus pinaster stands in Serra do Gerês (Bento-Gonçalves et al. 2011).

**Figure 3.** Junceda – Medium and High severity burnt areas.

The objectives of the research were: to test the role of pine needles in slopes affected by low to medium severity fires as protection for soil against erosion and compare it with the use of straw; to test a set of measures in channels, where there is a concentration of runoff in order to reduce the gully processes and the removal and transport of soil. This can be achieved by implementing structures, materials, and techniques which favor the retention of sediments and the possible consolidation of ridges and pre-existing gullies.

The measures were assessed in terms of their effectiveness in mitigating erosion (especially throughout time), as well as their cost/benefit.

*2.2. Methodologies and techniques applied to mitigate post-fire erosion on slopes and results*

Following the forest fires that broke out in the study area, we installed six plots[19], measuring 10 meters in length and 2.5 meters in width[20], in an area of a Pinus pinaster stand affected by medium severity fire and with an average slope of 15% (Fig. 4).

We then applied the different proposed treatments selected for evaluation, corresponding to straw (2, 4, and 8 kg) and pine needles (4 and 8 kg), spread over five plots. One plot was left over as a control plot (Fig. 5).

[19] The plots we implemented in the study area were based on the design used in Galicia. Our objective was to establish a comparison with the results obtained by the "Instituto de Investigaciones Agrobiológicas de Galicia". Nevertheless, we concluded that this type of plot isn't the most appropriate for the steep and rocky slopes present in our study area.

[20] Although the total area of each plot is about 25 m2, the use of the geotextile limited the useful area available and, therefore, for this analysis we calculated the effective area of each plot to be about 16 m2.

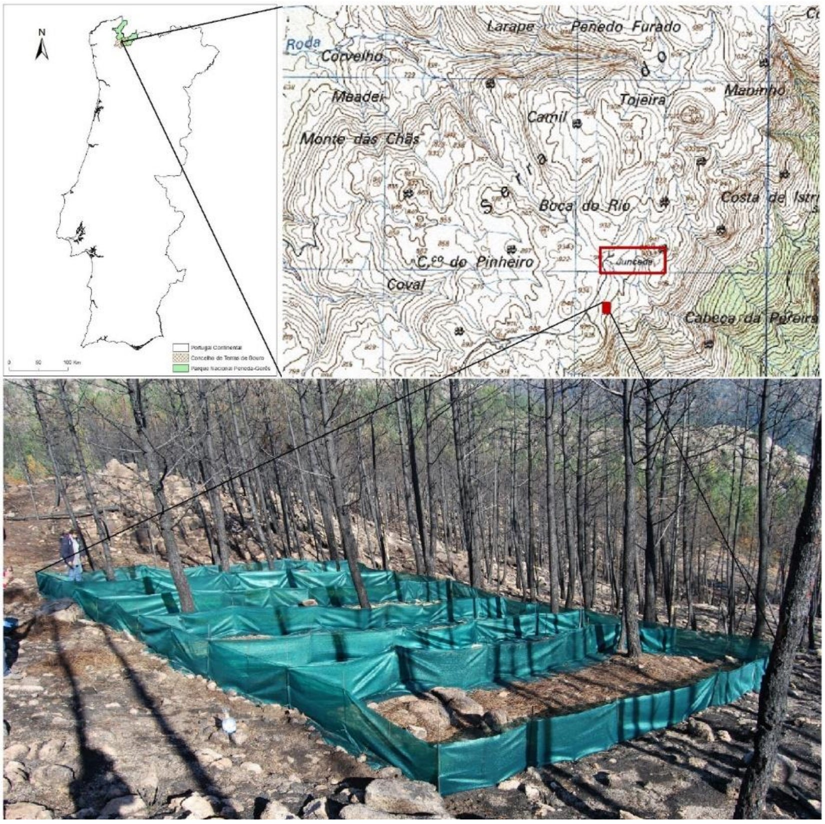
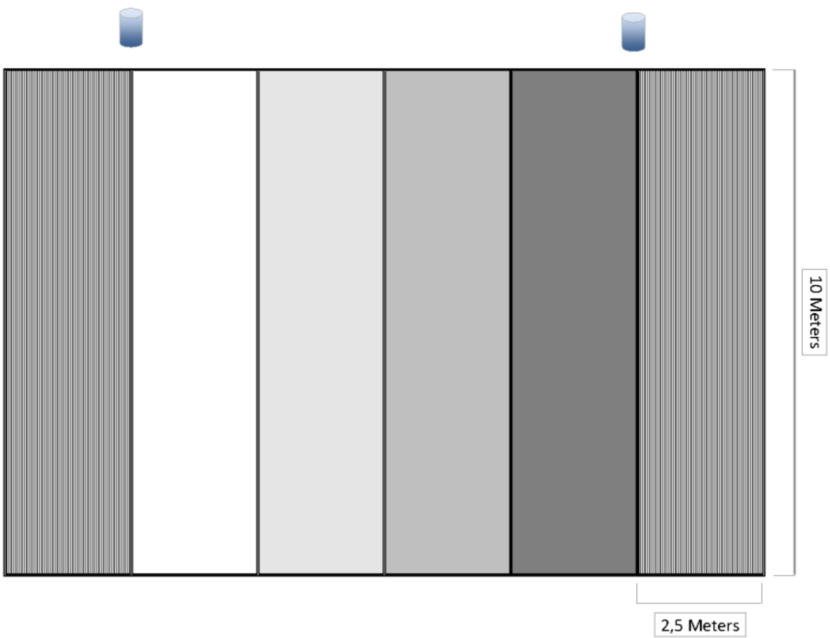



**Figure 4.** Area of installation of the plots (Junceda, Terras de Bouro).




| | | Different Treatments | |
|---|---|---|---|
| Plot 6 | | Pine Needles | 4 kg/plot |
| Plot 5 | | No treatment | - |
| Plot 4 | | Straw | 2 kg/plot |
| Plot 3 | | Straw | 4 kg/plot |
| Plot 2 | | Straw | 8 kg/plot |
| Plot 1 | | Pine Needles | 8 kg/plot |

Rain gauge

**Figure 5.** Experimental design for testing post-fire emergency measures for soil protection.

*Results and Discussion*

The analysis of the results of soil loss indicates that the annual erosion rates in the plots (with and without treatments) are not very significant (Fig. 6). Accordingly, the erosion can be considered tolerable.

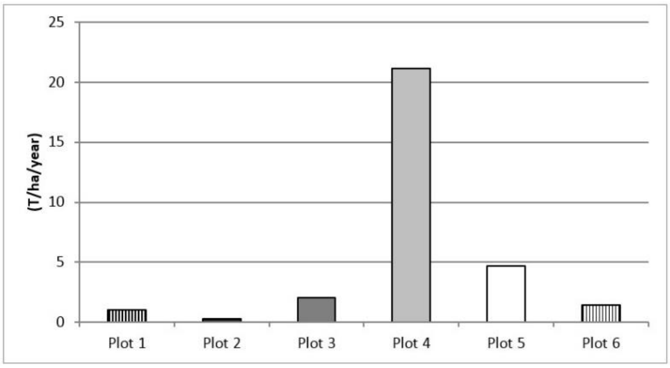



**Figure 6.** Erosion rates (T/ha/year).

In fact, in similar conditions to those verified in our study area, Diaz Fierros *et al*. (1982) identified three thresholds of erosion (for the Galiza region). The three levels correspond to 11, 30, and 100 ton/ha/year. As a result, up to 11 ton/ha/year erosion is considered tolerable. Between 11 and 30 ton/ha/year it is classified as consisting of slight erosion. When the levels of erosion are between 30 and 100 ton/ha/year they are considered moderate and anything over 100 ton/ha/year is grave.

FAO-PNUMA-UNESCO (1980) also presented a classification with three levels of severity for soil degradation, which correspond to 10, 50, and 100 ton/ha/year. In this classification, values below 10 ton/ha/year are considered low or inexistent. Between 10 and 50 ton/ha/year degradation is low, and between 50 and 200 ton/ha/year it is moderate. Above 200 ton/ha/year, it is considered to be high.

In our experiment, only plot 4 was an exception to the tolerable degradation. This plot was subject to a treatment of 1.25 tons of straw per hectare, and it clearly surpassed 10–11 ton/ha/year by claiming more than 21 ton/ha/year. Nevertheless, this value is due to the systemic reception of materials running off from plot 5 (control parcel). The impossibility of totally isolating the plots from one another was responsible for this outlier.

Therefore, one of the first results obtained was the verification of inadequacy of these types of plots in slopes with shallow soils and an irregular and rocky relief (Fig. 7). More precisely, the influence of a micro-relief with small "pools of sediments", which promotes the retention of a large amount of sediments, seems to overcome the influence of the implemented treatments.

**Figure 7.** Detailed image of rocky terrain in one of the trial plots.

The second conclusion from the results demonstrates the high efficacy in protecting the soil derived from all the types of soil covers applied (straw or pine needles).

However, that efficacy tends to progressively diminish after one year (Fig. 8). Although the first significant peak of erosion, characterized by a high volume of precipitation (613.33 mm), occurred between 18 December 2010 and 15 January 2011, the largest peak only occurred nine months later, between 14 September and 28 October 2011.

While the precipitation registered during this period was about half of that of the prior peak (290.75 mm) and the plots contained less material for mobilization, the covering material was already significantly damaged and thus favoring the transport of materials.

On the other hand, the low levels of precipitation in the months prior to this period also hindered the transport of materials and allowed for accumulation. Therefore, with a greater accumulation of materials and less retention capacity due to the damaged cover layer, it is natural that with a greater volume of rain and greater intensity, the quantity of transported material was the greatest in the period under analysis.

Comparing the efficacy of each of the materials in terms of the amount of material applied, we verified that, for the case of 0.5 kg/m$^2$ (5 ton/ha), the use of straw is more effective than that of the pine needles. This is due to the larger area covered by straw when compared with the pine needles and also to the fact that straw creates a higher aggregation of elements, producing a more effective protection—except in very exceptional situations (Fig. 7).

In the cases where the cover is of 0.25 kg/m$^2$ (2,5 ton/ha), the situation is the opposite. During the first year, the pine needles provided greater soil protection (Fig. 8).

Although the straw cover has demonstrated less durability, the results indicate that in the first year, straw is more effective for cover densities of 5 ton/ha. In contrast, pine needle cover revealed greater efficacy for covers of 2.5 ton/ha.

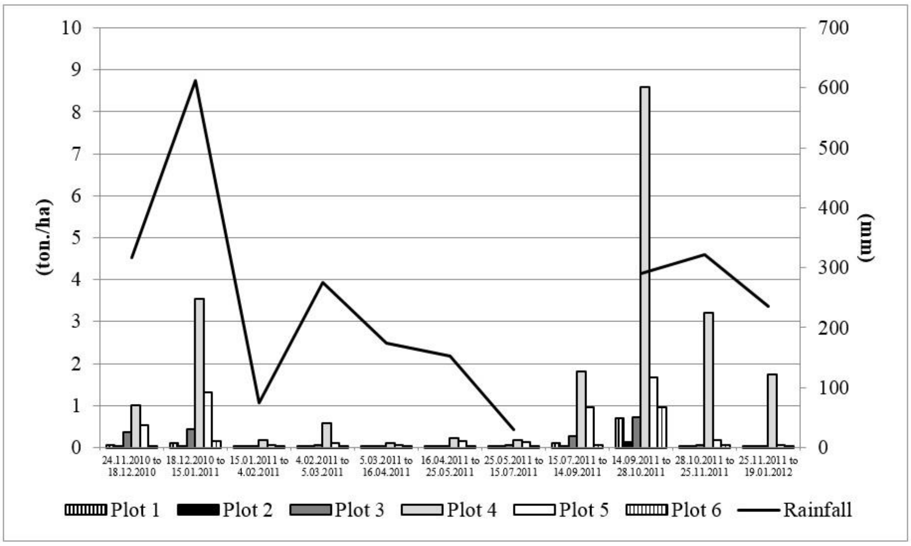



**Figure 8.** Evolution of the erosion rate (ton/ha) in each plot and precipitation (mm) between December 2010 and January 2012.

However, if we take into consideration that straw is an exogenous element in forest ecosystems and it carries seeds, which may alter the vegetation, pine needles may be the better option. Moreover, pine needles may be available locally and thus reduce the need to transport them from far away.

In addition, straw also presents a greater cost. Its purchase value is about €4 for a bale of 12 kg. Besides these costs, we must also add the costs involving its transportation and application in the field.

Taking these values into consideration, for an intervention using 0.25 kg/m$^2$ (2.5 ton/ha), a straw bale (20 kg) can cover an area of 80 m$^2$—that is, about 5 cents per square meter or € 500 per hectare (plus transportation and labor costs). Therefore, while pine needles seem to be the best option, we must take some precautions in their use. More precisely, we must not forget that if we transfer a large amount of pine needles from an area that has not been burned to another that has been scorched, we risk altering the area and leaving the original area unprotected. Thus, by removing the pine needles we are reducing the protective layer and organic materials in the soil. The removal may also imply moving the upper levels of the soil cover and risk depleting it, exposing it to the erosive agents.

Therefore, in case this solution is selected, we should always be careful not to remove the entire pine needle layer. We should limit ourselves to the upper level and avoid depleting the soil, particularly in areas with steep slopes.

*2.3. Methodologies and techniques applied to mitigate post-fire erosion on channels and results*

After the field recognition, a small catchment revealing high erosion risk and the development of gullies was identified and some critical spots were selected and prepared for intervention (Fig. 9). We proceeded with the installation of structural measures in the channels in order to evaluate its effectiveness on soil erosion mitigation. The selected area was subject to significant disturbance and increased risk of erosion after the fire due to the use of heavy machinery to remove burned timber.

**Figure 9.** Selected area for the implementation of channel erosion mitigation measures (the arrows indicate the gullies that were intervened).

The selected mitigation measures were particularly focused on the channels which served to drain the water from the slopes in the study area. The objective of these measures was to alter the flow of water and sediments in order to decrease the amount of soil spilling into the water lines and, consequently, the damaging effect of debris torrents on human infrastructures or agricultural production.

The techniques that we implemented consisted in log check dams, straw bale barriers, and barriers made from the remains of the cutting of the burnt pine trees.

The first dams (log check dams) required the use of mechanical means (tractors and electric saws) for their implementation. Accordingly, this technique is more demanding in terms of costs since it involves more man power for its implementation (Fig. 10).

**Figure 10.** Construction of log check dams.

The overarching objective of these measures is to apply locally collected trunks and, therefore, decrease the inherent costs of transporting materials from outside of the area. The trunks are placed perpendicular to the water flow in order to create a barrier to the sediments transported by water and the runoff from the slope. The accumulation of this material will decrease the speed of the seepage and, eventually, lessening the peak periods of seepage. The accumulation of sediments ("sediment pools") may ultimately catalyze the regeneration of vegetation.

The straw bale barriers are significantly easier to implement. Their objective is the same as that of the log check dams. However, their use should be limited to areas with slopes that are not as steep and in smaller gullies. The placement of the straw bales — preferably between three and five bales—should also be perpendicular to the water way. It is common to use rocks (or logs) in order to support the bales. In the barrier implemented in the study area (Fig. 11) we placed three straw bales which were secured by iron rods and supported by granite blocks.

