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Study of forest soil quality following fire period

Antoine Dubusse Allais

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Travail de fin d'études
pour le diplôme d'ingénieur de l'École nationale des travaux
publics de l'État

Étude de la récupération des sols après un feu de forêt

Soutenu le 01 septembre 2021

Devant le jury composé de :

Président du Jury : Jean-Philippe BEDELL

Maître de TFE : Nuno CORTEZ

Expert : Rafaël ANGULO-JARAMILLO

par

Antoine DUBUSSE ALLAIS

Voie d'approfondissement : Risques Pollutions Nuisances (RISPOL)

Année 2020-2021



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Notice analytique

Auteur

Nom	DUBUSSE ALLAIS
Prénom	Antoine

Organisme d'accueil

Nom de l'organisme	Instituto Superior de Agronomia
Localité	Lisbonne
Nom du tuteur	Nuno CORTEZ
Nom du cotuteur	Erika SANTOS

Analyse du TFE

Titre (français)	Étude de la récupération des sols après un feu de forêt
Titre (anglais)	Study of forest soil quality from South of Portugal following different fire periods
Résumé (français)	<p>Le réchauffement climatique est fortement lié à l'activité humaine et aux émissions de gaz à effet de serre qu'elle produit. Les derniers rapports du GIEC montrent qu'il est crucial de réduire fortement, rapidement et durablement ces émissions. Les feux de forêts, en relâchant sur une très courte période des grandes quantités de ces gaz, participent à ces émissions. REMAS, un groupe de travail européen, s'attache à chercher comment stocker plus de Carbon dans les sols afin de réduire les émissions de Carbone durant les feux de forêt. Durant ce stage, j'ai participé à la phase d'étude de la récupération des sols après un incendie.</p>

Résumé (anglais)	Global Warming is strongly linked with human activity and the greenhouse gases it produces. Last IPCC reports highlight how crucial it is to reduce a lot, fast and persistently these emissions. Forest fires, by releasing over a short period of time huge quantities of greenhouse gases, participate to the global emissions. The European project REMAS aims to investigate the possibilities to stock more Carbon in the soils in order to reduce the missions during wildfires. During my internship, I participated to the study of soil recuperation after a forest fire.
Mots-clefs (français)	Sols, Forêt, Incendie, Réchauffement climatique, Carbone
Mots-clefs (anglais)	Soils, Forest, Wildfires, Global Warming, Carbon
Termes géographiques (français)	Portugal, Algarve, Sud-Ouest-Européen (SUDOE)

Collation

Nombre de pages	Nombre d'annexes (nb de pages)	Nombre de références bibliographiques
58	0	39

Déclaration de travail personnel

Je déclare que ce rapport constitue l'aboutissement d'un travail personnel et ne peut être suspecté de plagiat.

Le travail présenté distingue explicitement ce que j'ai produit de ce que j'ai emprunté à d'autres. A ce titre, les citations sont clairement identifiables et les sources (écrits, images) qui ont alimenté ma réflexion sont référencées.

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1. Introduction

Global changes in climate are occurring in the present decades and affecting ecosystems in many ways. Forest fires of bigger intensities and frequencies are one of the numerous effects of those changes. European southern ecosystems, though used to forest fires, have been facing stronger catastrophes during the last few years due to those changes. In addition, each fire emit more greenhouse gas, enhancing the causes of the climate changes. As a response to those issues, an European cooperation between several countries affected by the forest fires problems is currently investigating the links between Global warming, forestry practices, and fires.

1.1 Global warming

One of the main preoccupation of the 21st century is, and will probably be for many years to come, Global Warming. This problem is known for several decades and has been publicly alarmed since the beginning of the years 1990. The Rio de Janeiro Earth Summit of 1992 was the first international summit to recognize Climate Change as a major environmental issue and enforce international conventions to tackle it [38].

Global warming description

Global warming is the name given to the climate change observed on Earth since the beginning of the industrial era. This change represents an increase

in the Earth surface global temperature [26]. It is important to differentiate "Climate" and "Weather". While the weather refers to an atmospheric situation at a local state and occurring over a short period of time (from minutes to hours), climate defines the rainfall, humidity and mean in temperature over a large area, or even globally during a long period of time (years to decades) [26]. The graph presented under in figure 1.1 represents the global Earth temperature deviation using the mean of the years 1951-1980 as a reference. We clearly observe an increase of this deviation, going faster from the years 1960. It is not the first time that the Earth is facing a Global warming, as temperatures on the surface of the planet have been following a cyclic pattern of heating and cooling during the last millenniums. However, it is the first time such and increase in terms of speed and impact, has been measured [7]. The Intergovernmental Panel on Climate Change (IPCC) acknowledges that the rise of global temperature can be linked with human activity up and that there is a strong correlation with greenhouse gases emissions. In its last report, the IPCC highlighted the fact that the Earth surface temperature increased faster during the last 50 years than ever in the last 2000 years, for a same amount of time (A.2.2) [20].

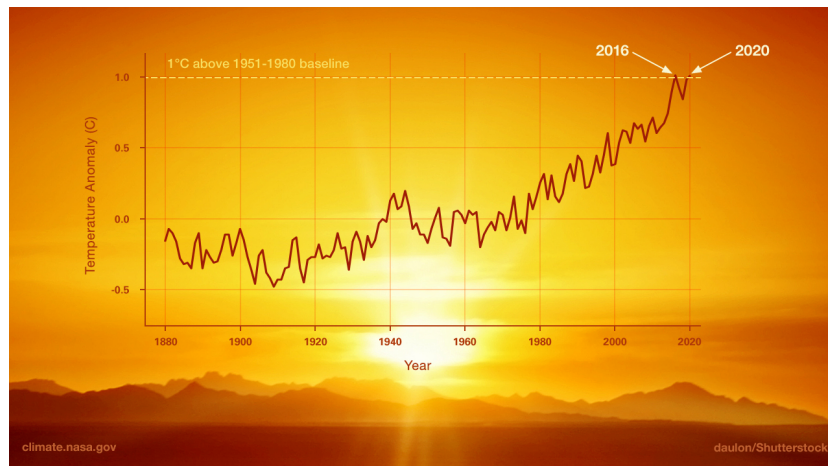


Figure 1.1: Global Earth Temperature deviation compared to the mean 1951-1980
From NASA website [26]

Global warming effects

This global warming affects ecosystems and human activity in many ways. The last report of IPCC dresses a portrait of the years to come and the several effects we will have to face. In some regions of the world, days of extreme temperature will be faced more frequently, and breaking all records. As an example, 10 of the hottest years since 1850 took place after 1990. Concerning the oceans, the sea level is expected to keep rising in the future alongside the retreat of the glaciers. This is due mostly to two phenomenon : the expansion of water due to its warming, and the loss of ice over land. In addition, the oceans represent 91% of the heating of the climate system. Moreover, the oceans water is getting abnormally acid on the surface, compared to the 2 previous million years, because of the dissolution of CO_2 . If CO_2 emissions keep rising, the IPCC models predict that the ocean sinks will be less effective in preventing the CO_2 to end up in the atmosphere. [20] Extreme events are expected to rise both in intensity and frequency. This concerns forest fires in a large portion of the globe, accompanied by change in vegetation. This adaptation will in fact increase the phenomenon. [22] Other phenomenon subject to a rise in intensity and frequency are cyclones, droughts and floods. [39] During my internship, I focused only on one type of event, being wildfires.

1.2 Forest fires

Encyclopaedia Britannica defines a "forest fire" as an uncontrolled fire affecting a vegetation of at least 1.8m of height [35]. In addition, French government website specify that at least half a hectare of vegetation has to go up in smoke for it to qualify as a forest fire [11].

Every year, approximately 348 millions hectares of forest are subject to forest fires in the world [10]. Within Europe, Portugal is one of the most widely affected countries and suffered many tragic losses during the past years. 2017 was a particularly difficult year as Portugal had to face two major fires in June and October. The European Super Case Study 4 mentions more than a hundred dead persons and a total burnt area for the two events

of 346 000 hectares [15]. In comparison, in France 15 000 hectares of ecosystems have been subject to wildfires in 2019 [24]. The figure 1.2, extracted from a guide against forest fires edited by CEMAGREF, shows a comparison between Mediterranean countries of the importance of forest fires during the two last decades of the 20th century [8]

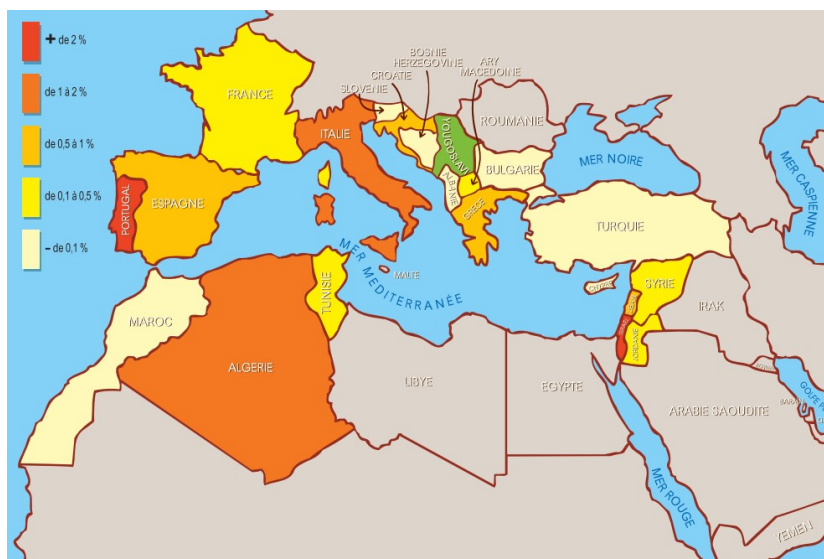


Figure 1.2: Relative surface burnt during the period 1981-1997 in the Mediterranean region

From CEMAGREF [8]

1.2.1 Causes of forest fires

There can be several causes to forest fires. The CEMAGREF guide to prevent forest fires establishes a clear classification of them based on the causes [8]. First, it separates natural causes to human causes. Natural causes are mostly due to lightnings. Nonetheless, it is the cause of a relatively small amount of forest fires in the Mediterranean region, as only up to 5% of the fires are due to natural causes. Therefore, most of the fires are the result of human activities. Again, two groups can be differentiated among forest fires. Some fires are caused in an involuntary way : agriculture, barbecue, cigarette, etc. The rest is lit intentionally as an act of pyromania, vengeance or economic and social interest. Global warming is also an important factor in the frequency

and intensity of forest fires. The work of Scholze & al shows that for three different scenarios of global temperature increase ($T < 2^{\circ}C$, $2^{\circ}C < T < 3^{\circ}C$, $T > 3^{\circ}C$) the wildfires frequency is expected to increase as much as 50% in the Mediterranean European countries [31].