**Figure 11.** Straw bale barrier implemented.

This method involves taking into consideration the costs of the straw bales and their transportation. The manual labor involved is significantly less demanding and the handling of the bales is relatively easy.

The barriers made from the remains of the cutting of the burnt pine trees are made from materials available in the area. This strategy is one of the least expensive methods and the easiest to implement. For this reason, it is the measure that logging companies may systematically implement after extracting the wood. This is a variant of a technique applied in the US (Napper 2006) in which the canopies of the trees that have been cut are placed along the water ways.

In the study area, the removal of wood (essentially trunks with some economic potential) left large quantities of accumulated materials, such as pine branches, twigs, and other left over materials. This allowed us to implement this strategy in many other locales along the water ways and complement the measures initially planned. This sort of intervention requires very limited labor, taking into consideration that all the necessary resources are locally available.

*Results and discussion*

The techniques applied in order to mitigate erosion in channels include log check dams, straw bale barriers, and barriers made from the remains of cutting of the burnt pine trees. These different techniques were implemented in the early winter months of 2011 and the objective was to evaluate their efficacy in controlling erosion and fixating sediments, particularly in terms of cost/benefit.

The heavy rainfall that occurred immediately after the installation of these measures produced considerable erosion on the slopes of the intervened drainage basin (the average annual rainfall in this region is about 2500 mm). The rainfall caused an intense removal of sediments, which were deposited in the waterways that were part of the experiment. Accordingly, by verifying the accumulation of sediments, this phenomenon allowed us to attest to the efficacy of these techniques.

As a result, we verify that all the techniques applied were capable of retaining sediments. Of the two log check dams installed, one effectively served as a flux absorber and facilitated the accumulation of sediments upstream (Fig. 12 and 13).

The total station survey made on this log check dam, in 2012, 2013 and 2014, allowed us to monitor the sediment accumulation in the dam reservoir and to observe the increment of sedimentation, especially in 2013 (Fig. 14). From 2012 to 2013 an increment in the volume of sediments of 0,8$m^3$ was registered, mainly in the upper part of the retention structure. From 2013 to 2014 the increment in sediment retention was more significant, reaching a volume of 17,9$m^3$. Although not fully filled, the volume of sediments almost reached the top of the dam.

**Figure 12.** Accumulation of sediments in the log check dam (when it was installed and at the last survey).

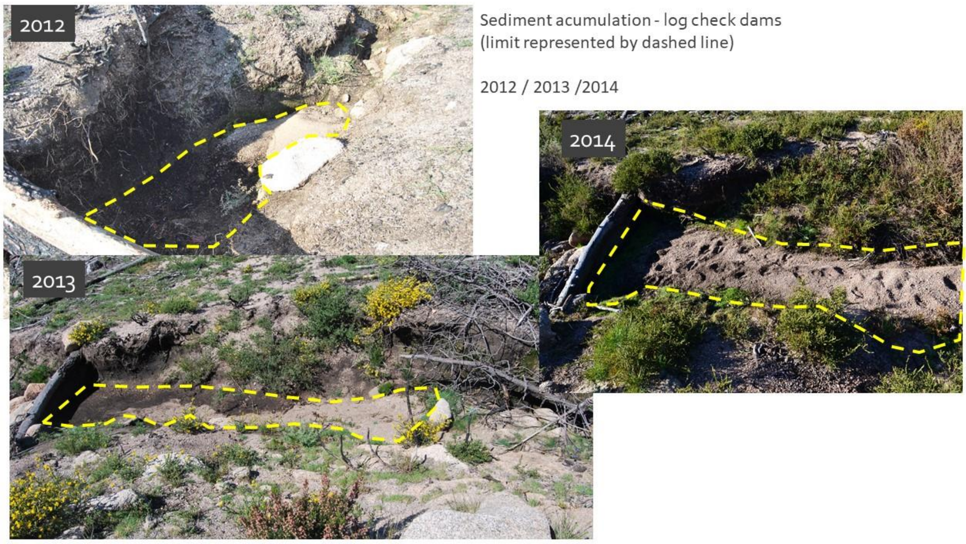



**Figure 13.** Evolution of accumulation of sediments in the log check dam.

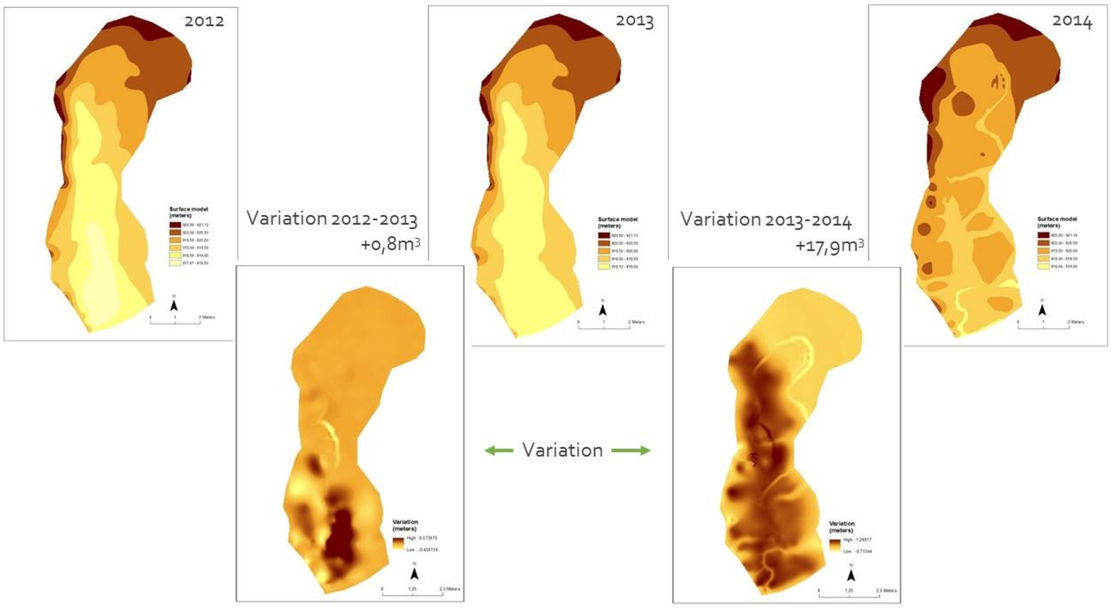



**Figure 14.** Modelling and quantification of the evolution of sediments accumulation in the log check dam.

When assessing the role of the straw bale barriers, we verified their positive effect in sediment retention (Fig. 15). Its efficacy is, in our analysis, highly significant. Its main advantage consists in allowing for the adequate flow of water and avoiding situations of rupture of the system due to the retention of high volumes of water. Nevertheless, this technique is less robust than the barriers constructed from logs and trunks and has a much shorter durability cycle—probably no more than one year.


**Figure 15.** Evolution of accumulation of sediments in a straw bale barrier.

The modeling made on this straw bale barriers, in 2012, 2013 and 2014, allowed us to implement the same monitoring process of sediment accumulation in the dam reservoir (Fig. 16). From 2012 to 2013 an increment in the volume of sediments of 0,6m$^3$ was registered. From 2013 to 2014 the increment in sediment retention was more significant, reaching a volume of 7,6m$^3$. Although the problems that affected this barrier, it was possible to maintain and continue to accumulate significant volume of sediments, till its fragmentation.

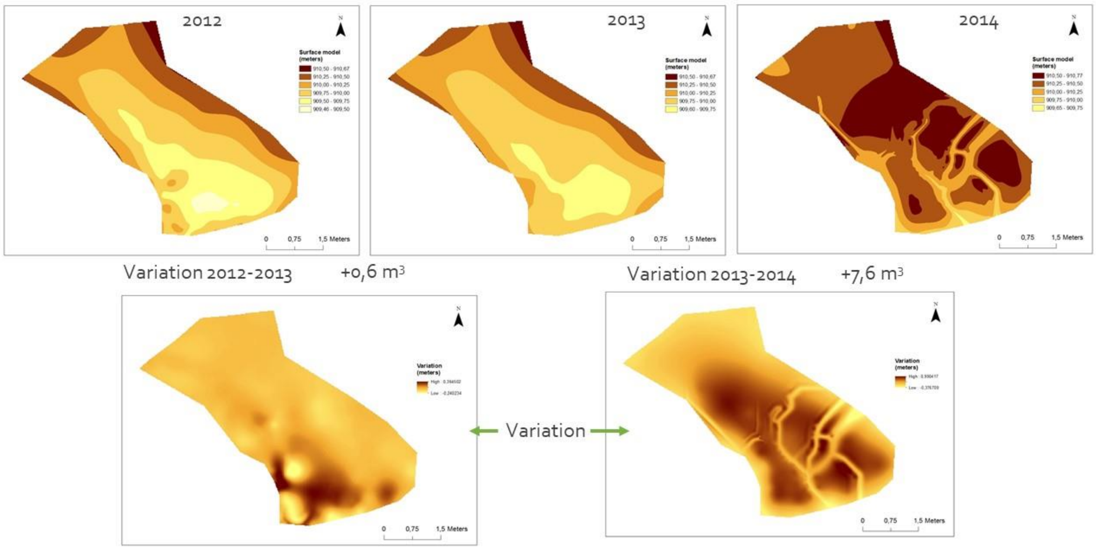



**Figure 16.** Modelling and quantification of the evolution of sediments accumulation in the straw bale barrier.

The barriers constructed from the remains of burnt pine trees and pine needles produced the most significant results. Regardless of the simplicity of this approach, its efficacy in retaining sediments is high. In all the barriers where this technique was implemented, we verified the retention of sediments. In many of these plots, the quantity of sediments retained was very high considering the type of structure used (Fig. 17).

In sum, the observations allow us to conclude that the techniques applied possess a significant efficacy in retaining sediments transported by the gullies and, thus, contributing to the creation of sediment “pools” which may function as privileged locales for the recovery of plant life. Therefore, it is imperative to create conditions in these mountain areas, which favor the fixation of the existing soil cover and avoid the transport and deposit of sediments downstream, where it can affect human infrastructures and populations. On the other hand, the results do reveal some differences between the techniques, particularly when assessing their cost/benefit. More precisely, the barriers made of the remains of the removal of burnt pine trees and pine needles are a low cost solution, which produces very satisfactory results in terms of mitigating the effects of erosion.


**Figure 17.** Evolution of accumulation of sediments in barriers made from the remains of burnt pines and pine needles.

*Conclusions*

The analysis of the results of the research carried out allows us to conclude that the techniques applied both in channels and in slopes, have a significant degree of effectiveness in soil erosion mitigation.

Although the measures applied to slopes presented different behavior, taking into account the amount of material used in each plot, both methods revealed efficacy in the mitigation of soil erosion. Straw is more effective when we applied 0.5 kg/m$^2$ (5 ton/ha), because of the larger area covered by straw when compared with the pine needles and because it creates a higher aggregation of elements, producing a more effective protection. Nevertheless, straw cover has demonstrated less durability, providing effective protection only in the first year. On the other hand, pine needles provided greater soil protection when the cover is of 0.25 kg/m$^2$ (2,5 ton/ha). If we consider the relation cost/benefit, pine needles can be considered the most adequate technique to implement.

Regarding the measures applied to channels, all techniques showed similar efficiency in trapping sediments carried by drainage channels of the water overflow, contributing to the creation of sediment “pools”. Indeed, it is imperative to create conditions in these mountainous areas so that the small quantity of soil that is remaining is maintained, while simultaneously avoiding its transport and deposit in unwanted areas, namely downstream, where human settlements are located, where there is a dam, and other human infrastructures. Nevertheless, the results suggest a differentiation of techniques regarding the cost/benefit ratio. More precisely, the barriers made from the cut debris, pine rot, and needles revealed satisfactory erosion mitigation capacity at relatively low costs.

Although the results were encouraging, the generalized implementation of these techniques is difficult. Once most parts of forest properties are private and the fire risk is very high, it is necessary to promote awareness campaigns for land owners and national forest authorities, in order to show them that soil protection is fundamental, especially after forest fires, to assure long term productivity.

## 5. The 2017 Braga fire and erosive effects occurred after storm Ana

### *5.1. The forest fire*

The large forest fire of Braga, which occurred in the second episode of large forest fires of 2017, started on October 12, in the municipality of Guimarães (Leitões), and entered the municipality of Braga on October 15. This fire burned 1007 hectares (967 hectares of stands and 40 hectares of brush), in an area where eucalyptus trees (Eucaliptus globulus) predominated, but with a significant patch of oaks (Quercus robur) and cork oaks (Quercus suber), and unprotected the steep and cluttered wildland-urban interface (Bento-Gonçalves *et al.*, 2019) of the city of Braga. Its occurrence was enhanced by climatic conditions generated by the extratropical storm Ophelia.

However, 2017 had particular conditions that may, in part, justify the catastrophe experienced, such as the passage of the Extratropical Storm Ophelia, which was responsible for the exceptional weather conditions on October 15.

Extratropical Storm Ophelia, formed in the middle of the North Atlantic, followed an unusual trajectory, moving towards Portugal, which increased both cloud cover and winds, which, in a way, facilitates the spread of fire (Fig. 18).

Although climatic conditions are determinant for the occurrence and progression of forest fires in Portugal, other aspects influence this phenomenon, namely those related to vegetation.

As mentioned earlier, it was in this context that the great forest fire of Braga developed, burning about 1007 hectares (967 hectares of stands and 40 hectares of brush), in an area where eucalyptus trees predominated, but with a significant patch of oaks and cork oaks (Fig. 19).

The fire swept through the steep and disorderly wildland-urban interface (WUI) of the city of Braga, stripping the slopes of their undergrowth, which, combined with steep slopes and heavy rainfall, generated serious problems downstream, as for example in the first rainy episode that occurred after the fire, on December 10 when storm "Ana" passed through.

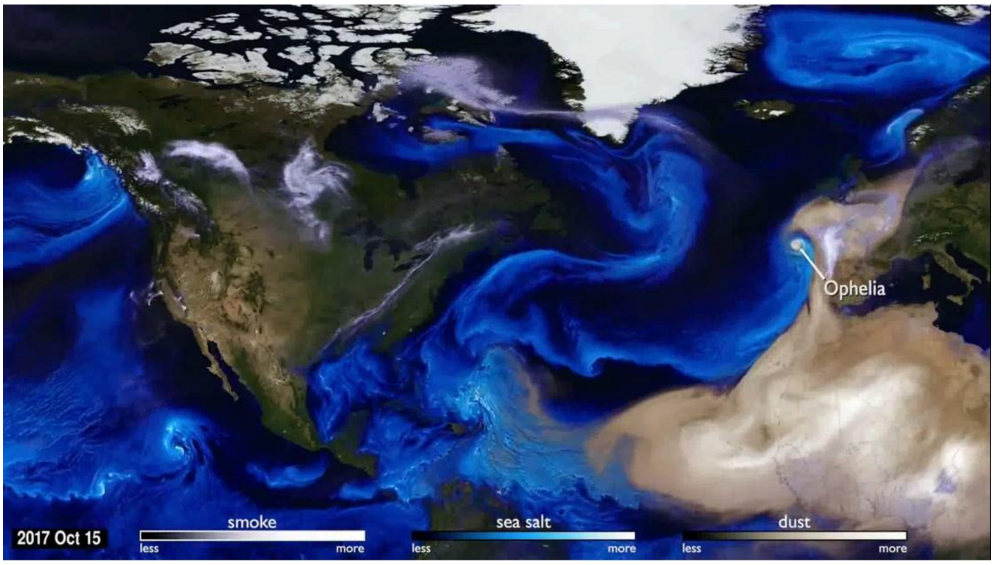



**Figure 18.** Extratropical Storm Ophelia in Portugal on October 15, 2017. Source: GSFC/NASA.

The whole slope of Sameiro and Falperra is an extensive area of WUI, where there has been a progressive advance of the built environment towards the forest area, with a significant increase in risk for the areas in contact.

In figure 20 we can clearly identify the patch of forest affected by fire, which is delimited by the urban area, where the firefighting effort was concentrated, not avoiding, in any case, the destruction of some houses for agricultural support.

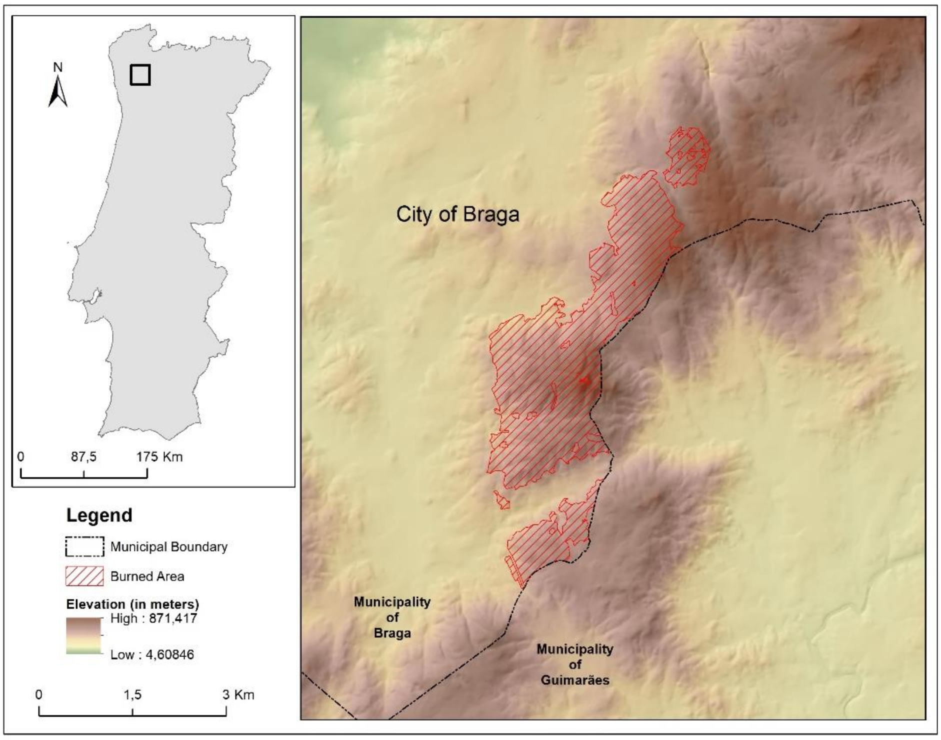



**Figure 19.** Location of the area affected by the 2017 forest fire in the municipality of Braga.

**Figure 20.** Panoramic view of the Sameiro slope after the fire. Photos: A. Vieira, 2017.

### *5.2. Erosive effects of storm Ana*

As a result of this tempestuous phenomenon, direct consequences were observed in these areas heavily affected by the fire.

Indeed, on December 10th, the area was strongly affected by the storm Ana (that passed north of the Iberian Peninsula), with high rainfall amounts. Thus, only on day 10, precipitation values exceeding 100 mm were recorded in Braga (rain gauge installed near the GNR station in Sameiro), with a concentration of precipitation in the afternoon, as early as 12:00, but more intense at 17:00 and extending into the night, with the highest value to be recorded at 20:00 (Figure 21). As a consequence, dozens of occurrences were registered in Braga, particularly in the fire area and in urbanized areas downstream, with special emphasis on the parishes of Esporões and Fraião.

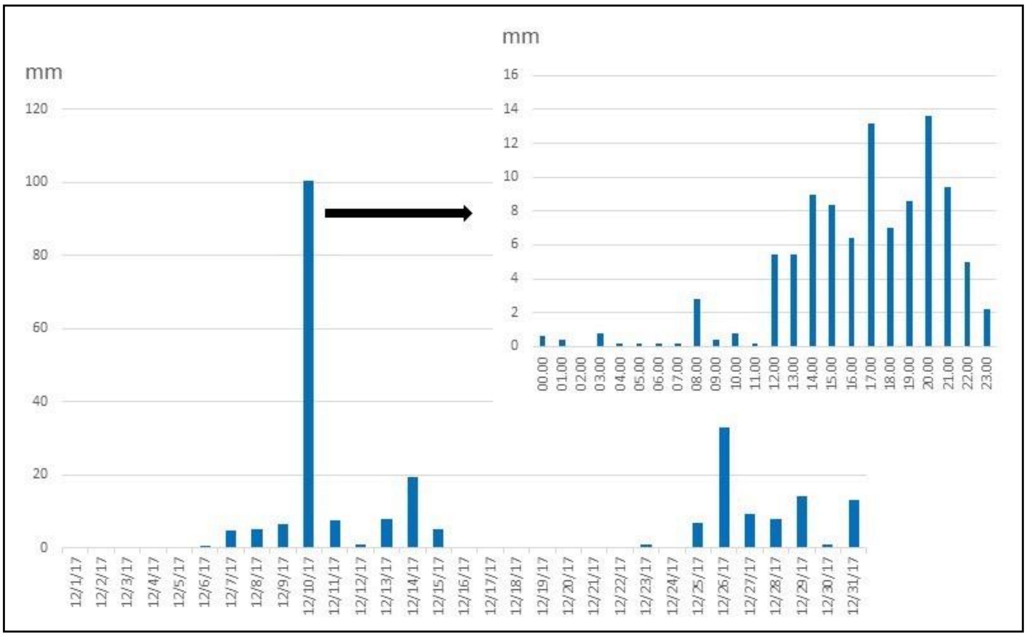



**Figure 21.** Daily distribution of precipitation in December and hourly on December 10, 2019.

As a consequence, dozens of occurrences were registered in Braga, particularly in the area of the fire and in the urbanized areas downstream, with special emphasis on the parishes of Esporões and Fraião. We mapped the occurrences of December 10th , based on the "record of requests for help or services of the Braga Sappers Fire Department", provided by the Civil Protection Service of Braga City Hall, crossing them with the information and surveys collected in the field on the day of the event and later, correlating the effects of Storm Ana with the impacts of the fire (Figure 22).

An exploratory risk assessment conducted after the occurrence of the 2017 fire already indicated the existence of quite vulnerable areas, namely in Fraião (Figure 23).

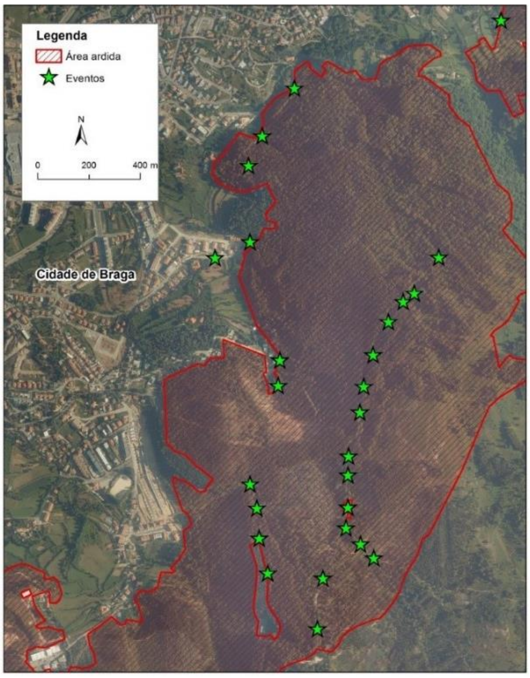



**Figure 22.** Location of reported and identified occurrences in the field.

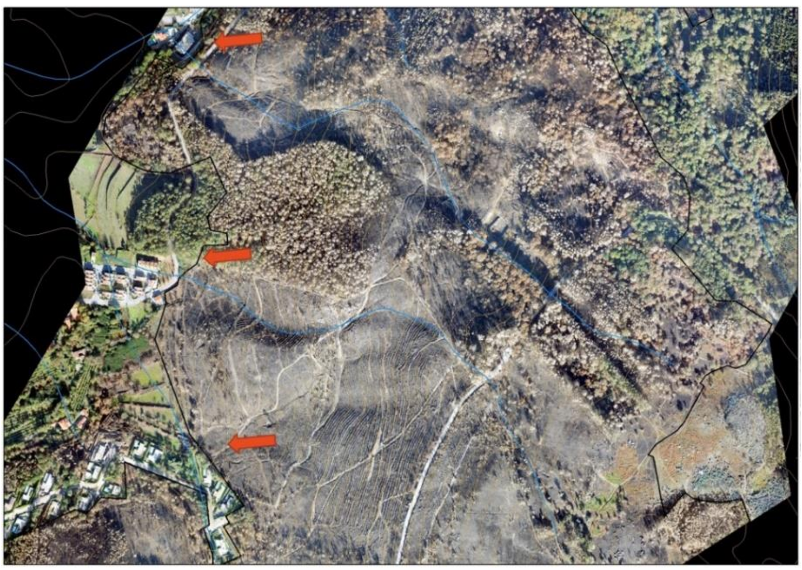


**Figura 23.** Identification of vulnerable areas in the Braga WUI.

Obviously, a direct consequence of the action of these erosive processes is the production of sediments that are transported down the slope, accumulating downstream. In the area under visit, an urbanized area of Braga, numerous situations of flooding of houses, obstruction of communication routes and occupation of agricultural lands with sediments were observed (Figure 24).

**Figure 24.** Urban infrastructure obstruction and sediment accumulation in agricultural areas. Photos: C. M. Braga.

The evidence we found in the area affected by the Braga fire and in the city itself demonstrates the serious impacts of forest fires on the soil, namely in terms of erosion and degradation, and the consequent impacts on downstream areas, especially when it comes to urban areas.

On the slopes of Bom Jesus de Braga and Sameiro, quite steep, following the intense and concentrated precipitation caused by Storm Ana, a generalized erosive action was observed along the slopes, where besides the impact of raindrops, the runoff itself acted, favored in its action in the areas affected by fires due to the absence of protective vegetation, but also due to the reduction of water infiltration capacity, particularly conditioned by the increase of soil repellency to water (Coelho *et al*., 2004; *Ferreira et al*., 2005), generating a sediments wash surface – sheet erosion (Figure 25).

However, the concentration of the runoff created more serious situations, by increasing the competence of the concentrated runoff to detach and transport the sediments on the slope. The generation of concentrated flow lines promoted the development of rills (Figure 25), leading to the appearance of gullies (Figure 26).

The visual assessment of the erosive action on slopes in burned areas detected the development of critical areas of higher concentration of erosion, in the areas most affected by fire, with steep slopes and where anthropic action is more active (roads and other anthropic infrastructures) (Figure 26).

Following this episode with serious erosion effects in the WUI areas previously affected by the forest fire, Braga municipality implemented a recovery plan for the most affected areas and infrastructure rehabilitation, including strategies to mitigate the erosion and erosion effects observed. The north and northwestern slopes of Santa Marta das

Cortiças were subject to several interventions (Figure 27), including the implementation of measures to mitigate the intense erosion that occurred along water lines and roads.

**Figure 25.** Sheet erosion and rill erosion. Photos: A. Vieira, 2018.

**Figure 26.** Trail destruction by the action of water erosion. Photos: A. Vieira, 2018.

*Conclusion*

As synthetic conclusions we can say that wildfire is an important, and sometimes the most important, driving force behind landscape degradation in the Mediterranean region (e.g. Naveh, 1975; Andreu *et al*., 2001; Dimitrakopoulos and Seilopoulos, 2002; Alloza and Vallejo, 2006; Mayor *et al*., 2007). In fact, wildfires can have profound effects on a watershed, and burned catchments are at increased hydrological risk and respond faster to rainfall than unburned catchments.

Flooding and soil erosion also represent some of the most significant off-site impacts of wildfires, causing serious damage to public infrastructures and private property and promoting an increased psychological stress for the affected population.

Post-fire debris flows are generally triggered by one of two processes: surface erosion caused by rainfall runoff; landslides caused by the infiltration of rainfall into the ground.

Runoff-dominated processes are by far the most common, since fires usually reduce the infiltration capacity of soils, which increases runoff and erosion.


**Figure 27.** Photos of mitigation measures implemented in areas affected by erosion following Storm Ana. Photos: A. Vieira, 2018.

In the study areas: we have registered that high intensity rainfall events produced generalized sheet erosion and rill erosion on unprotected slopes (burned areas). We have also concluded that high intensity rainfall events were determinant for the development and increase of gully erosion. Moreover, significant volume of sediments were transported downslope, producing infrastructure damage and huge sedimentation in agriculture fields.

The mitigation measures implemented after the Storm Ana allowed the vegetation recovery and slopes protection.

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## Chapter 7. Laboratory techniques for fire affected soils

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### Introduction

Soil is the outermost part of the earth's crust, consisting of a highly varied mixture of altered mineral particles, waste organic matter, living organisms, gases and liquid solutions. Soils are the main support and source of nutrition for terrestrial plants and provide several ecosystem service to human beings. The characteristics of different soils have been determined by climate, substrate, surface formations, macro- and micro-organisms and topography that have acted as factors in their genesis and evolution; the consequences of past and present human activities on soils must also be considered. The solid mineral and organic part may constitute only half of the volume of some soils; the remaining space is occupied by gases and water. Soil is not the end product of a process, but rather a stage or step in a never-ending continuum of physical, chemical and biotic activities, which for each place and time presents itself in a specific way.

Internationally, the science that studies soil is called Pedology, from the Greek pedon, which means "soil that is trodden on", and deals with its physical, chemical and biological characteristics, as well as its genesis and classification. In Spain, Huguet del Villar included the term Edaphology, from the Greek edaphos, which also means earth but includes the idea of thickness, which defines soil much better. However, Huguet del Villar proposed the term Geo-Edafology because it included human aspects such as the agricultural use of soils or land use.

Soil science is closely related to other aspects of Physical Geography. Climate and vegetation determine the properties of soil development. Geomorphological dynamics (stability, erosion and accumulation) also influence soil conditions. From hydrological point of view, the soil is a water regulating and transmitting store. Moreover, soil is studied from different points of view and within different specialties, such as: agronomy; chemistry; geology; ecology; geography; hydrology and; pharmacy.

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Soil can be defined as a natural body, resulting from the interaction of parent material, climate, topography, organisms and time; locally one of these factors may have a dominant influence. Organisms are also the determinants of the type, amount and location of soil organic matter, while they stir the soil and are involved in many important soil reactions. The parent material is altered in relation to the environment created by climate, topography and organisms. Time under some geographical condition determines the degree to which the material is altered by the other soil-forming factors.