1.2.2 Forest fire properties

The CEMAGREF guide to prevent forest fires reminds us that for a fire to be lit, three elements must be reunited : fuel, oxidant and initial energy intake [8]. The level of interaction between these three elements will influence the force of the fire. The guide provides the example of a fire affecting pine needles. If they fell recently, there is a lot of air in between the needles and the contact fuel (needles) and oxidant (oxygen) is improved. On the contrary, if they fell a long time ago and settled, the contact area between these two components is reduced. The fire generated in the first scenario will be stronger [8].

The temperature measured during a forest fire can exceed $1500^{\circ}C$. Nonetheless, Knicker & al. estimate that forest fires normally generate a temperature around $200^{\circ}C$ to $300^{\circ}C$ [16]. Even though some points of the fire reach these high temperatures, the soil is colder. For instance, Scotter observed in a fire reaching $300^{\circ}C$ on soil surface that the ground temperature at a depth of 4cm never exceeded $40^{\circ}C$. With an initial temperature of $25^{\circ}C$, this represents a difference of only $10^{\circ}C$ [32]. Nevertheless, as Knicker notes, ground temperature is highly dependent to the initial moisture, as a moist soils have a better thermal conductivity [16].

1.2.3 Effects of forest fires

Effects on the soil

Soils are complex ecosystems, hosting many interactions. Forest fires will affect soils in different ways and interfere with the normal life-cycle of the ecosystem. First, the physical and chemical properties will directly be affected by the burning and it will take from a very short time to several

decades to go back to the initial values. The availability of macro-nutrients will also be modified and have consequences for the recolonization of flora and fauna, whose balance have been broken. Figure 1.3, from Mataix and Solera, summarize the effects of a wildfire on soil properties [21].

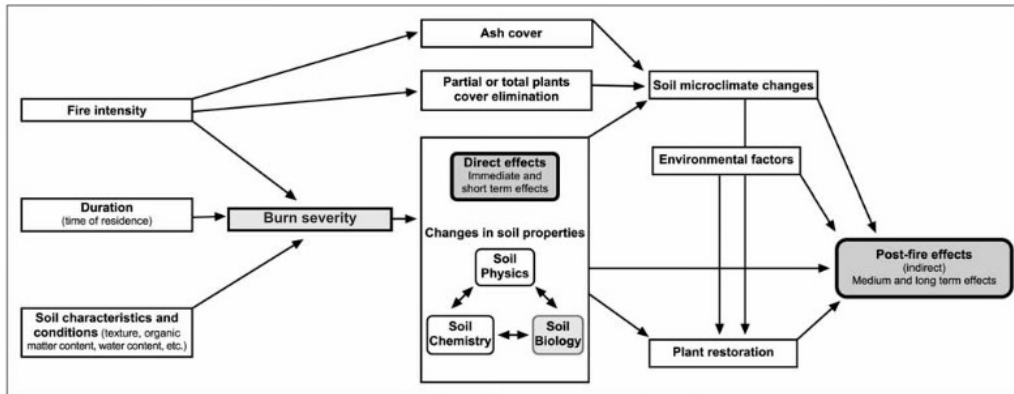


Figure 1.3: Forest fire effects on soil properties.
From Mataix and Solera [21]

Physical properties Soil structure in itself will be altered by the fire. The formation of a water-repellent layer near the soil surface decreases water infiltration [4]. Therefore, runoff is shown to considerably increase after a forest fires [13, 33]. In the south of France, Lavabre has noticed an increased of 25% to 30% in runoff during the first year after a wildfire [18, 4]. This increase is caused by the absence of vegetation leading to having more water available for runoff, and less obstacle on the way and an infiltration decrease related with some hydrophobicity resulting from the fire and the accumulation of ash on the ground surface [33]. Increased runoff can cause floods in other ecosystems and over human lands [13]. The runoff increase is often accompanied by an augmentation in sediment yield during rainfalls [4], which causes soil loss and transport of minerals and pollutants [13]. Figure 1.4 from Benavides-Solorio work on post-fire runoff and erosion shows clearly the effect of fire on sediment transportation.

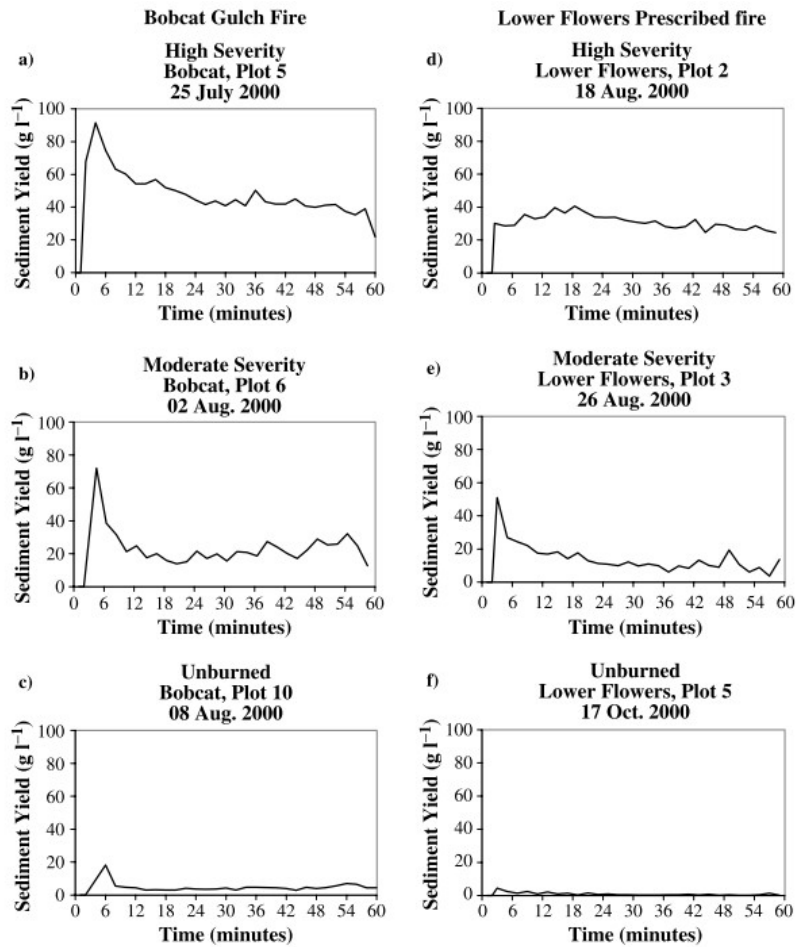


Figure 1.4: Sedigraphs from two fires (Bobcat, Lower Flowers) at different burning severity

From Benavides-Solorio and MacDonald work on post-fire runoff and erosion [4]

Chemical properties pH is known to increase after a forest fire because of the ash-bed deposit on the surface [6] and this increase can reach up to 3 units of pH [16]. This is referred to in literature as the "Lime-effect", and can be noticed up to 3 years after the burning [16]. Electrical conductivity (EC) is also subject to an increase in soil solution after a fire, because of inorganic ions release resulting from the combustion of the organic matter [28, 12, 16]. The EC goes back fast to its initial value because of precipitations and salt fixation [12]. On the contrary, Cation Exchange Capacity (CEC) is expected to drop after a forest fire due to the loss of adsorption sites [2].

Nutrients Fire affects nutrients availability in the soil. In general the aftermath of a wildfire consist of an increase of nutrients in soils. This was observed by Hernández et al. for Phosphorus, Potassium and Nitrogen in forms available for plants [12]. However, Knicker highlights the fact that without plant uptake, NH_4^+ and NO_3^- will disappear from the ecosystem because of denitrification and leaching. In addition, fire destroys aboveground forms of P and N faster than the mineral extraction. Therefore, the absence of vegetation recolonization will result in a decrease of productivity. Sometimes recovery is very slow and even after dozens or hundred of years, initial levels are not re-established [16].

Microbiology Soil microorganisms are more than essential to the ecosystem, as they are playing key roles in the nutrients cycles. Most of the biomass is located in the 0-2.5cm layer and the concentration decreases fast with the depth [16]. By being close to the surface and where the wildfire takes place, burning affects significantly microorganisms. Mataix and Solera give a thorough description of fire effects on microbiology. Directly after the fire, an increase in bacteria quantity is noticed, due to the favorable pH conditions, better use of soluble organic compounds and absence in battle for nutrients. On the long term, the levels of bacteria go back to normal or lower than usual, mostly because of the lack of interaction with the vegetation [21]. Concerning fungi, opposite effects are observed, based on soil and fire properties. While the pH increase creates a good developing environment, fungi are more affected than bacteria because they are destroyed at lower temperatures. The resettlement depends a lot on fire distribution and proximity of an inoculum potential source in an non-burned area [21]. As regards to macro-invertebrates, there is a significant decrease both in mass and diversity after a forest fire [21]. Finally, the levels of indicators of microbial activity such as enzymes are found lower than the usual ones [21].

Effects on atmosphere

It has been estimated by Mieville et al. that forest fires emit around 4.5 Gt of CO_2 yearly, with a strong variability between the years. They also note

that forest fires represents 45% of CO_2 emissions due to burning biomass [23]. In fact, these kind of fires emit CO_2 through two processes which are first, the combustion, and second, the decomposition of killed vegetation [17]. But fire doesn't only emit CO_2 , as different chemical species are also released because of the incomplete combustion of the biomass, including greenhouse gases with more impact on global warming than CO_2 such as CH_4 [1]. As we can see, forest fires contribute a lot to the 57.4 Gt CO_2 eq emitted yearly and globally [27]. As a matter of fact, Miranda et al. already tackled that issue for Portugal in 1994. They found that forest fires could become the cause to up 7% of Portugal global CO_2 emissions and highlight the vicious circle that this situation is. In effect, by releasing more greenhouse gases in the atmosphere, forest fires reinforce the effects of climate change and consequently lead to an environment more suitable to wildfires [25]. We showed that there are strong links between forest fires and Global Warming. Therefore, reducing their emissions could be a strong lever for action against climate change.

1.3 Project REMAS

1.3.1 Objectives

Forest fire management represents a huge challenge for the future due to the double-sided interactions between wildfires and global warming. Forests appear at the same time part of the problem and one interesting solution to fight the climate change. In effect, on the one hand a forest fire can release an big load of greenhouse gases (GHG) in the atmosphere in a matter of hours ; but on the other hand forest and their soils offer a promising Carbon sink that could be used to mitigate the global greenhouse gases emissions.