Although the physical and chemical processes involved in the edafogenesis or pedogenesis of different soils are the same, they intervene at different levels and act on different parent materials. The intensity of hydrolysis, hydration, oxidation-reduction, dissolution, particle movement and organic matter deposition is a function of the five soil-forming factors.

The aim of this document is to provide information on the different laboratory methods used for physico-chemical analysis of burnt soils to serve as a guideline for such analysis. The information synthetized in this document comes from different bibliographic sources: Rhoades (1983), Porta et al. (1993), Úbeda y Sala (1995), Buurman et al. (1996), Flores y Alcalá (2010) and Pereira et al. (2019).

**1. Soil sampling**

The sample represents soil conditions at a particular location, therefore the sampling points have to be carefully selected to be truly representative of the soil type (Soil Survey Staff, 1992). Therefore, to take a uniform number of samples is needed. To determine the nature and magnitude of variations in a particular area, several independent samples have to be taken. Generally, sampling refers not only to the action of taking a piece of soil from a particular location, but also to the selection of a point for an in situ test or analysis, such as infiltrometry. The fact of selection to be representative of a site is the same as selecting a sample. The sample is not always taken in the same way, but depends on the type of analysis we want to perform on the sample (Úbeda and Sala, 1995). For example, it may be necessary that the sample does not alter the soil structure and then we will use cylinders in which we will keep the sample, but this is not always essential. Sometimes it is necessary to extract the sample by differentiating the horizons, layers or facies, while sometimes it is necessary to take composite samples, in order to homogenize the whole soil profile or its top horizons in a single sample.

There are special devices for soil sampling, such as soil shovels, of which there are different models, depending on the volume and depth requirements. But for the extraction of samples for most of the tests explained below, it is not necessary to have very sophisticated equipment; sometimes it is more important to have expertise in the process of extraction than the importance of having good sampling equipment. As for most of the tests the sample volume needed to perform them is not very large, different analyses can be performed with one sample. This is possible if the sample is well prepared so that it does not spoil. Drying, preserving and sieving the sample, would be enough important steps that are explained below. It is interesting to note that the small part of the sample taken for analysis has to be representative of the whole sample; this is achieved by homogenizing the sample and quartering it or by repeated analysis of the sample. It is important to replicate samples.

When characterizing a given area, it is necessary to take a sufficiently large number of samples to be able to correct for possible errors. The study area in question must be fully represented in the samples, and it must be clear at what exact point they were taken in case it is decided to take a sample in the same place at some other time, for example to determine temporal differences. In order to achieve this, it is very practical to design a grid covering the field or showing the points where sampling has taken place. Geographic Information Systems (GIS) and nowadays Geographical Positioning Systems (GPS) help to locate the sampling points.

Before designing the grid, you have to know how many samples you want to take. The easiest way to sample is at the intersection point of the grid lines, or at the centre of the squares that appear. To lay out the grid in the field, it is sufficient to have a level to draw straight lines. If the site is step, then a theodolite or total station will be necessary. This will be more practical as at the same time we can digitally map the area to be sampled. Depending on the type of area we are working on, a marker can be used at the sampling point so that it can be easily identified on other occasions, and a number or a key should be used to identify it.

It may be the case that the field where we want to carry out the analysis cannot be marked at all, for example, because it is a crop field in production. Then, one solution is to design a grid of imaginary lines, with the references outside the field. The intersections of these lines are the sampling points. In order to explain this, a real case carried out in a crop field is presented. In this case, every time you want to find a point, you have to find the orientation with a compass of the parallels of the external references. Although it is more complex, once you want to take samples, you can take them all at the same time and, knowing the distance between each sample, the work becomes easier. Once the samples have been extracted, it is necessary to give them a name. This can be indicated in many ways; with initials and an order number, with a number and the date, etc. There are many possibilities, depending on your needs. What needs to be clear is exactly where the sample is from, what label it was taken from, the date, and who took the sample. The sample can be placed in plastic or paper bags, or kept in the same object used for its extraction, depending on the type of analysis to be carried out. It is important to know, depending on the analysis, the weight of the bag to be used to carry the sample. An important consideration is that many of the methods require sampling campaigns to collect samples on the same day. The characteristics of the samples must be known at the same time. For example, if it rains in the middle of a sampling campaign, it will no longer be possible to compare moisture retention between samples, or to perform infiltration analysis with the same moisture status. To collect samples under the same conditions is over (Roquero y Porta 1990).

## 2. Sample preparation

### *2.1. Drying and preservation*

In order to get the results from the analyses correct, the samples must be preserved so they will not lose any of their properties.

Once the samples are in the laboratory, they must be sorted in such a way that it is known exactly which sample they are. If the person who will carry out the analysis is not the same as the person who extracted the samples, they will have to agree on the terminology to be used. One possible method for sorting is to put an order number and the year (1/99) (Porta et al., 1993), another is to keep the name we wrote down on during fieldwork, but there are many others. You have to have a laboratory notebook to write down everything you do, every step you take and to keep the samples in order. The next thing to do is to dry the samples until they are equilibrated with the ambient moisture. They have to be air-dried, except when a certain method recommends drying them in an oven. The aim, apart from removing the water contained in the sample, is also to avoid oxidation of the soil and to stop biological activity that could spoil the sample. It is also not advisable to dry the samples too quickly or too intensively.

Samples should be stored in closed, dry containers until analysis. Although soil samples can be stored for a long time, for some analyses, such as pH, changes can occur if they are stored for many days.

### *2.2. Sieving*

The most important division for soil analysis is between coarse elements (> 2 mm) and fine soil (< 2 mm). In most of the methods explained later, the fine-particle soil is used. In order to have all available soil less than 2 mm, it is necessary to break up all aggregates, and this can be done either by roller or by hand, and sieve again at 2 mm. When breaking up the aggregates, care must be taken not to break up the gravels as they would then be wrongly counted in the fine fraction. As for some analyses, such as the amount of organic matter, very small quantities are required, a complete homogenization is necessary, and the sample has to be powdered to a diameter of less than 0.2 mm. To do this, a ball mill or a mortar can be used, trying to clean the mortar very well between samples.

All fractions resulting from the sieving should be saved and sorted so that they are not misused. The coarse elements remaining above 2 mm should be saved. For each method explained below, it will be stated which sieve is needed, as the same size of aggregates or the same amount of fine soil is not always required. In addition, it will be mentioned in the methods whether further dispersion of the sample with a dispersant is necessary.

## 3. Physical properties

Soil has a number of physical properties from which a few have been conventionally taken and which, properly quantified or at least systematized, have been used as a method of diagnosing the physical conditions of the soil or properties related to them. Soils evolve differently depending, for example, on their drainage, their water storage capacity, their greater or lesser oxygenation capacity, etc. These physical properties, which we could consider to be the main ones, actually represent the state of water and air in the soil, with soil that does not become waterlogged but has high water retention and at the same time good aeration being considered optimal. These conditions allow a high-level of bio-edaphic activity, making the soil richer in nutrients, and at the same time allowing continuous water supply to the plants and proper oxygenation of their roots.

Other physical characteristics, no less important, simply refer to the soil's ease of penetration by the root system and its ability to support the plants, or its greater or lesser resistance to erosion, etc. However, it must be keep in mind that these soil characteristics, which we call "physical", are determined only partly by physical properties of the soil, and partly also by chemical and biological properties.

### *3.1. Soil moisture*

Water is essential for the existence and development of any form of life on Earth, and know how much water a soil is capable of storing, or how much is in the soil at any given time, is important. A simple way to estimate the amount of water in the soil is to evaporate it while quantifying the weight loss in this process. When a soil is heated, the water it contains evaporates. The difference in weight before and after heating will then give the moisture content.

To find out what percentage of water was in 100 g of dry soil or what is the weight of water in 100 g of wet soil, the following technique has been developed:

Take a small amount of sample from 25 to 40 g, specifically from the place you want to analyze. The sample should be weighed as soon as possible after extraction. Once it has dried completely in the oven at a temperature of 105ºC for 24 hours, it is weighed again, after it has been left cooling in a desiccator.

A plastic bag can be used to store the sample correctly until it is weighed. If a larger sample has been taken for analysis, only a part of the sample is used. It should carry out the weighing using the same perfectly untare weight container.

We can obtained two types of results:

- Grams of water in 100 g of moist soil.

Grams of water = [(P1 - tare) - (P2 - tare) / (P1 - tare)] x 100

- % water per 100 grams of dry soil.

% of water = [(P1 - tare) - (P2 - tare) / (P2 - tare)] x 100

Where P1 is the weight of the wet sample and P2 is the weight of the dry sample.

It is very useful to make analyses of this type in comparative studies of the same soil, located on different orientations or slopes. It allows to know how water is stored in certain places, how much water is stored after a certain rainfall, or how long it takes for a soil to evaporate water. It is also useful to observe soil moisture conditions in a given study period. It is a very important and complementary to other methods.

*3.2. Soil texture*

The term texture refers to the size of the different particles that make up the soil, also called granulometry. A first division that can be established is that of coarse elements, which are those larger than 2 mm in diameter, and those smaller than this measure, called fine soil. In this work, we will follow the USDA classification (United States Department of Agriculture, 1973), but there are others, which are presented in this lesson. Even though it is a classification determined by measurement, the physical and chemical properties of each fraction are different for each of them and it is precisely this fact that makes them even more interesting to study. The fine soil is the really active fraction of the soil, the coarse elements are not taken into account when classifying textures. Fine soil is divided into sands, silts and clays, and the percentage of these fractions in the soil will give the texture into which it can be classified.

The texture of a soil is of great importance in soil physics, together with the structure it tells us about the state of air and water in the soil. The infiltration and water retention capacity will be determined by these properties and these are important for plant life, as well as for preventing soil loss through runoff and erosion. Although coarse elements do not take part of the texture classification, they still play an important role, e.g. in soil structure, in the ease of water infiltration, in oxy-redox process, or in the formation of pores necessary for plant root penetration.

*3.2.1. Coarse elements*

As they do not form part of the fraction directly involved in the classification of texture, their physical importance has often been underestimated. It should be keep in mind that a clay-textured soil, for example, will behave very differently if it has no coarse elements or if they are present in abundance, since in the latter case the problems of lack of aeration will be alleviated by the presence of macroporosity.

Coarse calcareous elements also play an important role in facilitating water retention. Likewise, in Mediterranean climates, for example, the coarse elements of slate materials can, on slopes of over 50%, constitute an erosion protection factor, together with a reduction in evapotranspiration due to the breakage of the microcapillaries. Therefore, the qualitative and quantitative content of coarse elements should be studied, in order to recognize whether their functionality is beneficial for the soil's fertility and edaphogenetic processes.

According to USDA (1973), coarse elements larger than 2 mm in diameter are designated as follows:

Gravels: elements from 2 to 20 mm
Stones: elements from 20 to 200 mm
Blocks: elements larger than 200 mm

### *3.2.2. Fine soil*

This is the active fraction of the soil, both from a physical and biochemical point of view. Sand and silt, especially coarse silt, constitute a so-called skeleton, while clays and small portions of fine silt form the edaphic colloid (together with colloidal humus and colloidal limestone, which, granulometrically, is part of the clay fraction). Therefore, the role of sand and silt, in addition to being a source of minerals, is to facilitate the formation of structural aggregates cemented by clay and other colloids.

Soils with sandy textures are abundant in areas where granitic material has broken up and deposited. They are generally poor in nutrient ions and tend to be acidic, especially if the lack of clay is not compensated by the presence of colloidal humus, which causes the exchange complex to be desaturated. The slow micrometeorization of the sand also contributes to this, i.e. the slow liberalization of new ions in the soil, combined with the progressive loss of soluble ions due to the lack of an absorbent complex to retain them. If we look at their physical properties, sandy soils have good drainage, excess washability and good aeration favored by a high macroporosity; and lack of water retention (low field capacity) which limits vegetation in arid climate areas.

Silt-textured soils areas are not very frequent, and they are preferably limited to alluvial accumulation sectors, although kaolinitic clayey materials, which are very abundant in large sedimentary areas, have edaphic properties very similar to those of fine silts, although mineralogically they are clays. If they are not compensated with humic colloids, they have a reduced cation exchange capacity, their acidity or basicity depending on the nature of the original material. From a physical point of view, silty textured soils have the following characteristics: poor drainage and aeration of the profile due to low total porosity and absence of macroporosity; low water reserve in dry areas and susceptibility to hydromorphism in humid areas.

Clay soils are characterised by high electrical (conductivity?) activity (especially if the clays are vermiculite or montmorillonite), which gives them a high cation exchange capacity and the possibility of base saturation, i.e. basicity, if there are basic cations in the profile, as they are retained, preventing them from being washed away. From a strictly physical point of view, a distinction must be made between swelling clays and those that do not have this property. The latter, of the kaolinite type, are more closely related to the physical characteristics of silts than to clay-textured soils. Indeed, montmorillonite clays, in particular, show properties of swelling and shrinkage when wetted and dried. According to Henin (1976), the volume of a dry clay soil, subjected to progressive hydration, does not change until water represents 28% of the total soil volume. From this amount of water (and up to 35%), the soil experiences a gradual but gentle increase in volume. And it is from this 35% of water volume that, as the volume of water increases, the volume of soil increases at the same time. As a consequence, clay textures have the following characteristics: good drainage until the soil reaches water saturation, but possible waterlogging when swelling has taken place, at which point aeration is very deficient; good water reserves, but their full use requires plant species with a high absorption pressure (high pF), as much of the water is in the capillary micropores.

### *3.2.3. Loamy texture*

The loamy texture is a proportionate mixture of granulometries (from 15 and 25% sand, from 40 to 70% silt and from 20 to 30% clay) which compensates for the defects and virtues of each of the fractions in relation to each other. The loamy texture stimulates the formation of built-up structures, which in turn, affect to all physical, chemical and biological processes in the soil, with good profile development and increased stable concentrations of nutrient ions, water and air, facilitating good vegetation development.

The formation of a loam texture, although largely dependent on the original materials, is sometimes achieved through the compensation provided by the humic colloid. Clay textures, for example, are improved by the presence of colloidal humus, which provides cohesion and, consequently, a granular structure that improves aeration conditions, water movement and, ultimately, ionic exchanges. A similar situation occurs in originally loamy soils.

In order to assess the texture, the textural distribution of the horizons must also be taken into account. A similar texture throughout the profile is not the same as the existence of textural variations that attenuate, as a whole, the negative characteristics of the texture of a certain horizon. It is a question of assessing the presence of a different texture in the different horizons of the profile.

### *3.2.4. Approximation of soil texture in field*

The test consists of taking a smallportion of sample, from which the coarse elements are removed. It is then moistened until it sticks to the hands and mixed with a knife. With the wet sample, try to make a cylinder with a diameter of 3 mm on a flat surface or on your hands. If this is not possible, it means that the sample is more than 80% sand, and therefore difficult to adhere to when wet. If it is possible, then try to make a cylinder of 1 mm diameter, if it is not possible, it means that the sample has between 65 and 80% sand. With the 3 mm diameter cylinder, an attempt is made to make a ring with a perimeter of 10 cm. If this ring breaks, the sample has 40 to 65% sand. If it is finally possible to make the ring, the same is attempted with the 1 mm diameter cylinder. If the ring breaks, it means that the sample has a predominance of silt, if it is feasible to make the ring, it means that there is a predominance of clay.

Silt samples do not harden as much as clay samples when dried. Dry clay samples are very hard and it is impossible to break the aggregates with the fingers, whereas wet clay samples stick to the fingers.

It is important not to put too much water on the sample from the beginning, as it is no good if it is too wet. It is not necessary to keep the whole sample until the end; you can remove the sample as you make the cylinders or rings.

Although it will not be possible to determine the exact percentage of each fraction, by doing this first texture test, even if it is approximate, we can state a series of typical soil characteristics related to certain textures.

### *3.2.5. Approximation of soil texture under laboratory conditions*

Hydrometer method (Burt, 2004)

Materials

- Standard hydrometer, ASTM No. 152 H, with Bouyoucos scale in g/L
- Set of 7.6 cm Ø sieves, with apertures of 1000, 500, 250, 106, 75 and 53 µm
- Electric stirrer for dispersion (blender type, with 10,000 rpm motor)
- Plastic stirrer for 1 L graduated cylinders
- 1 L graduated cylinders, 36 cm ± 2
- 600 ml beakers with high necks
- Plastic bottles with lids for mechanical stirring
- Motorized stirrer for dispersion
- Soil drying oven at 105° C
- Garnet balance
- Porcelain capsules
- Sieve shaker
- Electric grill or water bath

Reagents

- Amyl alcohol
- Sodium hexametaphosphate (HMF) solution 50g/L

Procedure

Calibration of the hydrometer - Add 100 ml of the HMF solution to a measuring cylinder and make up to 1 L in a temperature controlled room. Mix vigorously with the plastic stirrer and take the temperature. Insert the hydrometer into the solution and determine RL (hydrometer reading of the test tube that was used as a blank) by reading the top of the meniscus on the hydrometer scale. Periodically check RL during texture analysis. The RL calibration values are used in the analysis to correct the viscosity of the solution and to correct the concentration of the soil in the C-suspension.

Soil dispersion - Weigh 40.0 g of soil and place in a 600 ml high neck beaker, add 250 ml of distilled water, 100 ml of HMF solution, and allow the sample to soak overnight. The size of the sample depends on the type of soil texture. 10 to 20 g could be used for fine textured soils: silts and clays; and 60 to 100 g for coarse textured soils, giving reproducible results. Transfer the dispersant-treated sample to the metal beaker of the electric shaker (blender type) and shake for 5 min, or transfer the suspension to bottles and shake mechanically overnight in a horizontal position. Transfer the suspension to a 1 L beaker and add distilled water up to the mark. Recommendation: For silty or sandy textured soils leave the bottles shaking horizontally overnight, rather than shaking the sample in the blender.

Hydrometer readings - Allow time for the suspension to equilibrate and note the temperature. Insert the hand shaker into the cylinder, and mix the suspension vigorously but carefully, holding the cylinder at the bottom to prevent it from falling over. Make sure that sand are moved from the bottom of the cylinder, and shake for 1 min. Add a few drops of amyl-alcohol if the surface of the suspension is covered with foam. As soon as you have finished shaking, introduce the hydrometer into the suspension and take a reading after 30 sec, and another reading after 1 min. Remove the hydrometer, rinse and dry. Again, carefully insert the hydrometer 10 sec before the following reading times: 3, 10, 30, 60, 90, 120 and 1440 min. These times can be modified according to the particular needs of the analyst. Remove and rinse the hydrometer after each reading. Record the readings (R) each time you take them. Take a hydrometer reading in the blank solution (without soil), and record the reading as RL, besides the temperature of the solution.

Separation of sand fractions - Pass the sediment and suspension from the 1 L test tube through a 270 mesh (53 µm aperture) 8" Ø sieve. Wash the sediment remaining on the screen using a sieve strainer or running tap water. The screen may be wetted with a soap solution to improve sample passage and flow rate. Transfer the sands to a pre-weighed aluminium capsule, dry at 105°C and weigh. Transfer the dry sands to a set of sieves arranged from top to bottom with the following diameters: 1000, 500, 250, and 106 µm, shake for 3 min and weigh each fraction, in addition, weigh the residual silt and clay that passed through the 53 µm sieve.

Calculation of particle size - Determine the soil concentration (C) in suspension in g/L, with the following expression: C = R - RL where R is the uncorrected hydrometer reading in g/L, and RL is the hydrometer reading of the test tube that was used as a blank. R and RL are readings taken at each interval indicated.

*3.3. Soil structure*

This property refers to the shape, size and degree of development of the particle agglomerates, i.e. the naturally or artificially produced structured form of the different primary soil particles forming units. The finer, colloidal material is the cement between the particles. Structure also refers to the way these units are arranged and the voids and fissures that form within them.

The way in which aggregates are formed is given by the interaction between organisms, roots, and mineral matter. Also important are the excrements of some earthworms and small animals which, together with the pressure of the soil itself, form larger aggregate structures. In cultivated soils, agricultural work performs these structuring functions.

A thorough analysis of the structure of a soil will tell us a lot about its development, the difference of horizons, it is possible structuring process due to external or internal causes of the soil itself, its stability, soil compaction and oxygenation/aeration etc.

The analysis of the structure is important when describing the profile (shovels, picks, etc.). A knife is also very useful to pick up part of the soil, a magnifying glass can also be important. There are books (e.g. Soil Survey Field Handbook, 1975; 1976), where divisions of measurements and shapes are indicated to distinguish and classify the corresponding structure.

The structure can be divided by the shape of its aggregates and their arrangement and by its degree of development. It is necessary to see the structure of a soil in situ in the profile and to take part of the soil to break up the structure and see by what type of aggregates it is formed.

Structure will be very important to understand soil porosity, aeration and water content, which are discussed in the following sections.

There are several interpretations of structure, the following is based on its shape and was elaborated by the Soil Survey Field (1976):

- Unstructured: because it consists of loose grains without cohesion due to the finer material acting as cement, or because the structure can be considered massive, i.e. compacted by clays or silts.

- Angular structure: formed by angular and square blocks. Four categories can be made according to the size of the aggregates: small (<10mm diameter), medium (10-20mm), large (20-50mm), and very large (>50mm).

- Granular structure: formed by more or less perfect spherical aggregates. Small (<2mm), medium (2-5mm), large (5-10mm), and very large (>10mm).

- Prismatic structure: These are columnar structures; also called fractionation structures because they are due to expansion and retraction processes of the soil. Small (<20mm), medium (20-50mm), large (50-100mm), and very large (>100mm).

- Lamellar structure: Structure in the form of overlapping sheets of varying thickness. According to their thickness they are distinguished: small (<2mm thick), medium (2-5mm), large (5-10mm) and very large (>10mm thick).

By their degree of development:

- Poor development: there is no cohesion between the primary material; no distinguishable aggregates in the soil.

- Moderate development: There is cohesion, the aggregates are easily fragmented and split into many parts.

- Strong development: Aggregates are very evident in the profile and quite resistant at the moment of breaking them, and when they break up they do so in medium-sized pieces.

A good structure is one that allows gaps so that roots and germinated seeds can penetrate easily but have sufficient stability in the soil. Granular structures are well suited to allow voids for air and water to circulate. Structures that are too compact do not allow this circulation, and structures that are too loose encourage it. Inconsistent structures can cause surface crusts in contact with water.

*Water-stable aggregates:*

Water-stable aggregates is a characteristic of the structure and is defined as the resistance of the soil aggregates to disintegration by the action of water. To evaluate this resistance it is necessary to experimentally subject the aggregates to the action of water in order to see the reactions.

Aggregate stability is an aspect of great practical importance. Some aggregates break down very quickly due to the impact of rainfall, moisture or agricultural practices. Others, on the other hand, resist disintegration, thus stimulating their relatively easy maintenance of a suitable soil structure. Differences in Water-stable aggregates seem to be related to the presence or absence of certain soil binding agents.

Aggregates from soils rich in organic matter are more resistant than those poor in this constituent. Those with little organic matter separate easily when wet, while those rich in organic matter maintain their stability. Other inorganic components, e.g. iron oxides and aluminum, have a definite cementing effect, resulting in stable granules. As a general rule, macro-aggregates have a lower stability.

*TDI (Ten Drop Impact) for the determination of the structural stability of a soil.*

To test the dispensability of soil aggregates when subjected to ten drop impacts, in order to establish a degree of stability.

Infrastructure and equipment

- Desiccator per (for wetting and drying)

- Burette pipette allowing distilled water to fall drop by drop from a height of one metre.

- 2.8 mm sieve.

- Analytical balance.

The TDI consists of dropping 10 drops on 10 aggregates, and weighing the material retained on the 2.8 mm sieve and the material that has passed through the sieve, which will be called sediment. This is counted as the percentage of disaggregated material. With this test, a stability index can be obtained for samples that are less susceptible to disaggregation. The test can be repeated twice for each sample.

Knowing the weight of the aggregate output, it is only necessary to know how much material has passed through the sieve to know the percentage that has been disaggregated. In order to pass the sediment, it must first be dried at 105°C in the oven for 24 hours and then left to cool in the desiccator. It is preferable to put aluminum foil on the base of the sieve to collect the sediment; this avoids losing some of the sediment and putting the base of the sieve in the oven. If this is done, the weight of the aluminum foil must first be known.

It has already been said that the results will be given as a percentage of disaggregated material in 10 aggregates, and a table of this type can be constructed:

The interpretation of this test is straightforward by looking at the results, it will be more unstable the higher the percentage of material disintegrated by the impact of the 10 drops.

*3.4. Density and Porosity*

A consequence of soil structure and texture is soil porosity, which directly influences the water content, as we have seen so far, and the maintenance of proper aeration, essential for soil bioactivity and for plants. Total porosity is the percentage of empty volume in relation to the total volume of the soil, expressed by the formula:

$$\% \text{ porosity} = (1-D/d)*100$$

Where "D" is the so-called bulk density, i.e. the density of the soil in situ, including void volumes; while "d" is the real density, i.e. the soil without voids or pores.

However, this total porosity is not related, quantitatively, to the aeration properties of the soil. Indeed, a soil can have a high percentage of porosity (more than 60%) and yet be poorly aerated. This is due to the size of the pores, so that the porosity of small diameter conduits, i.e. capillaries (less than 5 microns), can not be used by the air, but only by the porosity of larger diameter, distinguishing, in this sense: capillary porosity (or microporosity) and macroporosity.

Soils with granular and lumpy structures and loamy textures are those with the most balanced porosity (around 65% of total porosity divided equally between microporosity and macroporosity). These loamy soils are the ones that provide the best aeration and water reserve (medium field capacity and medium-high useful water reserve).

However, soils without built-up structures and with extreme textures have inadequate porosity for the proper functioning of aeration and water circulation processes in the soil:

(a) In sandy textures excess macroporosity (good aeration but low field capacity and low useful water reserve).

b) In silty textures, low total porosity (around 40%) with hardly any macroporosity (lack of aeration and medium field capacity with good useful water reserve as little water is retained at the permanent wilting point).

c) In clay textures high total porosity (around 60%), but no macroporosity (lack of aeration and high field capacity, but with a very high hydroscopic water volume, resulting in a medium level of useful water reserve for plants).

The pore organization of soils not only influences water circulation and water reserves, but these, in turn, act on the pore system by constantly modifying it, in a continuous interaction due to the characteristics of water movement and the dissolved substances that accompany it.

Determination of total porosity

To know the ratio between the volume of gaps and the total volume of soil mass.

- A ring to take the samples (8 cm diameter by 5 cm high).

- A hammer.

To carry out this experiment it is necessary to extract the sample without destroying the structure. It is not possible to take samples with the ring from all the soils, as the important thing is to have the whole volume described by the ring occupied by the soil. A very stony soil does not allow to ensure exactly this volume. Before extracting the sample, we will have weighed the ring, and also the wood we have used to hold the sample.

It is placed in the oven at 105ºC until it is completely dry (around 24 h.). Once it is dry, it is put in the desiccator to cool down, and then it can be weighed. As you will have the weight of the wood and the ring before, subtract it from the total weight to know the weight of the dry soil.

This method can have errors if the sample is broken inside the ring during transport or treatment.

The total porosity is composed of capillary and non-capillary porosity, the latter being determined by the aeration pores. The water in the latter pores is usually retained because it is subject to the force of gravity. Pores containing capillary water are called "active pores" and contain water subject to capillary laws.

The actual particle density (d) can be determined by the pycnometer directly in the field. However, the number that is used almost as a constant to substitute the formula is 2.65 g/cm3. If the sample had a lot of organic matter then we would use the value of 2.50 g/cm3.

Calculation and expression of results

The first thing to calculate is the "D" bulk density of the sample. This is the dry weight of the sample divided by the volume of the sample. The weight is obtained by weighing the sample, as explained above, and the volume will be the volume of the ring. Knowing this, the general formula can be applied:

$$\%Porosity = 100 [1-(D/d)].$$

D" being the bulk density.

Where "d" is the real density of the particles.

The result is expressed as a percentage of pores of the total sample.

Knowing the porosity we can establish whether the soil analyzed has an adequate porosity or not.

**Table I.** Qualitative description of the meanings of the percentages.

| **Total porosity (%)** | **Qualitative assessment** |
|---|---|
| >70 | Excessive porosity. Very spongy soil. |
| 55-65 | Excellent porosity. Good for cultivable layers |
| 50-55 | Porosity satisfactory. |
| <50 | Low porosity for cultivation |
| 40 -25 | Porosity too low. Compacted illuvial horizons |

This type of analysis is very suitable for agricultural soils. The importance of doing this experiment to make comparisons between soils and tests on soils that have undergone some kind of disturbance is not yet ruled out.

*3.5. Soil color*

The color of the soil is a consequence of its development and composition. By observing the color we can have a further judgement of its classification. The Munsell table (1990) is used to determine the color of a soil in comparison with the color tables it contains.

The Munsell tables show different aspects of soil colour. 1) The hue (Hue) can be red (R), yellow (Y), green (G), blue (B), and purple (P). 2) Their luminosity (value), and 3) their chroma value, or color strength for the same luminosity.

Many of the soil names refer to their color. The color of the soil reflects the characteristics of its genesis - through the color of its parent rock -, its soil climate, its chemical and biological processes, its composition (mineral and organic) and its fertility. By means of the color, which would be another aspect to take into account when describing the profile, we can differentiate horizons and establish processes of leaching or washing of the profile.

Infrastructure and material

- Munsell Soil Color Chart

- Knife

Once a profile has been made, the different soil horizons can be observed. For the observation of the color, horizons of different color shades or shades of the same or different colors for different parts of the profile, established by their different texture or state of aggregation, have to be differentiated first.

Once these horizons have been established, a soil sample is taken and compared with the colors of the Munsell Table, placing a piece of soil under the leaf that is thought to be suitable, viewing it through the holes that appear. Note the leaf number (example: 5YR). You can see that the hole is between two colored squares, first note down the value, which can be the number (5) or between two numbers (between 5 and 6 will be 5.5), (example: 5YR 5.5). Finally, the "chroma" value (6) is observed, or if it is between 6 and 8 we will call it 7. The final example could be 5YR 5.5/7. On the other sheet of the Munsell book, the names for each selected color are observed, in this case two names can be read, among which the analyzed soil would be "yellowish red/reddish yellow". This has to be done twice, once when the soil is wet and once when it is dry, which can be in the laboratory. The color varies depending on the humidity at the time.