In agreement with these statements, different public organisms and universities from South West European countries launched project with the aim to characterize and investigate the possible ways to act on forest fires against global warming. The communication website of the REMAS project summarize the aim of this program as follows :

”REMAS will analyze, in addition to the material, environ-

mental and social consequences, the impact of forest fires on CO_2 emissions. All the study is framed in a context where CO_2 emissions risk management in forest fires is crucial to turn the vicious circle: forest fires – GHG emissions – climate change, into an opportunity for the forestry sector. The forest area is the largest manageable carbon sink and its correct management makes it a powerful climate change mitigation tool.” [30]

The three main objectives of this project will be 1) to define and evaluate the emission risk of fire in forest ecosystems in order to 2) elaborate solutions to increase Carbon storage capacity after a wildfire and 3) include the GHG emission from forest fires risk into the planning regulations and fire prevention policies. The project started 1st October 2019 for a duration of 36 month, under the direction of the Municipal Forest Association of the Valencian Community (AMUFOR).

Working packages

In order to reach the objectives settled for the project, different working packages have been introduced in the beginning of the project. They will be presented briefly underneath.

- ”WP1 : Estimation of the risk GHG emissions from an integrated soil-vegetation system due to forest fires”

Modeling emission risk in the forest system in different scenarios in order to determine the parts of the forest management system that should be revised first.

- ”WP2 : Pilot areas in cross-border cooperation”

Proposing steps to enhance the sustainable forest management in order to keep more carbon in the forest system during and after the forest fire.

- ”WP3: Development of GHG emission prevention and risk management guidelines”

Writing precise guidelines taking into account the emission risk inside the planning tools of every region participating to the project.

- "WP4: Capitalization and transfer"

Spread information and engage to an active exchange with all the related actors.

My participation to the project REMAS will take place under the scope of the working package 1, as I will intend to characterize the recuperation mechanism of soils after a forest fire.

1.3.2 Actors and funding

The project REMAS is led by various actors from 3 different countries of the South European area. Those are France, Portugal and Spain. The majority of the funding comes from a European Union programme named Interreg SUDOE.

Programme Interreg SUDOE

The programme Interreg SUDOE is a transnational cooperation programme of the European Union. It is financed by the European Regional Development Fund (ERDF). Figure synthesizes the European structural funding system.

This particular programme concerns the Southwest European Countries as SUDOE stands for "Sud Ouest Européen". It actually covers 5 countries : Portugal, Spain, France, the Principality of Andorra and the United Kingdom. The total budget of this programme is of 141 million euros and it can be used to fund research and development and small to medium-sized companies of low competitiveness.

In the case of REMAS, the project was mostly funded by the Interreg SUDOE programme as it financed 75% of the 1,8 million euros of budget.

Actors

The beneficiaries of this project are listed below and organized by country.

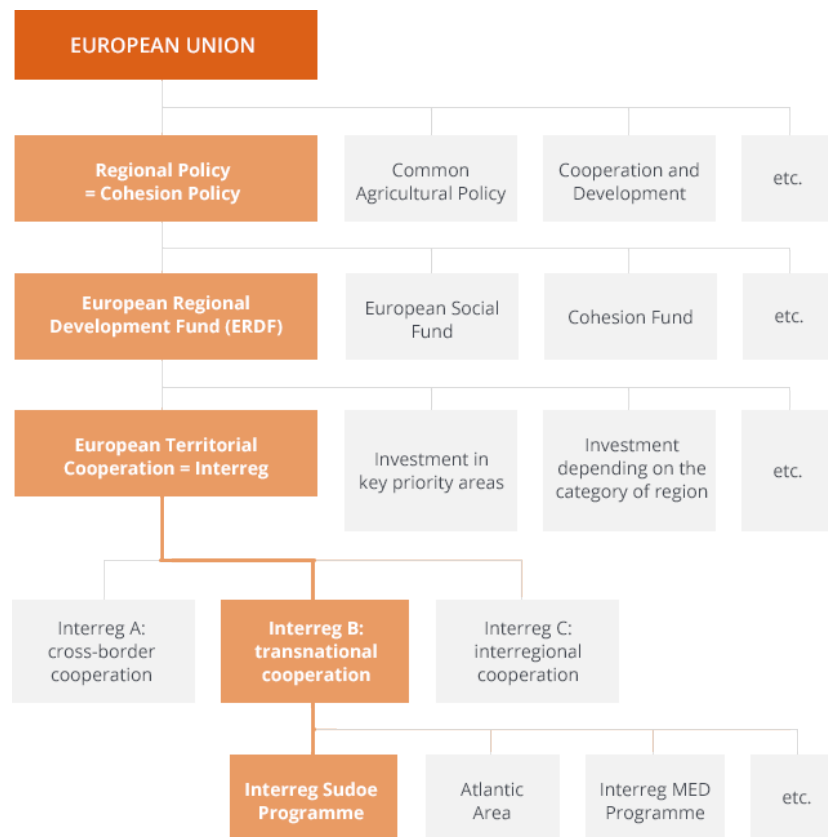


Figure 1.5: Interreg organizational chart
From the Interreg SUDOE communication website [14]

- In Spain :
 - AMUFOR – Association of Forest Municipalities of the Comunitat Valenciana. This entity is the coordinator of the project
 - UPV- ITACA –ICT group versus Climate Change
 - CSIC-CIDE Desertification Research Center and UV University of Valencia
 - CAMACCDR, Generalitat Valenciana
- In Portugal :
 - ISA University of Lisbon
 - Portuguese public management entity

- Loulé Municipality
- In France :
 - National Institute of Agronomic Research
 - National Geographic Institute

1.4 Problematic

The planet is facing a climate change, also known as Global warming, with many effects for the environment : temperature increase, water rising, events like bushfires, storms or droughts increasing both in frequency and size. Those aftermaths will be affecting directly and indirectly human populations. For instance the rising waters will erase some cities and even some countries from the maps, the increase of the temperature will make some part of the world impossible to live in, the bigger catastrophic events will kill many unprotected populations, etc. It is proven that this climate change is not part of the normal heating and cooling cycles of the Earth, and that the human activity is highly responsible of this change. Researchers also showed the correlation between greenhouse gases emissions and global warming. In addition, after releasing several models based on probable global temperature increase scenarios, the IPCC highlighted the importance to reduce fast, quantitatively and efficiently the greenhouse gases emissions in order to contain the effects of Global Warming under a manageable level. The key role of soils as a Carbon sink, temporizing greenhouse gases emissions, is now well acknowledged by the scientific community. In addition, the participation of forest fires to greenhouse gases emissions induce a vicious circle : they increase the impacts of Global Warming that, in return, increase the frequency and force of forest fires. Therefore, it has been pointed out that forest fires were a useful tool that could be used in order to reduce global greenhouse gases emissions fast, as recommended by IPCC. This problem was tackled by different actors from South-West European countries that decided to turn it into a research project known as REMAS. This project investigate the pos-

sibility to store more Carbon in the forest soils, in order to reduce the greenhouse gases release during a forest fire. In order to develop such strategies, it is crucial to know the interactions between soils parameters and wildfires. Researchers need to clarify and quantify different process before to be able to elaborate forestry plans aiming to reduce forest fires Carbon emissions. The team I integrated at the Insituto Superior de Agronomia (ISA), School of Agronomy, focused on one of this problems. How soils recuperate after a forest fire ? We will intend to characterize the soil medium-term response to fire thanks to an experiment based on the analysis of samples collected over an area divided in 3 zones : never touched by fire, burned in 2004 and burned in 2012. The statistical and geostatistical treatment of the soil analysis will give some insights of the recuperation process over the years.

2. Methodology

In this part I will present the general methodology the team used to characterize soil recuperation after a forest fire. I will also present the area of study and detail the different protocols we used to run the analysis over different soil parameters.

2.1 General methodology

The goal of the part of the project I contributed to was to characterize soil recuperation on the years following a forest fire. In order to do so, it was necessary to analyze several soil parameters such as pH, Carbon concentration, Nitrogen concentration, etc., at different times after a forest fire. In a practical matter, and because the project is set to only have a 3 year duration, the team preferred to study an area that was burned twice, with an 8 years difference. Therefore we benefit from samples originating from the same area of three types : 1) not touched by fire, 2) burnt only in 2004 and 3) burnt only in 2012. The sampling area will be defined in order to get samples from these tree groups. Therefore, we will obtain a chronology of the soil parameters after the fire. Through data analysis, the team expects to observe the evolution of these parameters and characterize the recuperation of the soils.

2.2 Area of study and sampling

In order to comply with the project duration and the main method I detail in introduction to this part, the REMAS investigation team had to find and define an area of study that was subject to several forest fires, over two distinct areas and a few years apart. It was not chosen to use experiment and controlled fire. Once the study area was chosen and defined, a sampling protocol was defined and soil samples were collected homogeneously over the zone.

2.2.1 Studied area and sampling

The studied area is located in Serra do Caldeirão in the District of Faro, Loulé Municipality, in the South of Portugal. Serra do Caldeirão presents relatively low altitude mountains (max 577m) and separates the littoral from the peneplains of the Alentejo region. Cork oaks are the predominant species in this area. In the studied area occurred two different fires, with a time difference of 8 years. The first fire occurred in 2004 and burned the most western part of the zone, and the second one occurred in 2012 and affected the eastern part of the studied area. In Serra do Caldeirão, there is some unburned area. within this scenario, three zones were selected relatively to the fire situation: unburned, burned in 2004 and burned in 2012. Figure 2.1 presents the sampling areas inside Serra do Caldeirão and shows the fire distribution within the studied area.