A soil sample is taken from each horizon and the same operation is carried out.

It is necessary to have good light to be able to classify the color adequately, it is advisable not to do this analysis at certain times of the day with little light. The structure can also influence the color, a granular soil appears darker than a soil without structure. If the color is not homogeneous over the whole horizon, e.g. if there are patches, the main color and the color of the patches must be shaded.

Depending on the color, one can begin to know what the soil is composed of. There are a number of main compounds that determine it.

- Humus: gives a black or grey color, very typical of the top horizons. But, not always the dark color can be caused by humus, some oxides also give black stains and in marshy soils it can be a consequence of ferrous sulphide.

- Iron compounds: these are related to red, orange and yellow soils. They indicate the presence of anhydrous oxides and hydroxides. Ferrous oxide compounds, on the other hand, give blue and bluish-grey tones.

- Silicic acid, calcium carbonates and kaolin are responsible for white colors in the soil.

The combination of these three groups determines the final color of the soil. There are, however, more substances that can give a certain color in specific cases, and further analysis will complete the information. The color of the horizons can also indicate past events, as in the case of black, the accumulation of carbon due to a previous fire.

*3.6. Soil Water Repellency*

Under certain circumstances (e.g. after a low intensity fire), or under certain types of vegetation cover (e.g. pine forests), soils may show a certain water repellency or hydrophobicity.

This has repercussions on the hydrological behavior of the soil, as water repellency limits the infiltration capacity of the soil, leading to increased rainfall runoff, which may eventually trigger water erosion phenomena.

The detection of hydrophobicity is relatively simple, since it is only necessary to deposit a drop of water on the soil surface and measure the time it takes for it to penetrate the soil pores. This determination is often referred to as the Water Drop Penetration Test (WDPT).

To estimate the water repellency by measuring the time required for the penetration of a drop of water into the soil. A drop of water into the soil.

Material and methods

- Water dropper

- Stopwatch

To measure the hydrophobicity, it is only necessary to place a drop of water on the soil, preferably dry, and to time the time until the drop has preferably dry soil and time how long it takes for the drop to penetrate the soil penetrated the soil.

Logically, longer penetration times correspond to higher degrees of hydrophobicity. hydrophobicity.

## 4. Chemical properties

Soils are formed at the expense of mineral and organic materials at the same time. These materials are progressively transformed into soluble mineral compounds which, together with water, form the soil solution. Part of this soil solution is used by plants for their nutrition, both water and mineral, and part is retained in the soil depending on the field capacity. There is also a part that is lost through deep drainage.

### *4.1. Organic Matter*

Organic matter (OM) has been defined as a group of substances ranging from the remains of undecomposed plants and animals to the products of their decomposition and recombination, these have dark colors, have lost the structure of the material they come from and are called "humus", and also include substances of microbial synthesis.

Soil organic matter compounds can be grouped as follows:

- Plants, micro-organisms and animal remains, which can be decomposed
- Humus, which represents already transformed and stable organic matter
- Polymerised forms of elemental C (charcoal).

The contribution of organic matter comes from the fall of plant and animal remains that form the humus. A distinction can be made between minor and major debris:

- Minor remains: leaves, gems, flowers, fruits, bark fragments, animals (and their consequences).
- Major remains: stems, branches and trunks.

In order to be able to evaluate fresh organic matter, it is first necessary to determine how we consider it in the field. Humus as such is divided into three sub-horizons: L (litter), F (fermentation), H (humification). We consider the "L" sub-horizon as fresh organic matter, and the "F" sub-horizon as long as no more than 50% of the initial remainder is fermented. This will be easier in some soils than others depending on whether they have a humus mull or mor.

The (OM) in the soil undergoes a series of transformations due to microbial and biochemical processes that break it down into simpler compounds. On the one hand, decomposition produces inorganic products (CO2, H2O, CH4, NH3) and on the other, colloidal organic substances that form humus. These are of heterogeneous composition and have a set of very particular physical, chemical and biochemical characteristics: dark color, high molecular weight, colloidal character, great ion retention capacity, ease of binding to clays forming the clay-humic complex and great resistance to biodegradation.

All these characteristics mean that humus plays an important role in soil fertility, because of its high cation retention capacity, because it improves soil structure and increases water holding capacity, and finally it facilitates microbial development. The humus type, its dynamics and evolution are taken into account for soil classification.

Much has been studied about the changes that tree leaves undergo once they have reached the soil. But even before the leaf falls, there is a microbial population on the leaf. These organisms can be parasites, fungi, which once they are on the ground can be displaced by other organisms typical of the soil surface, which take care of their complete decomposition.

This fresh organic matter starts to degrade in one way or another not only because of its own characteristics but also because of the characteristics of the soil and the climate. Soil microfauna and microflora are involved in this degradation as well as physical and chemical alteration processes. For these processes to take place there must be a certain humidity, temperature, oxygen (for oxidation). The end result of humification is humus, and this will be different depending on the source material and the location (type of climate). So this transformation can be faster or slower and this transformation to simpler forms can be perceived or not depending on the speed of degradation.

Soil fertility can be defined as the ability of the soil to supply nutrients to vegetation. This means that the soil has an ideal chemical fertility so that all the essential elements for plants are in the soil in an assimilable form, that they are not deficient (which would mean that some species could not live, or could not survive, or excessively so, which could lead to toxicity). The pH of the soil is totally related to this assimilation of nutrients.

Soil fertility should not be confused with soil productivity. Always we talk about soil productivity, we must always talk about it in economic terms. In other words, a forest in a natural park may or may not have fertile soil, but it is not more or less productive. The term "productive" is used when there are special practices, fertilization and mechanization. Soil can be made more productive, nutrients can be incorporated in an assimilable state, or pH modifying elements can be incorporated so that certain elements can be assimilated by plants, or to plant certain plant species.

Determination of soil organic matter. Loss on ignition method (Heiri et al. 2001).

To know approximately the percentage of soil organic matter and the percentage of organic carbon.

Infrastructure and equipment
- Precision balance
- Muffle furnace
- Desiccator
- High-temperature resistant porcelain vessel

Operating technique or method

Take 1 g of fine soil and place it inside the muffle furnace at 450°C for 8 hours, inside a tared porcelain container. It is placed at 1100ºC for 5 minutes if you want to do the "loss on ignition (LOI)" where the total organic carbon will be known. Once the sample is calcined, it is cooled inside the muffle and removed and placed in a desiccator before weighing.

The result we will obtain if we burn at 1100ºC will be the so-called PAF, which is not only the percentage of organic matter since we will also have calcined water contained in the clay minerals and approximately 45% of the total carbonates. For this reason, this method is only suitable for soils with a high organic matter content and only in this case the result of the PAF and the percentage of organic matter are approximate.

The following formula is used to calculate the amount of organic matter:

$$\% \text{ M.O.} = ((P1-P2)/P1)*100$$

The result will be the percentage of organic matter. If we divide the result by 1.724 (Van Bemmelen factor) we will obtain the percentage of organic carbon.

Interpretation of the results

<1% of O.M. = highly mineralised, subject to strong erosion
1-1,5% of m.o. = mineralised, low quality
1.5-2% of m.o. = mineral-organic, high quality
>2% o.m. = organic, very good quality

*4.2. pH*

The pH is a measure of the H+ ion activity in the soil. The acidity, neutrality or basicity of a soil is therefore conditioned by the presence of hydrogen ions. We can express this presence in milli equivalents of hydrogen per 100 g of soil or by the pH value.

The pH is defined as the negative logarithm of the H+ ion activity.

$$pH = \log 1/H+ = -\log (H+)$$

To establish the acidity or basicity of a soil, the pH of the soil solution is determined, and the soil solution will be acidic for values below 7, neutral for 7, and alkaline or basic for values above this value.

In order to understand the method we have to differentiate between "actual" or "real" acidity of the soil solution (caused by free H+ ions) and potential acidity (H+ ions of the sorbent complex). The actual acidity is determined by suspension of the soil with distilled water or with the paste saturated with distilled water. To determine the potential acidity, a suspension or a paste saturated with 1N KCl (potassium chloride 1 normal) must be made. Potential acidity, also called "hidden" acidity, is divided into exchange and hydrolytic acidity.

The importance of knowing the pH of a soil, i.e. its acidity or basicity, is essential to understand, first, the mobility of elements in the soil. Depending on the pH there will be elements that are either absorbable or not absorbable by plants or may be absorbable to the point of being toxic. The chemical properties directly influence the physical and biological properties in the soil. A change in pH can therefore affect the whole system (nutrient availability, toxicity, biological activity, etc.).

Knowing the pH will not only highlight problems, but is also necessary when it comes to remedies and solutions, such as the use of lime to counteract the acidity of the soil or to make use of fertilizers to enrich the soil. The change in pH value also gives an idea of a possible impact on the environment.

**Table II.** Main expected effects for the different ranges established by the USDA (1971).

| pH | Evaluation | Expected effects |
|---|---|---|
| <4,5 | Extremely acidic | Conditions very unfavourable |
| 4,5 – 5,0 | Very strongly acidic | Possible $Al^{+++}$ toxicity |
| 5,1 – 5,5 | Strongly acidic | Excess of: Co, Cu, Fe. Mn, Zn |
| | | Deficiency of: Ca, K, N, Mg, Mo, P, S |
| | | Soils without calcium carbonate |
| | | Ordinary concrete is attacked |
| | | Low bacterial activity |
| 5,6 – 6,0 | Moderately acidic | Range suitable for most crops |
| 6,1 – 6,5 | Slightly acidic | Maximum nutrient availability |
| 6,6 – 7,3 | Neutral | Minimal toxic effects, below pH = 7 no calcium carbonate in the soil |
| 7,4 – 7,8 | Moderately basic | Soils generally with $CaCO_3$ |
| 7,9 – 8,4 | Basic | Decreases availability of P and B |
| | | Increasing deficiency of: Co, Cu, Fe, Mn, Zn |
| | | Iron chlorosis |
| 8,5 – 9,0 | Slightly alkaline | In soils with carbonates, these high pH may be due to $MgCO_3$, if there is no exchangeable sodium. |
| | | Major iron chlorosis problems |
| 9,1 – 10,0 | Alkaline | Presence of sodium carbonate |
| >10,0 | Strongly alkaline | High percentage of exchangeable sodium (ESP = 15%) |
| | | Toxicity: Na, B |
| | | Mobility of P as $Na_3PO_4$ |
| | | Low microbial activity |
| | | Micronutrients poorly available, except Mo |

Determination of soil pH. Potentiometric method

To determine the pH of the soil

Infrastructure and equipment
- 50 ml beaker
- Beakers
- Spatula
- Phimeter with glass electrode
- Magnetic stirrer

- 1N KCl (74,55 g KCl in one litre)

Operating technique or method.

Take 20 g of fine soil and place it in a beaker. Add 50 ml MilliQ water and mix with a spatula. Stir for half an hour on a magnetic stirrer.

The electrode is then inserted and the photometer is read, calibrating the temperature on the apparatus if necessary.

The measurement with KCl is carried out in the same way as the measurement with distilled water.

Calculation and expression of results

The pH value shall be the value shown on the pHimeter display.

It must be taken into account that the pH of the soil varies when the sample is extracted and also when the sample is dried and re-wetted, so the results can be taken as indicative.

The electrodes of the pH-meter and all electrodes in general have to be carefully washed between measurements.

The pH values of water-saturated slurry are generally 0.5-1.5 units higher than the pH values of KCl-saturated slurry. This difference gives an idea of the degree of saturation of the soil. If the difference is zero or smaller, it indicates that there is a tendency to salinization (the soil is base saturated). If the difference is larger, it indicates a tendency to acidification.

*4.3. Electrical Conductivity*

Electrical conductivity is the physical capacity of water to transmit an electrical current through the ionic substances dissolved in it. It is an indirect measure of the amount of dissolved charge carried by a flow of water; it is a global value with which it is not possible to know which chemical substances are dissolved in the water, but it is possible to know the degree of mineralization. Thus, the higher the number of ions present in the water, the higher the conductivity value will be.

To know the electrical conductivity of water in order to have an approximation of the quantity of dissolved elements in a water sample.

Field or laboratory (measurement directly in the field is preferable).

Infrastructure and equipment

- Field or bench-top conductivity meter. Modern conductivity meters do not need temperature correction and give the value taking into account that the conductivity is standard for 25ºC. Older devices require a temperature measurement and a table, which is attached below, to transform the conductivity meter value at the water temperature to the conductivity that the sample would have if the water were at 25ºC. In other words, sometimes we may need a:

- Thermometer
- Glass

Insert the probe of the conductivity meter and the temperature probe if necessary and wait until the reading stabilizes. Normally, conductivity meters have 3 or 4 measuring ranges. The first range, first button, measures conductivities from 0 to 200 S/cm, the second button measures conductivities ranging from 200 to 2000 S/cm-1, the third button is for measuring higher conductivities and the value is already expressed in mS/cm, and ranges from 2 mS/cm (2000 S/cm) to 20 mS/cm, the third button measures higher conductivities.

As with any device or instrument, it is necessary to read the instructions of the conductivity meter. Not all of them work in the same way and, what is very important, not all of them have the same rules for their conservation. Some devices are not allowed to be washed with ultrapure water, while others recommend it.

The calibration of the conductivity meter is carried out with a 0.01 N KCl solution, which indicates a conductivity of 1.4120 S/cm at 25°C temperature.

The reading of the conductivity meter is direct, you only have to observe the value that appears on the display. But we have already said that in older devices the reading has to be transformed to the conductivity that the water in the sample would have if it were at 25ºC.

To determine the electrical conductivity, the same proportions [1:2.5] are used as for the determination of the pH of the soil, so that the measurement can be done together.

*4.4. Exchangeable Bases and Cation exchange capacity*

Determination of Exchangeable Bases ($Ca^{++}$, $Mg^{++}$, $Na^{+}$ and $K^{+}$). Extraction with ammonium acetate.

The exchange complex consists of all clay and humus particles that can absorb exchangeable cations. In soil the most frequent exchange cations are: $H^{+}$, $Ca^{++}$, $Mg^{++}$, $Na^{+}$, $K^{+}$; and $Mn^{++}$, Zn, $Cu^{++}$, $Fe^{++}$, $Fe^{+++}$, $Al^{+++}$ and $NH_4^{+}$ in small proportions. The relative intensity with which the cations are retained depends on the type of colloidal material (type of clay and humus) and the characteristics of the cation. Thus, for example, for organic matter, $H^{+}$ is the most strongly bound. On the other hand, for a montmorillonite type clay, the following sequence represents the relative strength of cation fixation (from the strongest to the weakest retained):

$$Al^{+++} > Ca^{++} > Mg^{++} > K^{+} > Na^{+}$$

The characteristics of the cation that determine the strength with which it is retained are the radius of the ion, the degree of hydration and the valency.