2.2.2 Sampling methods

The sampling was done by REMAS team and other soil researchers in November-December of 2020. The samples of litter and two soil layers (0-5 cm and from 5 until the maximum depth) were collected on a total of 57 plots distributed over the study area. For some plots, not every layer was collected. The number of samples to get for each component was defined according to an order of priority. For instance, there is more samples of the 0-5cm because this is the layer is the most affected by fires. The locations of the plots were chosen

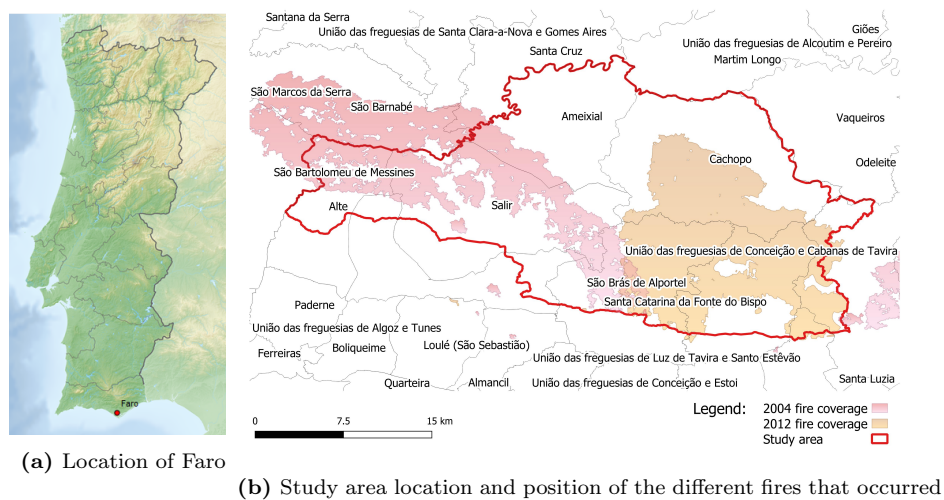


Figure 2.1: Location of situation of the study area

taking account the forest inventory and inside each plot the soil sampling (3 points per plot) was realized randomly through a GIS system (ArcGIS). Each plot was located thanks to a center point that was used to delimit a 21mx21m square. Within each plot, 3 samples were collected. Figure 2.2 illustrates this sampling strategy within a 21mx21m plot area.

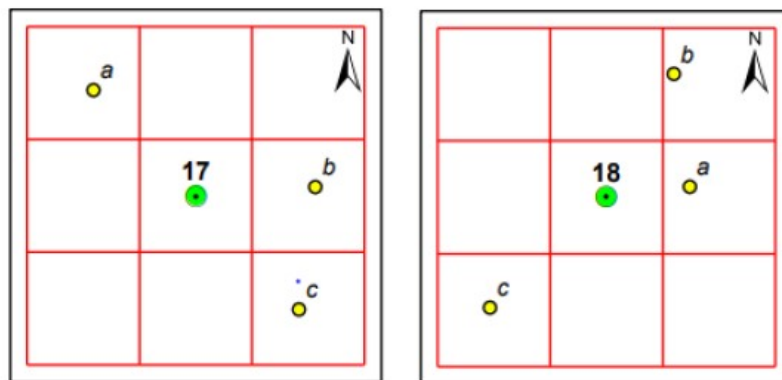


Figure 2.2: Two different plots showing different random sampling distributions

2.3 Analyses

The goal of the study is to conduct analyses over the two layers of the soil: 0-5cm and 5-30cm. However, because of the total number of soil samples to analyze (245), it was not possible during the time of my internship to run every analyses on both layers. For some of the parameters, I only did the measurements on the layer 0-5cm. This still makes sense, as we expect the fire to affect more the first centimeters of the soil. After collection, soil samples were homogenized and a part of these samples were frozen for soil enzymatic analysis while the remaining sub-samples were air-dried for physical and chemical analysis. For both types of parameters, biological and physico-chemical, the samples were sieved at 2 mm. Fraction lower 2 mm was used in all analyses.

2.3.1 pH and Electrical Conductivity

In a soil:water solution with a ratio of 1:2,5 (m:V), after mixed regularly during 1 hour, pH and electrical conductivity (EC) was measured with a potentiometric meter.

2.3.2 Carbon

The Carbon contained in the soil can be divided in several fractions according to its stability and form. This partition offers a valuable representation of C dynamic in the soil and consequent properties and quality. For the part of the study I participated to, we evaluated the Total Carbon, the Total Organic Carbon and the Labile Organic Carbon.

Total Carbon

The Total Carbon contained in the soil samples was measured by LECO equipment.

Total organic carbon and labile carbon

Total organic carbon concentration was measured using wet digestion (Walkley-Black method). In this protocol, the organic matter is oxidized using Potassium dichromate in a sulfuric acid solution heated around 160°C. The excess of dichromate is titrated with a ferrous sulfate solution of known title and using Difenilamina as a color indicator.

The hot water soluble fraction of C in one of the organic fractions that is easily accessible for the use of the various organisms of the ecosystem. To measure it, we used a hot water extraction method. A 1:5 solution of air-dried soil and water was heated at 80°C and mixed regularly during 1 hour in a hot bath. After centrifuging that solution, the subnatant was then placed in 50 mL erlenmeyer and put in a desiccator at 100°C. The Carbon was finally measured using the Walkley-Black method.

2.3.3 Nitrogen

Nitrogen is an important nutrient for vegetation and soil biomass. It can be found in many forms in the soil following a cycle of life that is well characterized. The diagram in figure 2.3 presents the Nitrogen journey between its different forms in the soil. The predominant inorganic, or mineral, forms of Nitrogen are the ions Ammonium (NH_4^+) and Nitrate (NO_3^+). These two forms constitute the majority of the Nitrogen available for the plants [36].

Total Nitrogen

The Total nitrogen contained in the samples was also measured by LECO equipment.

Ammonium and Nitrates

We realized the measurement of both mineral fractions of N (Ammonium and Nitrates) contained in the samples by a spectroscopic method. The extraction was realised in a solution of 1:10 (m:V) with KCl solution during 1 hour using an rotary shaker. The solution was centrifuged and filtered.

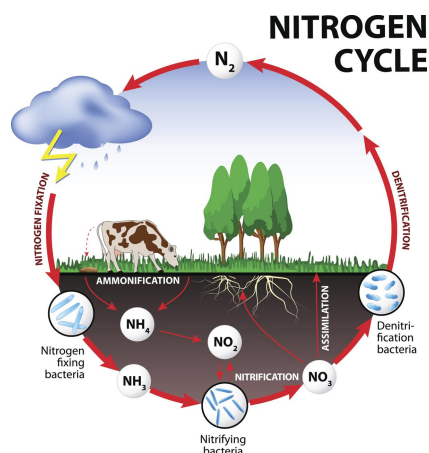


Figure 2.3: The cycle of Nitrogen
Extracted from the website BiologyWise [5]

The NH_4^+ and NO_3^- contained in the extracts concentrations were measured using MAE-UV/VIS (ThermoUnicam M Series).

2.3.4 Extractable Phosphorus

Extractable Phosphorus, also called available P, was measured using the Olsen method. In this method, orthophosphates (PO_4^{3-}) are desorbed from soil particles and colloids with a Sodium bicarbonate at 0.5 N and pH 8.5 solution at a ratio 1:20. The solution is agitated during 1 hour in a rotary shaker and then centrifuged and filtered. The filtrate is cleared using activated charcoal if needed. The ions orthophosphate react with ammonium molybdate and antimony potassium tartrate to form a complex that is reduced by ascorbic acid to give another blue complex which has a maximum of absorbance at 882 nm. The concentration of this complex is measured using a UV-VIS spectrophotometer and it is possible to deduce the Phosphorus concentration in the soil sample [37].

2.3.5 Cation-Exchange Capacity

The Cation Exchange Capacity (CEC) is a measure of the ability of the soil to retain cations, i.e positively charged ions such as Ca^{++} , Mg^{++} , K^+ , Na^+ , etc. Moreover, NSW government ministry of agriculture website highlights

that it can be a good indicator of the soil fertility. It shows indeed the capacity of the soil to stock three major nutrients : Calcium, Magnesium and Potassium [19]. To determine the CEC, we used a solution 1:10 (m:V) with Ammonium Acetate solution at pH 7. After agitating during 1 hour in a rotary shaker, centrifuging and filtrating, we read the cations concentrations with an atomic absorption spectrophotometer. For the samples exceeding the standard curve, we diluted the filtrate in order to obtain a concentration in concentration range.



Figure 2.4: Reading of the Cations concentrations with the atomic absorption spectrophotometer of ISA

2.3.6 Microbial activity

In order to characterize the microbial activity in the soil, we measured the activity of several enzymes in the soil samples. Encyclopaedia Britannica defines an enzyme as follows : "a substance that acts as a catalyst in living organisms, regulating the rate at which chemical reactions proceed without

itself being altered in the process” [34]. Measuring the activity of those enzymes gives interesting insights of the process taking place in the soil, and the dynamics between the soil microbial communities. We measured 5 different enzymes: Dehydrogenase, Cellulase, β -Glucosidases, Acid Phosphatase and Urease.

2.4 Data analysis

After realizing the analyses, we obtained data for 3 different groups being Unburned (or control group), ”Fire in 2004” and ”Fire in 2012”. We needed to arrange this raw data in order to prepare it for further analyses and representations.

I used an Excel spreadsheet to store all data attached to every sample. I started by eliminating the odd values such as negative numbers or abnormally high or low values. For several analyses, values were under the detection limit of the equipment. In these cases, I used half of the detection limit in order to get a quantitative result. Following this data cleaning process, we obtained a table which an extract is given in table 2.2 as an example.

Label	Fire year	Soil properties	
		C tot %	C org %
1a		3,06	3,70
1b	2012	3,33	3,62
1c	2004	3,76	5,61

Table 2.2: Extract from the Excel spreadsheet containing all the parameters values

From this general table, I separated the values in 3 sheets corresponding to the groups by using a filter on the Fire year column. From this general spreadsheet, I created a specific .csv file for each parameter to be used by other programs in the following of the data analyses.

2.4.1 Statistical analysis

I used the programming language R with the software R studio to do further statistical analysis of the data we collected. For every parameter, I represented the box-plots of every group and ran an ANOVA followed by a Tukey HSD test to check what group were significantly different from each other in terms of means. When observed, this difference between groups was represented by different letters on the plot.

2.4.2 GIS representation

In order to observe the spatial distribution of the parameters values over the studied area, I represented them on maps. It was interesting to represent the values on a superposition of a map of the project because a spatial representation of the parameters can allow the research team to notice correlations and trends that can be ignored during statistical analysis.

I used two different software : QGIS and SAGA. I was provided by the team the shapefiles of the study area, the 2004 fire, the 2012 fire, and the 57 sampling points. I used these shapes in QGIS to identify what samples belonged to what fire group. Once this was done, for each parameter I joined the .csv data to the sample shapefile to obtain a new layer definition file containing at the same time the position of the sample and the parameter values. I imported that file in the SAGA software to run a Kriging algorithm in order to extrapolate the values of the parameter all over the study area. I used SAGA because I found this software more suitable and stable to produce the raster files than the integrated tools of QGIS. I used the raster files to represent the extrapolated value of the different soil parameters over the study area.

3. Results and discussion

3.1 Carbon concentrations

3.1.1 Total Carbon

The Total Carbon soil concentrations, with group means around 3%, appear to be consequent to the expected typical values for a forest soil in that area [3]. The box-plots of the Total Carbon presented in figure 3.1 show for both layers 0-5cm and 5-30cm that there is a significant difference between the control group (No fire) and the "Fire in 2004" group. In the layer 5-30cm, we also notice a significant difference between the "Fire in 2012" and "Fire in 2004" groups. Comparing the means of the different groups, it seems that the concentrations of total Carbon increase with the time after the fire being significantly higher than the C amount in control. We can verify those results with the spatial distribution of the concentrations. We see on the map that the coloring pattern matches the three different areas.

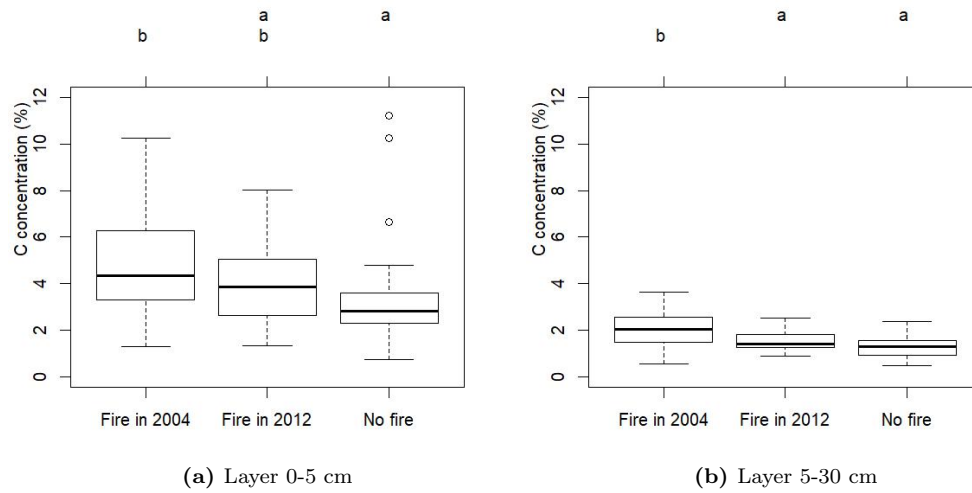


Figure 3.1: Comparison of box-plots of total C soil concentration for two different depths. Groups identified by the same letter are not significantly different regarding the mean ($\alpha = 0.05$, Tukey-HSD)

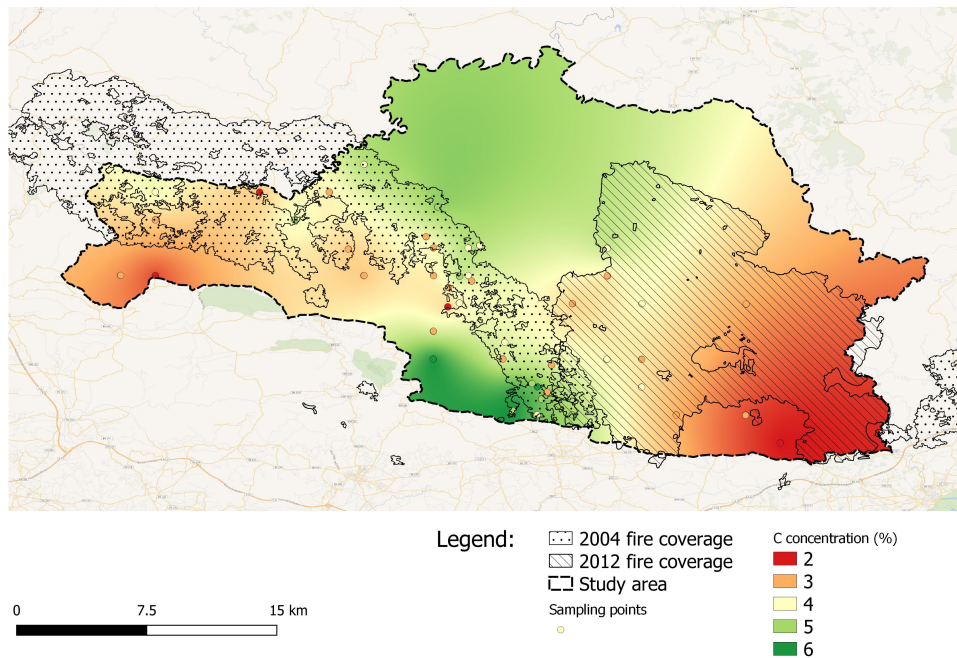


Figure 3.2: Spatial distribution of Total Carbon concentrations over the study area

3.1.2 Total Organic Carbon

The Organic C fraction corresponded to almost total C amounts. We can divide the groups in two using the significant difference : the 2004 group is different from the 2012 and control group. As for the Total Carbon, we observe an increase in Organic Carbon inside the 2004 fire group. This tendency is well observable on the map.

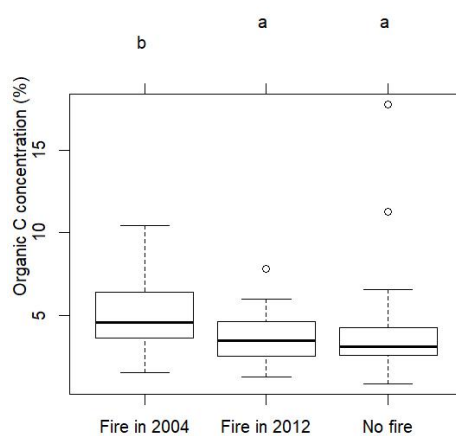


Figure 3.3: Comparison of box-plots of Organic C soil concentration for two different depths.

Groups identified by the same letter are not significantly different regarding the mean ($\alpha = 0.05$, Tukey-HSD)

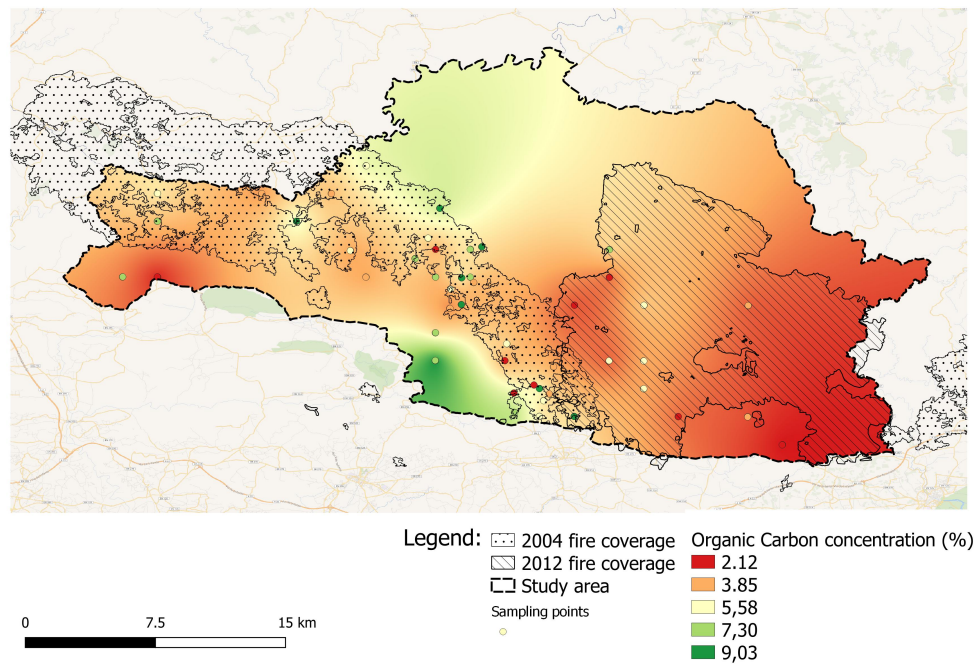


Figure 3.4: Spatial distribution of Organic Carbon concentrations over the study area

3.1.3 Hot soluble fraction of Carbon (Labile fraction)

The Hot-Water Extractable Carbon concentrations are around 0.5%. The Labile Carbon is only a fraction of the organic Carbon, and as we expected, these values were very small. The statistical analysis doesn't allow us to differentiate any group between the 3 conditions and we verify this result on the map generated by kriging. The colored zones on the maps intersect the 3 groups areas without following any clear pattern.

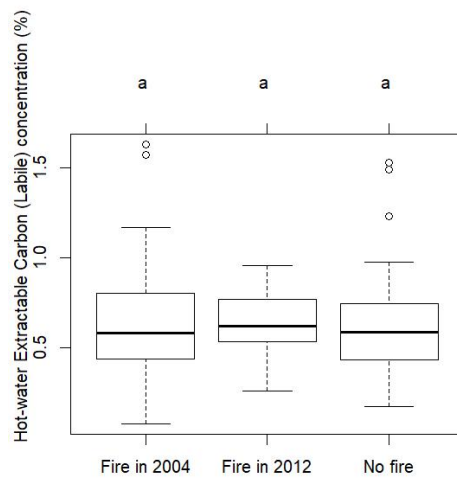


Figure 3.5: Comparison of box-plots of labile C soil concentration for two different depths.