In a soil under normal conditions, calcium, magnesium, sodium and potassium are eliminated, either by washing or by passing on to the plant. If the mineral reserves are sufficient and the soil solution is therefore rich, the remaining free charges will be taken up by other similar cations, but if the cation content of the solution is very low, the charges are compensated by protons. These protons are responsible for the acidification of the soil.

Infrastructure and equipment:
- 250 ml Erlenmeyer flask
- Balance
- Automatic turner
- Filtering equipment
- 1N ammonium acetate at pH 7 (77.08 g $NH_4^+$ in 1 litre $H_2O$ milliQ).

Weigh 5 g of fine earth and place in a 250 ml Erlenmeyer flask. Add 100 ml of ammonium acetate. Shake by hand and leave in a tumbler for 24 hours. After this time the extract is filtered to determine the cations. Once this extract is obtained, it can be analyzed by Atomic Absorption Spectroscopy (AAS) or Induction Plasma Physics (ICP), bearing in mind that the sample may need to be diluted. It can also be analyzed by colorimetry as if it were water.

The ammonium acetate must be at pH 7, if the pH of the sample is high, it can be adjusted to pH 8 by adding a few drops of ammonia.

Once the extract has been analyzed, the values obtained are mg/l or ppm of each element, as in the following example:

$$Ca^{++} = 30 \text{ ppm}$$

We started from an extract to which a 1/50 dilution had to be made, then:

$$30 \text{ ppm} * 50 = 1500 \text{ ppm}$$

as the extract was made using a mixture of 5g of fine earth/100ml of ammonium acetate, the result must be multiplied by 20 = 100/5.

$$1500 \text{ ppm} * 20 = 30000 \text{ ppm}$$

The result can be expressed in meq/100 g of fine soil, then:

$$30000 \text{ ppm}/20.04 = 1497.0 \text{ meq/k} / 10 = 149.7 \text{ meq/100 g fine soil.}$$

Exchangeable cations come from weathering of the parent material, mineralization of organic matter, and external surface and subsurface inputs. In nature, an exchange complex with an ionic species can rarely be found. The most frequent exchangeable cations are less than ten and the presence and predominance of one or the other will depend on the conditions of the medium and the interactions at the interface. Exchangeable cations are found in considerably higher proportions than cations in solution. They represent 1% or less, except in saline soils. Based on some significant characteristics, the exchange cations are as follows:

- Calcareous soils of semi-arid and arid regions: $Ca^{++} > Mg^{++} > Na^{+} > K^{+}$.

- Sodic soils and nitric endopedions:

The percentage of exchangeable sodium is given by the expression:

$$ESP = (Na^{+}/CIC) * 100$$

The presence of exchange sodium above 5-15% causes unfavourable effects on the soil structure. A value of ESP = 5 can create problems in soils without limestone.

- Soils in humid areas: the percolating moisture regime causes a progressive acidification by loss of bases through leaching:

CEC = exchange bases + acidifying cations

- Strongly acidic mineral soils ($pH < 5.5$). The most important exchangeable cation is aluminium in its various forms, followed by calcium, magnesium and, to a lesser extent, $H^{+}$ ions.

- Acidic organic soils: in this case $H^{+}$ ions are important as an exchangeable cation.

Determination of the cation exchange capacity (CEC) of a soil

In the study of CEC, two different aspects are taken into account:

a) the exchangeable cations

b) the exchange capacity

When a sample is saturated with ammonium acetate, the exchangeable cations (Ca, Mg, Na and K) are displaced. $NH_4^{+}$ displaces these cations. To determine the exchange capacity, the same sample, saturated with ammonium salt, is washed with alcohol to remove the excess ammonium ion and saturated again, this time with NaCl, so that the $Na^{+}$ will replace the $NH_4^{+}$, which will remain in the solution.

Infrastructure and material:
- 250 ml Erlenmeyer flask
- Balance
- Automatic turner
- Filtering equipment
- 1 funnel
- Sea sand
- Glass wool
- 1N ammonium acetate at pH 7
- 96º ethanol
- NaCl 0,5 N (29,22 g NaCl in 1 l.$H_2O$ milliQ)

Weigh 5 g of fine earth and place in a 250 ml Erlenmeyer flask. Add 100 ml of ammonium acetate. Shake by hand and leave in a tumbler for 24 hours. After this time, the soil and extract are placed in a funnel in which glass wool and pure sea sand have been placed as a filter cushion. The extract is filtered and discarded (unless it is to be used for the analysis of exchange cations, Ca, Mg, Na, K). Wash the soil remaining in the funnel with 30 ml of 96° alcohol to remove excess ammonium. The operation is repeated two more times. The electrical conductivity of the filtered liquid must be less than 40s/cm, otherwise it must be washed again with alcohol.

Repeat the previous operation, but this time with 0,5N NaCl. Three extractions of 30, 30 and 40 ml, making a total of 100 ml. This extract is analysed for $NH_4^+$ ammonium and will be equivalent to the CEC.

The ammonium acetate should be at pH 7, if the pH of the sample is high it can be adjusted to pH 8 by adding a few drops of ammonia.

The ammonium value will be equivalent to the CEC.

The interpretation of the results is different according to the soil and the use made of it.

## 5. Conclusions

There are different methods used to analyze each of the above properties. This document has outlined the most common methods used in laboratory analysis.

The reliability of the methods is very high but will ultimately depend to a large extent on the use of the same method for all samples and sampling and the accuracy of the instrumentation in the laboratory work. It should not be forgotten that this is painstaking work, so in the laboratory it is advisable to be cautious and very methodical in order to adjust the method as much as possible.

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## Chapter 8. Modeling fire severity and soil loss: example from Braga municipality

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### Introduction

The development of research related to post-fire soil erosion is fundamental for understanding the phenomena and evaluate and propose mitigation measures. The increasing large Wildfires that affect the Mediterranean area are being influenced by the climate changes, human activities, and consequent changes in the soil and land use, with profound changes in the landscape. In different locations around the world, such as California (USA), Canada, Portugal, Spain and Australia, the intensity of these natural events is enhanced by the effects of climate change and overexploitation of natural resources by the population (Carracedo *et al*., 2018; Iriarte-Gõni and Ayuda, 2018; Miller *et al*., 2012; Nauslar *et al*., 2018; Pereira *et al*., 2013; Russell-Smith *et al*., 2020; Tedim *et al*., 2013).

The occurrence of wildfires alters all the natural dynamics. With wildfires, the topsoil is easily mobilized, changing the dynamics of infiltration and runoff, accelerating erosion and nutrient transport, affecting the quality and quantity of water in the watershed. In the current climate change scenario, there is a tendency to increase the frequency of large wildfires (Cerdà and Doerr, 2005; Ferreira *et al*., 2005; MacDonald and Stednick, 2003; Aldersley *et al*., 2011; Perchony and Shindell, 2010; Bento-Gonçalves and Vieira, 2020; Bento-Gonçalves *et al*., 2019), contributing for the aggravation of the mentioned impacts.

Studies carried out in different countries have demonstrated the high flow and soil erosion after wildfires. Generally, in regions of Mediterranean climate, in the first six months after the wildfires, the potential for erosive processes is greater due to the wildfires being concentrated in the summer (July to August) and the intense post-fire rains occur between autumn and next winter (November to January) (Andreu *et al*., 2001; Shakesby, 2011).

Besides, extreme climatic conditions increase the occurrence and propagation of wildfires, accelerating erosion processes. The Northern region of Portugal has a high recurrence of these events, with high intensity and dimension, ceasing to be a natural event for the renewal of ecosystems (Ferreira-Leite *et al*., 2015). During the 20th century, in addition to evidence of increased temperature and decreased rainfall, changes in land use and cover and variations in socioeconomic characteristics also

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influenced the increase in the number and intensity of wildfires (Bento-Gonçalves *et al*., 2012; Ferreira-Leite *et al*., 2016; Keeley *et al*., 2011).

The consequences of these events are direct and indirect on water, atmosphere, soil and vegetation. The reduction of vegetation cover exposes the soil to meteorological conditions, accelerating the erosive processes, material flow and nutrients existing in the superficial layers. Changes in the natural dynamics of ecosystems resulting from wildfires modify patterns in vegetation, in the physical and chemical properties of the soil and the processes of runoff and sedimentation (Deliti *et al*., 2005; Shakesby, 2011; Tessler *et al*., 2011).

The northern region of Portugal (NUTS II) has been successively affected by wildfires. This is the most populous region of Portugal, with 3,572,583 inhabitants (2018 data), concentrating 34.76% of the population of Portugal (INE, 2019). It also integrates three different hydrographic regions (RH1 Minho / Lima, RH2 Cávado / Ave / Leça, and RH3 Douro), and some important hydrographic basins fundamental for the public supply of the municipalities. According to the Management Plan of these hydrographic regions, their areas are frequently affected by wildfires, which subsequently increase runoff, soil erosion, and alter the quality of the water, namely its pH, making it more alkaline due to salts from the ashes. In relation to climate change, the region shows high vulnerability to its effects, related to the greater frequency of droughts and consequently wildfires, resulting in adverse effects on the watershed of the region (Bento-Gonçalves *et al*., 2011).

The central northern region of Portugal has high rates of soil erosion due to wildfires, this loss being one of the eight threats to the soil listed in the European Commission's Soil Thematic Strategy, due to the impacts caused mainly by food production, quality of drinking water and ecosystem services (Panagos *et al*., 2015).

According to a bibliographic survey carried out (Batista *et al*., 2019) in the period from 1985 to 2018, 550 articles were found with the search for the term “soil erosion model”, demonstrating its importance and applicability for modeling soil loss.

The Universal Soil Loss Equation (USLE) model is the more using and will be calculated in this tutorial using ArcGIS and Rstudio software, in addition to the Google Earth Engine (GEE) platform and data available on global open access platforms. The USLE is apply with the form:

$$A = R \times K \times LS \times C \times P$$

Where $A$ is the average annual soil loss per area (Mg ha$^{-1}$ yr$^{-1}$), $R$ is the rain erosion factor (MJ mm ha$^{-1}$ h$^{-1}$ yr$^{-1}$), $K$ is the erodibility factor of soils (Mg h MJ$^{-1}$ mm$^{-1}$), $L$ is the slope length factor (dimensionless), $S$ is the slope factor (dimensionless), $C$ is the land use and management factor (dimensionless) and $P$ is the factor of conservationist practice (dimensionless).

## Steps

*Fire Severity Calculator*

The normalized burn ratio will be applied to before and after images from a wildfire in Braga (NW Portugal) in 2017. By calculating the multitemporal difference of the NBR index (dNBR) the Burn Severity is derived, showing the spatial impact of the disturbance. The images used in this process come from Sentinel-2, but images from Landsat 8 can be used. The process was performed on the Google Earth Engine platform.

```
// Braga study area
var limite = ee.FeatureCollection ('users/SarahMoura/Braga')

////=========================SET TIME FRAME===================

// Set start and end dates of a period BEFORE the fire. Make sure it is
long enough for

var prefire_start = '2017-09-19';
var prefire_end = '2017-09-21';
// Now set the same parameters for AFTER the fire.
var postfire_start = '2017-11-10';
var postfire_end = '2017-11-12';

//select a satellite platform

var ImCol = ee.ImageCollection("COPERNICUS/S2");

// Set study area as map center.
Map.setCenter(-8.4286, 41.5462, 12);

//------ Select Sentinel imagery by time and location ----------------

var imagery = ee.ImageCollection(ImCol);
// In the following lines imagery will be collected in an
ImageCollection, depending on the
// location of our study area, a given time frame and the ratio of cloud
cover.
var prefireImCol = ee.ImageCollection(imagery
    // Filter by dates.
    .filterDate(prefire_start, prefire_end)
    // Filter by location.
    .filterBounds(limite));

    // Select all images that overlap with the study area from a given
time frame
// As a post-fire state we select the 25th of February 2017
var postfireImCol = ee.ImageCollection(imagery
    // Filter by dates.
    .filterDate(postfire_start, postfire_end)
    // Filter by location.
    .filterBounds(limite));

// Add the clipped images to the console on the right
print("Pre-fire Image Collection: ", prefireImCol);
print("Post-fire Image Collection: ", postfireImCol);
```

```
// number of images
var sizepre= prefireImCol.size();
print (sizepre, 'Number of images pre');
var sizepost= postfireImCol.size();
print (sizepost, 'Number of images post');

//list of images
var imagelistpre=prefireImCol.toList(sizepre);
print(imagelistpre, 'List of images pre');
var imagelistpost=postfireImCol.toList(sizepost);
print(imagelistpost, 'List of images post');

//select image to view
var imagepre= ee.Image(imagelistpre.get(1));
var imagepost= ee.Image(imagelistpost.get(1));

print(imagepre, 'Select image pre');
print(imagepost, 'Select image post');

var vistoa={
  bands: ['B12','B8A','B4'],
  min:[100],
  max:[3000]
};

Map.addLayer(imagepre.clip(limite),vistoa,"Image List pre", true);
Map.addLayer(imagepost.clip(limite),vistoa,"Image List post", true);

var printout= ee.Image(0).mask(0).paint(limite, 'AA0000',2);

var visgrid= {
  'pallette':'000000',
  'opacity':0.6
};

Map.addLayer(printout,visgrid,'Limite', true);

//-------------- Apply a cloud and snow mask ---------------------

// Function to mask clouds from the pixel quality band of Sentinel-2 SR
data.
function maskS2sr(image) {
  // Bits 10 and 11 are clouds and cirrus, respectively.
  var cloudBitMask = ee.Number(2).pow(10).int();
  var cirrusBitMask = ee.Number(2).pow(11).int();
  // Get the pixel QA band.
  var qa = image.select('QA60');
  // All flags should be set to zero, indicating clear conditions.
  var mask = qa.bitwiseAnd(cloudBitMask).eq(0)
      .and(qa.bitwiseAnd(cirrusBitMask).eq(0));
  // Return the masked image, scaled to TOA reflectance, without the QA
bands.
  return image.updateMask(mask)
      .copyProperties(image, ["system:time_start"]);
}

// Apply platform-specific cloud mask

  var prefire_CM_ImCol = prefireImCol.map(maskS2sr);
  var postfire_CM_ImCol = postfireImCol.map(maskS2sr);
```

```
  //-------- Mosaic and clip images to study area ---------------------

// This is especially important, if the collections created above contain
more than one image
// (if it is only one, the mosaic() does not affect the imagery).

var pre_mos = prefireImCol.mosaic().clip(limite);
var post_mos = postfireImCol.mosaic().clip(limite);

var pre_cm_mos = prefire_CM_ImCol.mosaic().clip(limite);
var post_cm_mos = postfire_CM_ImCol.mosaic().clip(limite);

// Add the clipped images to the console on the right
print("Pre-fire True Color Image: ", pre_mos);
print("Post-fire True Color Image: ", post_mos);

//--------- Calculate NBR for pre- and post-fire images ---------------

// Apply platform-specific NBR = (NIR-SWIR2) / (NIR+SWIR2)

  var preNBR = pre_cm_mos.normalizedDifference(['B8A', 'B12']);
  var postNBR = post_cm_mos.normalizedDifference(['B8A', 'B12']);


// Add the NBR images to the console on the right
//print("Pre-fire Normalized Burn Ratio: ", preNBR);
//print("Post-fire Normalized Burn Ratio: ", postNBR);

//---------- Calculate difference between pre- and post-fire images ---

// The result is called delta NBR or dNBR
var dNBR_unscaled = preNBR.subtract(postNBR);

// Scale product to USGS standards
var dNBR = dNBR_unscaled.multiply(1000);

// Add the difference image to the console on the right
print("Difference Normalized Burn Ratio: ", dNBR);

////------ Burn Ratio Product - Greyscale --------------
//
var grey = ['white', 'black'];
//
//// Remove comment-symbols (//) below to display pre- and post-fire NBR
seperately
Map.addLayer(preNBR,  {min:  -1,  max:  1,  palette:  grey},  'Prefire
Normalized Burn Ratio');
Map.addLayer(postNBR,  {min:  -1,  max:  1,  palette:  grey},  'Postfire
Normalized Burn Ratio');
//
Map.addLayer(dNBR,  {min:  -1000,  max:  1000,  palette:  grey},  'dNBR
greyscale');
//
//------------ Burn Ratio Product - Classification --------------------

// Define an SLD style of discrete intervals to apply to the image.
var sld_intervals =
  '<RasterSymbolizer>' +
    '<ColorMap type="intervals" extended="false" >' +
      '<ColorMapEntry color="#ffffff" quantity="-2000" label="-2000"/>'
+
```

```
      '<ColorMapEntry color="#008000" quantity="-250" label="-250" />'
+
      '<ColorMapEntry color="#32cd32" quantity="-100" label="-100" />'
+
      '<ColorMapEntry color="#00ff00" quantity="100" label="100" />' +
      '<ColorMapEntry color="#ffff00" quantity="270" label="270" />' +
      '<ColorMapEntry color="#ff4500" quantity="440" label="440" />' +
      '<ColorMapEntry color="#ff0000" quantity="660" label="660" />' +
      '<ColorMapEntry color="#800000" quantity="2000" label="2000" />'
+
    '</ColorMap>' +
  '</RasterSymbolizer>';

// Add the image to the map using both the color ramp and interval
schemes.
Map.addLayer(dNBR.sldStyle(sld_intervals), {}, 'dNBR classified');
//Map.addLayer(RdNBR.sldStyle(sld_intervals), {}, 'RdNBR classified');

// Seperate result into 8 burn severity classes
var thresholds = ee.Image([-2000, -251, -99, 99, 269, 439, 659, 2000]);
var classified = dNBR.lt(thresholds).reduce('sum').toInt();

//==================================================================
//                                     ADD A LEGEND

// set position of panel
var legend = ui.Panel({
  style: {
    position: 'bottom-left',
    padding: '8px 15px'
  }});

// Create legend title
var legendTitle = ui.Label({
  value: 'dNBR Class',
  style: {fontWeight: 'bold',
    fontSize: '18px',
    margin: '0 0 4px 0',
    padding: '0'
    }});

// Add the title to the panel
legend.add(legendTitle);

// Creates and styles 1 row of the legend.
var makeRow = function(color, name) {

      // Create the label that is actually the colored box.
      var colorBox = ui.Label({
        style: {
          backgroundColor: '#' + color,
          // Use padding to give the box height and width.
          padding: '8px',
          margin: '0 0 4px 0'
        }});

      // Create the label filled with the description text.
      var description = ui.Label({
        value: name,
        style: {margin: '0 0 4px 6px'}
      });
```

```
      // return the panel
      return ui.Panel({
        widgets: [colorBox, description],
        layout: ui.Panel.Layout.Flow('horizontal')
      })};

//  Palette with the colors
var  palette  =['008000',  '32cd32',  '00ff00',  'ffff00',  'ff4500',
'ff0000', '800000', 'ffffff'];

// name of the legend
var   names   =   ['Enhanced   Regrowth,   High','Enhanced   Regrowth,
Low','Unburned', 'Low Severity',
'Moderate-low  Severity',  'Moderate-high  Severity',  'High  Severity',
'NA'];

// Add color and and names
for (var i = 0; i < 8; i++) {
  legend.add(makeRow(palette[i], names[i]);
  }

// add legend to map (alternatively you can also print the legend to the
console)
Map.add(legend;

//================================================================
//                          PREPARE FILE EXPORT

var id = dNBR.id().getInfo();

Export.image.toDrive({image:  dNBR,  scale:  20,  description:  id,
fileNamePrefix: 'dNBR',
  region: limite, maxPixels: 1e10};


// Downloads will be availible in the 'Tasks'-tab on the right.
```