Groups identified by the same letter are not significantly different regarding the mean ($\alpha = 0.05$, Tukey-HSD)

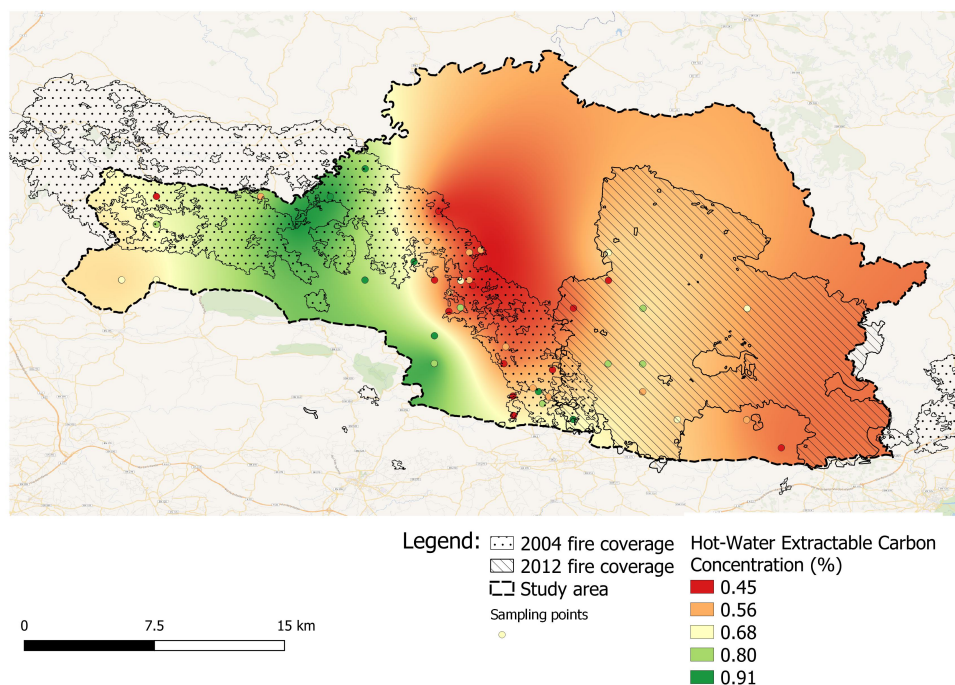


Figure 3.6: Spatial distribution of Labile Carbon concentrations over the study area

3.2 Nitrogen

Total N

For the Total Nitrogen measures, we notice on the box-plots presented in figure 3.7 the same trend as previously observed for the Total Carbon. A significant difference appears between the groups "No fire" and "Fire in 2004" for the layer 0-5cm. The same dynamic where the concentration increase with time and remains higher than the control group levels seem to appear in this case too. Concerning the layer 5-30cm, no difference between the groups can be noticed. This result is to observe on the map presented in figure 3.8. We saw that the concentrations in the areas without fire are the lowest in terms of concentrations. Two sampling areas seem to be having very low values in the zone located on the South of the 2012 area. Then we observe that the 2012 fire zone presents slightly bigger values, and the 2004 has the highest Total N concentrations on the study area.

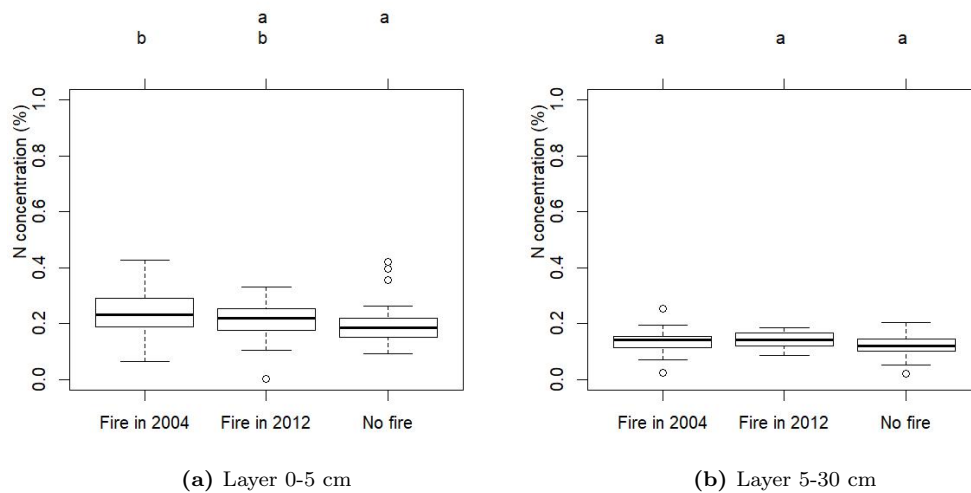


Figure 3.7: Comparison of box-plots of total N concentration for two different depths. Groups identified by the same letter are not significantly different regarding the mean ($\alpha = 0.05$, Tukey-HSD)

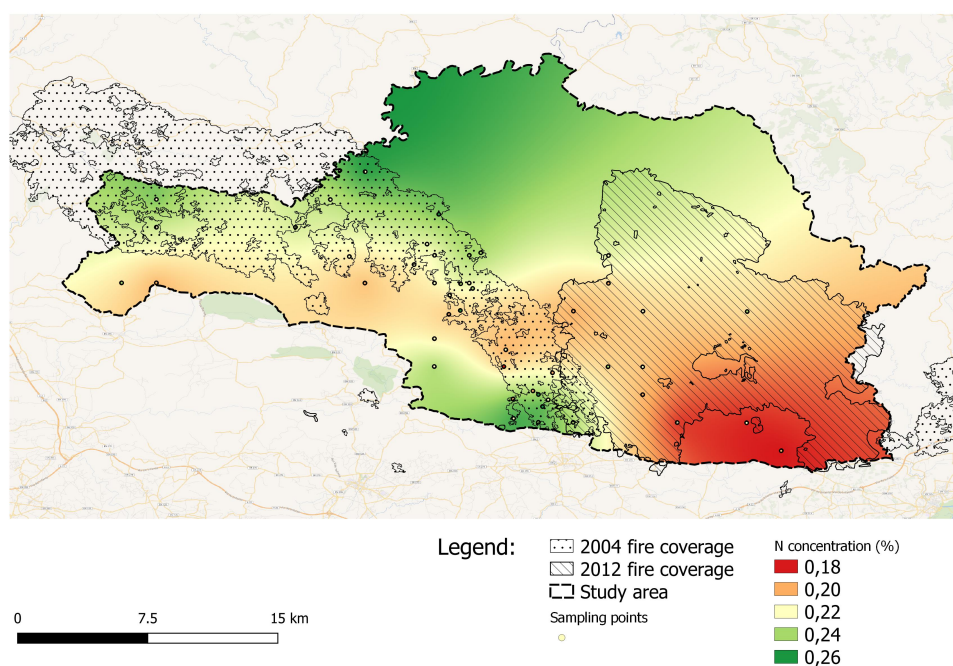


Figure 3.8: Spatial distribution of Total Nitrogen concentrations over the study area



The 3 groups present very similar characteristics concerning Ammonium concentrations as the 3 means are extremely close and roughly equal to 19 mg/kg. The Tukey-HSD test doesn't allow us to differentiate any group and the map in figure 3.10 allows us to understand better this result. In fact, the overall studied area seem to be separated in two in terms of NH_4^+ concentrations, from West to North-West, without following any identifiable pattern concerning the study groups. However, it seem to be coherent and as it follow the pattern already shown on the Total Nitrogen map.

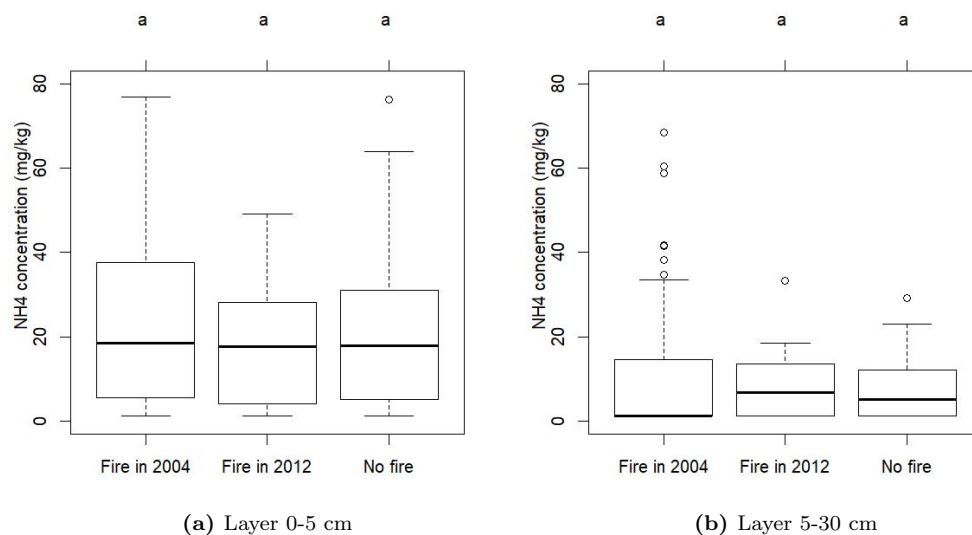


Figure 3.9: Comparison of box-plots of NH_4^+ concentration for two different depths. Groups identified by the same letter are not significantly different regarding the mean ($\alpha = 0.05$, Tukey-HSD)

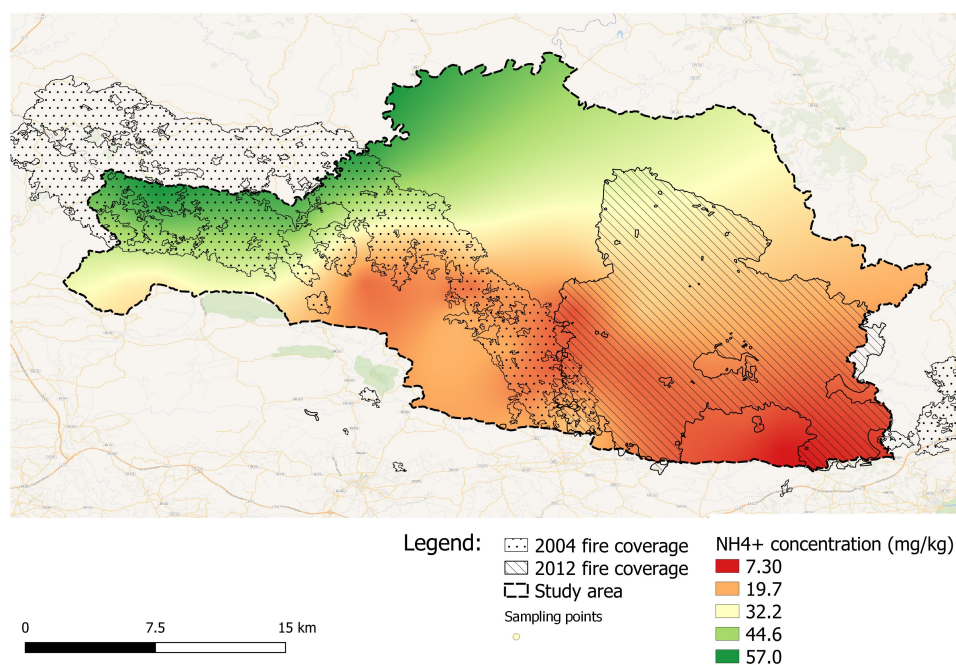


Figure 3.10: Spatial distribution of NH_4^+ concentrations over the study area

NO_3^-

As it was expected the values of NO_3^- are very low, probably due to fast use and leaching. They are in fact mostly under the detection value of the spectrometer, which is 2,5 mg/kg. Therefore, we obtain groups filled a lot of times with the same value as we have to replace those under detection limit by 1.25mg/kg. It is then difficult to conduct good statistical analysis of those results. The box-plots presented in figure ?? illustrate this problem and show how we are not able to observe any differences between the 3 groups for the values of NO_3^- concentrations.