*Soil loss data organization*

The soil loss calculation steps will be carried out in ArcGIS and Rstudio software, in addition to the Google Earth Engine platform and are based on the methods of Moore (1979) to calculate the R factor, Williams (1995) to calculate the K factor, Stone and Hilborn (2012) to calculate the LS factor, Van der Knijff *et al*. (2000) to calculate the C factor.

In the Rstudio software it is necessary to install the raster, maps, rastervis and rgdal packages. To install the packages it is necessary to use the command `install.packages()` and to load the package in Rstudio use the command `library()`.

To define the working directory in Rstudio, use the following code:

```
setwd("C:/Users/saulo/Desktop/IntensiveCursoICG")
```

*R factor*

The R factor was calculated using the map of Europe Union and Switzerland, developed to Panagos *et al*. (2015) and using the code bellow:

```
# The input file paths
R_file <- "~/IntensiveCursoICG/r_braga.tif"

#Loading the raster files
r <- raster(r_file)

summary(r)
hist(r, main = "Histogram of rainfall erosivity")
```

*K factor*

The K-factor calculation considers the properties of the soil fraction of sand, silt, clay and carbon in the soil (top layer). Among the most used methods is Williams (1995) widely used in agricultural and hydrological studies (Williams, 1995; Arnold *et al*., 1998). Soil physical properties are usually derived from global bases, one of the most used sets being SoilGrids (Hengl *et al*., 2017) accessed through the soilgrids.org link. The K-factor implementation followed the following steps: building the function, importing the sand, silt, clay and soil carbon fraction files, putting all files in the same exponential extent, dimension and projection, resetting the NA values in the rasters, correcting the image of soil organic carbon, overlay the rasters and write the raster output.

```
# Williams [1995] implementation in R

calculate_k_williams <- function(sndprc, sltprc, clyprc, orcprc){
  a <- (0.2 + 0.3*exp(-0.0256*sndprc*(1 - sltprc/100)))
  b <- (sltprc/(clyprc + sltprc))^0.3
  c <- 1 - (0.25*orcprc)/(orcprc + exp(3.72 - 2.95*orcprc))
  sn1 <- 1 - sndprc/100
  d <- 1 - (0.7*sn1)/(sn1 + exp(-5.51 + 22.9*sn1))
  k <- 0.1317*a*b*c*d
  return(k)
}

# The input file paths
clay_file <- "~/IntensiveCursoICG/soilgrids_clay0_30_Braga.tif"
sand_file <- "~/IntensiveCursoICG/soilgrids_sand0_30_Braga.tif"
silt_file <- "~/IntensiveCursoICG/soilgrids_silt0_30_Braga.tif"
orgc_file <- "~/IntensiveCursoICG/soilgrids_SOC_Braga.tif"

#Loading the raster files
sand <- raster(sand_file)
silt <- raster(silt_file)
clay <- raster(clay_file)
orgc <- raster(orgc_file)

# summary
summary(sand)
```

```
summary(silt)
summary(clay)
summary(orgc)

# Re-define the NA values of the raster layers
NAvalue(sand) <- 0
NAvalue(silt) <- 0
NAvalue(clay) <- 0
NAvalue(orgc) <- 0

# Correct the orgc layer
orgc <- orgc/100

#Again check if the statistics of the layers are now right
summary(orgc)

#Copy extent

extent(silt)<-extent(sand)
extent(clay)<-extent(sand)
extent(orgc)<-extent(sand)

#Overlay the rasters
k <- overlay(sand, silt, clay, orgc, fun = calculate_k_williams)

summary(k)
hist(k, main = "Histogram of erodibility")

writeRaster(k, filename = "~/IntensiveCursoICG/k.tif",
            overwrite = TRUE)
```

*LS factor*

The LS-factor was calculated in ArcGIS using the Raster Calculator tool and the methodology of Moore and Burch (1986):

$$LS = (\frac{l}{22.13})^m (\frac{0.043x^2 + 0.3x + 0.43}{6.613}$$

Where:

l = slope length in meters

x = slope in percent

m values

| **Slope** | < 3% | 4% | ≥ 5 |
|---|---|---|---|
| **m** | 0.3 | 0.4 | 0.5 |

To calculate the LS-factor, a Digital Terrain Model (DTM) is required. From this base the following rasters are derived: slope (%), flow direction and flow accumulation. The slope (%) and flow accumulation rasters are entered into the Raster Calculator tool to generate the LS-factor.

*C factor*

The C factor can be calculated using land cover products and agronomic statistics or derived from vegetation indices. In this course, the vegetation index will be used as a basis for calculating the C factor, based on the methodology of Van der Knijff *et al*. (2000).

The procedure for calculating the C-factor was implemented in the Google Earth Engine platform, extracting the average NDVI image for the period 2017-2021, following the steps of the script below:

```
//Study area boundary
var boundary =  ee.FeatureCollection(Braga);

//Vizualize area
//Map.setcenter()

var start= ee.Date('2017-01-01');
var end= ee.Date('2021-12-31');

var vistoa={
  bands: ['B7','B5','B4'],
  min:[0.0],
  max:[0.4]
};

//Landsat
var L8 =ee.ImageCollection ('LANDSAT/LC08/C01/T1_TOA')
          .filterBounds(Braga)
          .filterDate(start,end)
          .filterMetadata("CLOUD_COVER", "less_than", 10)

print(L8, 'Col L8')

//Number of images
var size = L8.size();
print(size, 'Number of images');

var colecao = L8.select("B5", "B4", "B7");

//Filter by mean
var mean = colecao.mean()
print(mean)

Map.addLayer (mean.clip(boundary), vistoa, 'Filter by mean');

//NDVI
var L8_indice =function(L8){
  var ndvi = L8.normalizedDifference(['B5','B4']).toFloat();
  return ndvi.copyProperties(L8, ['system:time_start'])
}


// Map functions across Landsat Collections
var ls8 = L8.map(L8_indice)
```

```
// Merge Landsat Collections
var lsCol = ee.ImageCollection(ls8);

print(lsCol, 'NDVI collection')

var icollToBand = function(collection, Bname){
  var empty = ee.Image();
  var band = ee.Image(collection.iterate(function(image, previous) {
    var name = ee.String(Bname+'_').cat(image.id());
    var band = image.rename(name);
    return ee.Image(previous).addBands(band);
  }, empty));

  var Nband = band.getInfo().bands.length
  var Sband = band.select(ee.List.sequence(1,Nband-1,1))

return Sband;
};

var NDVI = icollToBand(lsCol, 'NDVI');

print (NDVI, 'NDVI collection')

Map.addLayer (NDVI.clip(boundary), {}, 'NDVI')

//Filter by mean
var meanN = lsCol.mean()
print(meanN)

Map.addLayer (meanN.clip(boundary), {}, 'NDVI mean')

//Export

var id = meanN.id().getInfo();

Export.image.toDrive({image:   meanN,   scale:   20,   description:   id,
fileNamePrefix: 'NDVI',
  region: boundary, maxPixels: 1e10});
```

After downloading the NDVI image, it is inserted into Rstudio to calculate the C-factor, based on the methodology of Knijff (2000), using the steps below:

```
#Knijff function in R

calculate_c_knijff <- function(ndvi) {
  alpha <- 2 # as suggested by Knijff 2000
  beta <- 1 # as suggested by Knijff 2000
  c <- min(exp(-alpha * (ndvi/(beta - ndvi))), 1)
  return(c)
}

#Loading the raster file
ndvi_file <- "~IntensiveCursoICG/NDVI.tif"
ndvi <- raster(ndvi_file)

#C-factor
c_ndvi <- calc(ndvi, fun = calculate_c_knijff)

hist(c_ndvi, main = "Histogramm of cover management factor C")
```

```
writeRaster(c_ndvi, filename = "~IntensiveCursoICG/c_ndvi.tif",
            overwrite = TRUE)
```

*USLE calculation*

For the calculation of the USLE, first it is necessary to place all the raster in the same spatial extension, for this we use the R-Factor as default, placing C-Factor, LS, K-Factor to the same spatial extension as R-Factor. Then the USLE value was calculated for the municipality of Braga.

```
# Place the rasters in the same spatial extent
# First: create a vector with the extension
ext <- extent(r)

# Second: sum 0.1 from this created vector
ext1 <- ext+0.1

#Third: change extensions of other rasters based on ext1 vector
extent(r) <- extent(ext1)
extent(k) <- extent(ext1)
extent(ls) <- extent(ext1)
extent(c) <- extent(ext1)

#Colocar a imagem de segmentação na mesma projeção e dimensão das outras
imagens
k1 <- resample(k, r, method="bilinear")
ls1 <- resample(ls, r, method="bilinear")
c1 <- resample(c, r, method="bilinear")


# Compare raster
compareRaster(k1,  ls1,  c1,  r,  extent=TRUE,  rowcol=TRUE,  crs=TRUE,
res=TRUE, orig=TRUE,rotation=TRUE, stopiffalse=FALSE, showwarning=TRUE)

#USLE calculated
p <- 1

usle <- r*k1*ls1*c1*p

hist(usle, xlim = c(0, 500) ,
     main = "Histogramm of mean annual erosion")
```

*Mean soil erosion in Braga watersheds*

To calculate the average soil erosion in the watersheds of the municipality of Braga, we entered the limits of these basins and extracted the average values of the layer referring to the USLE result, according to the code below:

```
# Load the watershed boundaries
watersheds_file <- "~/IntensiveCursoICG/Braga_bacias.shp"
watersheds <- shapefile(watersheds_file)

# Calculate the mean erosion values
```

```
a_watersheds <- extract(usle, watersheds, fun = mean, na.rm = TRUE, sp
= TRUE)

# Convert the a_watersheds in raster
a_watersheds_raster <- rasterize(a_watersheds, usle, field = "layer")

# Load the hillshade and the NDVI
hillshade <- raster("~/IntensiveCursoICG/dtm_hillshade.tif")
mean_ndvi <- raster("~/IntensiveCursoICG/NDVI_braga.tif")

# Define custom color ramps
erosion_palette <- colorRampPalette(c("lightblue","coral3"))
veget_palette                                                    <-
colorRampPalette(c("lightyellow","lightyellow3","darkgreen"))

# Plotting the hillshade
plot(hillshade, col = grey(1:100/100), legend = FALSE)

# Adding the NDVI as proxy for vegetation in brown to green colors
plot(mean_ndvi, col = veget_palette(25), alpha = 0.75, add = TRUE, legend
= FALSE)

# The add the basin boundaries
lines(watersheds)

# Results of our assessment in blue (low erosion) to red (high erosion)
plot(a_watersheds_raster, add = TRUE , col = erosion_palette(25), alpha
= 0.7)
```

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## ORGANIZATION AND SUPPORTERS:

IAG GEOMORPHOLOGY GEOMORPHOLOGIE AIG

APGeom Associação Portuguesa de Geomorfólogos

CEGOT Centro de Estudos de Geografia e Ordenamento do Território

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