3.3 Extractable Phosphorus

The extractable Phosphorus concentrations are grouped around 5mg/kg, which seem coherent as regard to the typical concentrations of P-Olsen. The Tukey-HSD test allows to identify two groups between the study zones. In effect, it appears that the measures of the fire in 2012 concentrations are significantly different from the ones of the two other groups. We therefore observe an increase in P-Olsen concentrations for the samples where fire occurred in 2012, compared to the 2004 and 2012 groups. We can find this result on the map in figure 3.12 (even though the extrapolation probably exaggerates concentrations in the North zone where there has not been fire) : we notice a difference between the 2004 and 2012 areas, as well as the South no fire area. As an interpretation of these results, we can characterize the P reaction to fire as follows : an increase in concentration directly after the fire, followed by a decrease until reaching back to the initial levels. This observation is verifying the recuperation process for Phosphorus we described in "1.2.3 Effects of Forest Fire - Nutrients", based on the work of Hernandez et al. [12]. The levels in 2012 might be smaller because there is less vegetation uptake and use by microorganisms.

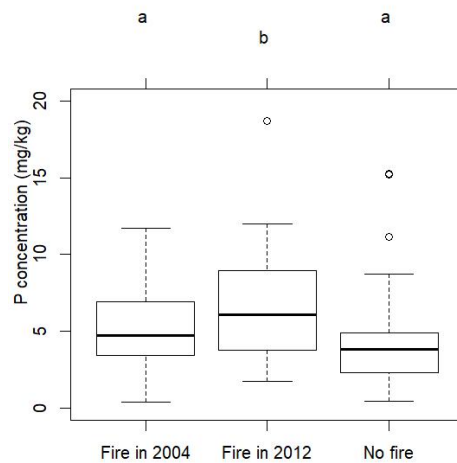


Figure 3.11: Comparison of box-plots of extractable P concentrations for two different depths.

Groups identified by the same letter are not significantly different regarding the mean ($\alpha = 0.05$, Tukey-HSD)

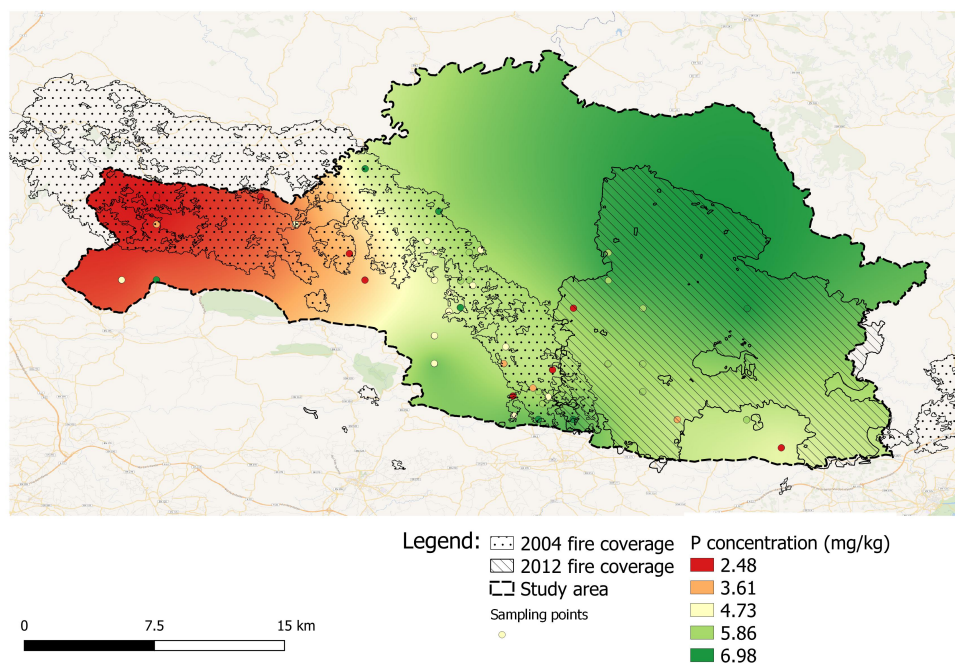


Figure 3.12: Spatial distribution of P concentrations over the study area

3.3.1 Cation Exchange Capacity

The Cation Exchange Capacity measures we realized over the soil samples at the lab show interesting results opposed to the behavior described in the introduction part "1.2.3 Effects of Forest Fire - Chemical properties", which mentions a drop in CEC values after the forest fire. In fact, the statistical analysis shows that only the 2012 group is significantly different from the others. In addition, the mean of this group is higher than the two other groups, and we identify this pattern on the map too. This leads us to think that the CEC would increase after a forest fire and then decrease until coming back to initial levels. However, we expected the opposite results : a decrease in CEC values, then reaching up to initial levels. This expectation was based on the scientific literature arguing that CEC decreases after a wildfire because of the loss of adsorption sites, which are essential in this case [2]. Therefore, this result is to be verified, as it doesn't appear to be reaching a consensus. An explanation to the observed behavior can be that CEC decreases immediately after the fire because of the degradation of organic matter. With time CEC increases at the same time as organic matter. Since it has been 8 years since the most recent fire, this is probable. It is also coherent with the observed levels of Carbon.

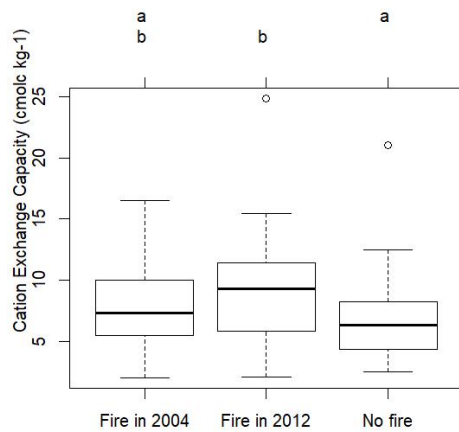


Figure 3.13: Comparison of box-plots of Cation Exchange Capacity
Groups identified by the same letter are not significantly different regarding the mean
($\alpha = 0.05$, Tukey-HSD)

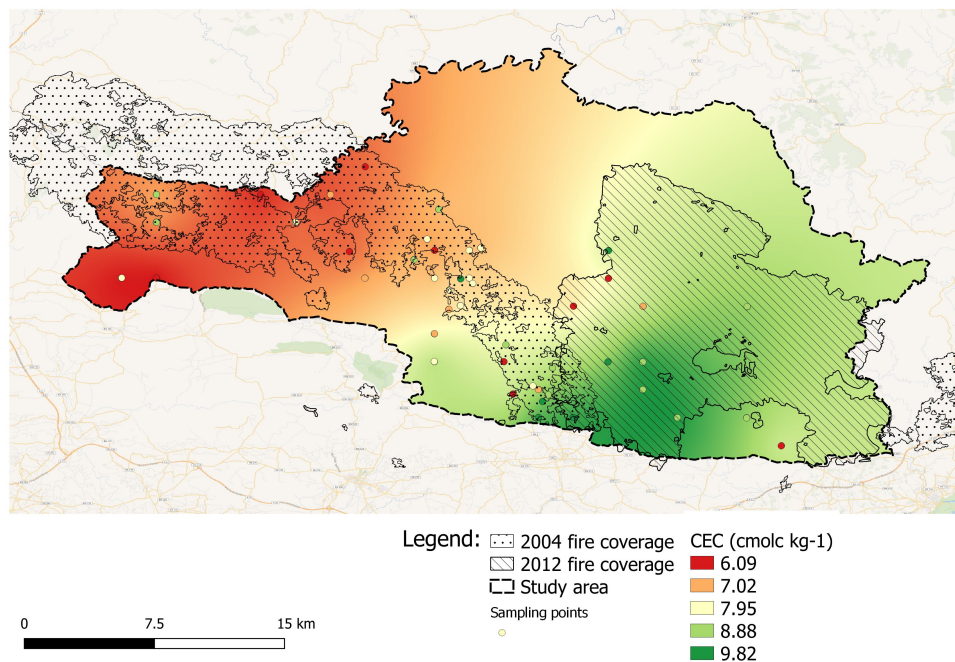


Figure 3.14: Spatial distribution of the Cation Exchange Capacity over the study area

3.3.2 Microbial activity

Dehydrogenase

Dehydrogenase acid activity measurements show a difference between the study groups as the box-plots in figure 3.15 highlight. It appears that the control group, where no fire occurred, is significantly different from the two groups where there was a wildfire. We can confirm on the map that the levels of Dehydrogenase activity appear to be notably higher in the 2012 fire region. However, it is more difficult to differentiate the difference between the no fire and fire in 2004 regions on the map than by using statistics methods because many points of the control group are close to the border.

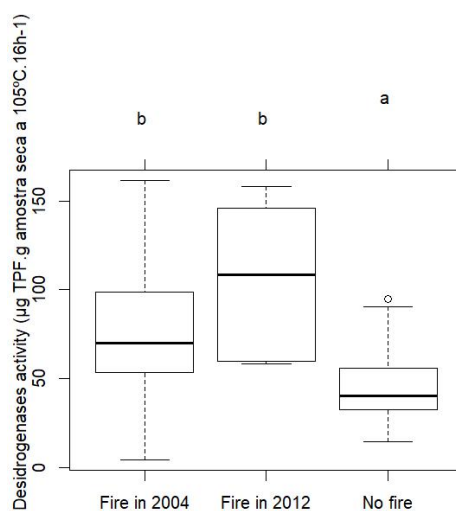


Figure 3.15: Comparison of box-plots of Dehydrogenase activity
Groups identified by the same letter are not significantly different regarding the mean
($\alpha = 0.05$, Tukey-HSD)

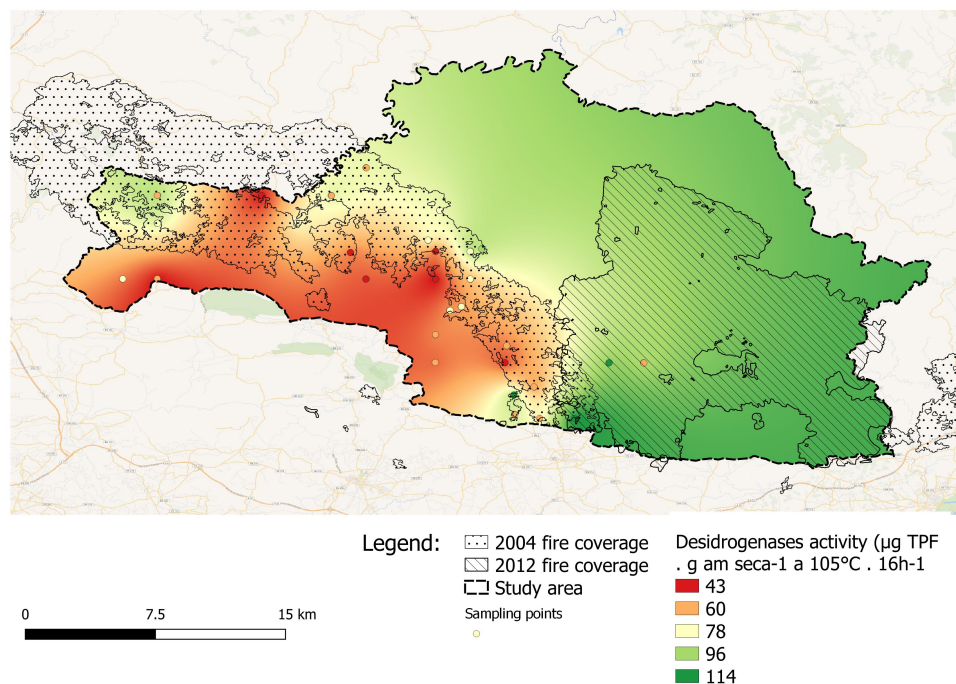


Figure 3.16: Spatial distribution of Dehydrogenase activity over the study area

Cellulase

The Cellulase activities we observed allow us to discern two groups among the fire areas through the Tukey-HSD test. In effect, the 2012 fire group is significantly different from the two others. We can observe this result very clearly on the box-plots, as well as on the map of the area. Both representations show that the 2012 group has higher Cellulase activities. This result is a bit odd as other researchers observed a decrease in Cellulase activity after a forest fire [9]. However, the decrease noticed by Fioretto et al. was on a scale of a few days to several months, when the closest fire occurred in 2012, 9 years ago. The difference observed might therefore as well be caused by another phenomenon affecting the microbial activity.

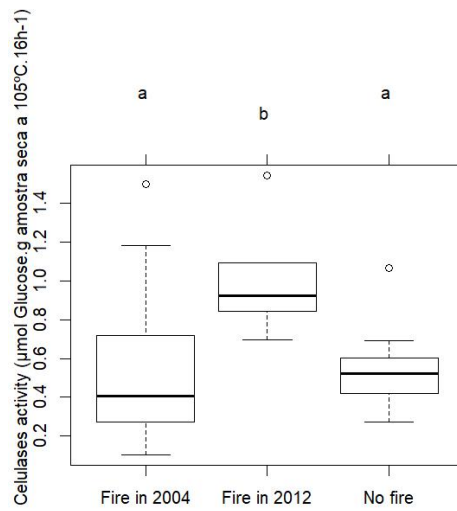


Figure 3.17: Comparison of box-plots of Cellulase activity
 Groups identified by the same letter are not significantly different regarding the mean
 ($\alpha = 0.05$, Tukey-HSD)

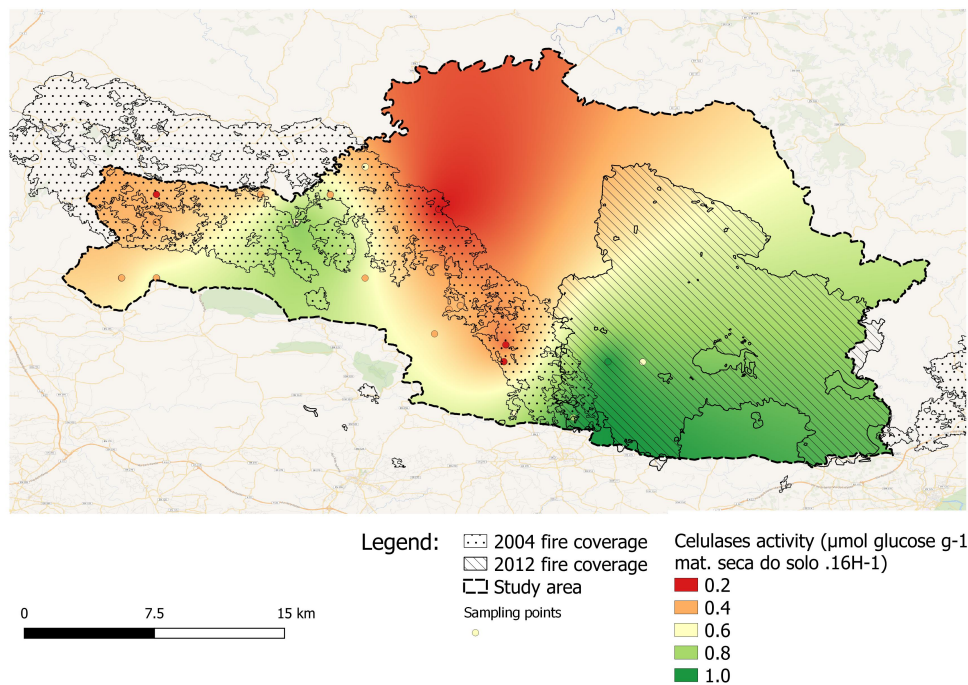


Figure 3.18: Spatial distribution of Cellulase activity over the study area

Glucosidases

The Glucosidase activity analysis gives odds results. The box-plots presented in figure 3.19 show that we can identify two groups as follows : Fire in 2012 + No fire) and (Fire in 2004 and No Fire). In addition, the box-plot of the 2012 group is significantly lower than the two other ones, and with a small variability. The map presented in figure 3.20 also illustrate this outcome : the area is divided in two parts, one with higher values on the West (partially 2004 and control group) and another one with small values on the East (Fire in 2012). Even though the overall result is coherent with the expected behavior, decrease in Enzyme Activity after the fire and levels going back up, it is probable that another factor is the cause of observed spatial fracture in Glucosidase activity.

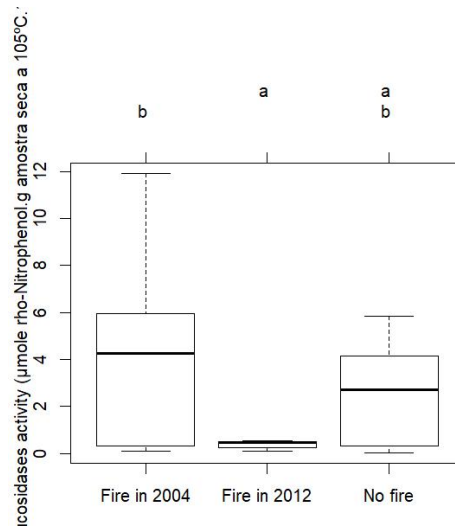


Figure 3.19: Comparison of box-plots of Glucosidases activity
Groups identified by the same letter are not significantly different regarding the mean
($\alpha = 0.05$, Tukey-HSD)

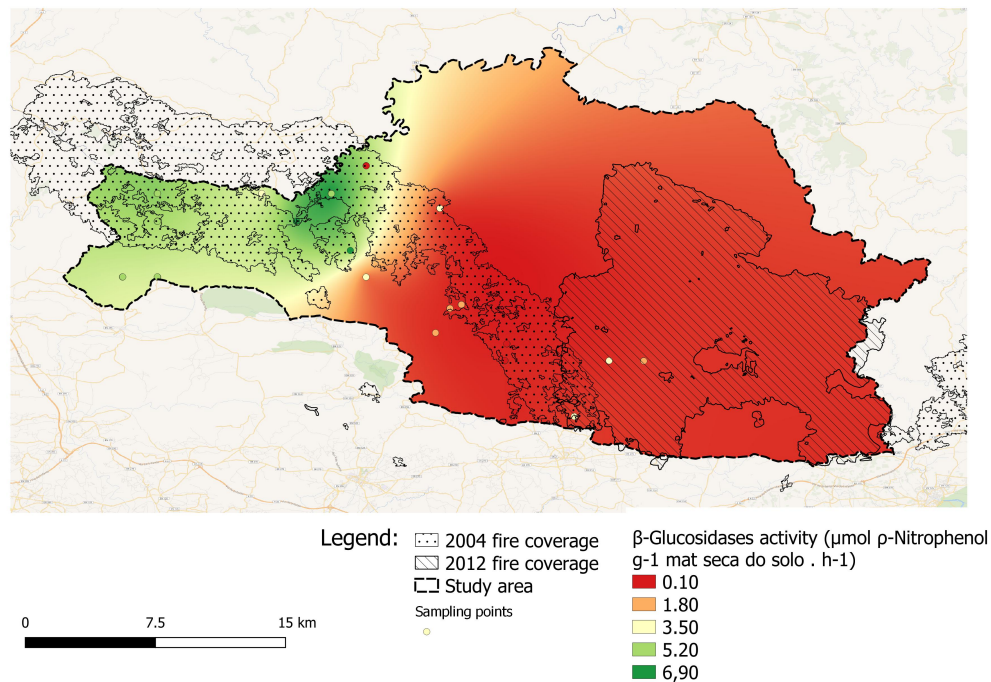


Figure 3.20: Spatial distribution of Glucosidases activity over the study area

Phosphatase

Phosphatase acid activity measurements, show no significant difference between the three groups in the 0-5cm layer as the box-plots show in figure 3.21. We can also notice on the map that the spatial distribution of the results seem to follow no rule between the groups. It appears to be coherent with the results of the scientific literature on the subject. For example Knicker et al. explain that Phosphatase activity know a decrease after forest fire that can last in a detectable way up to two years after the event [16]. Since the most recent fire, in 2012, happened 9 years before the soil sampling, it is understandable that this reaction to the fire is not detectable.

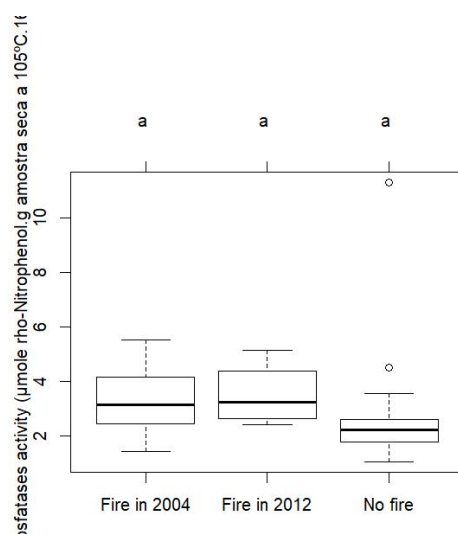


Figure 3.21: Comparison of box-plots of Phosphatase activity
Groups identified by the same letter are not significantly different regarding the mean
($\alpha = 0.05$, Tukey-HSD)

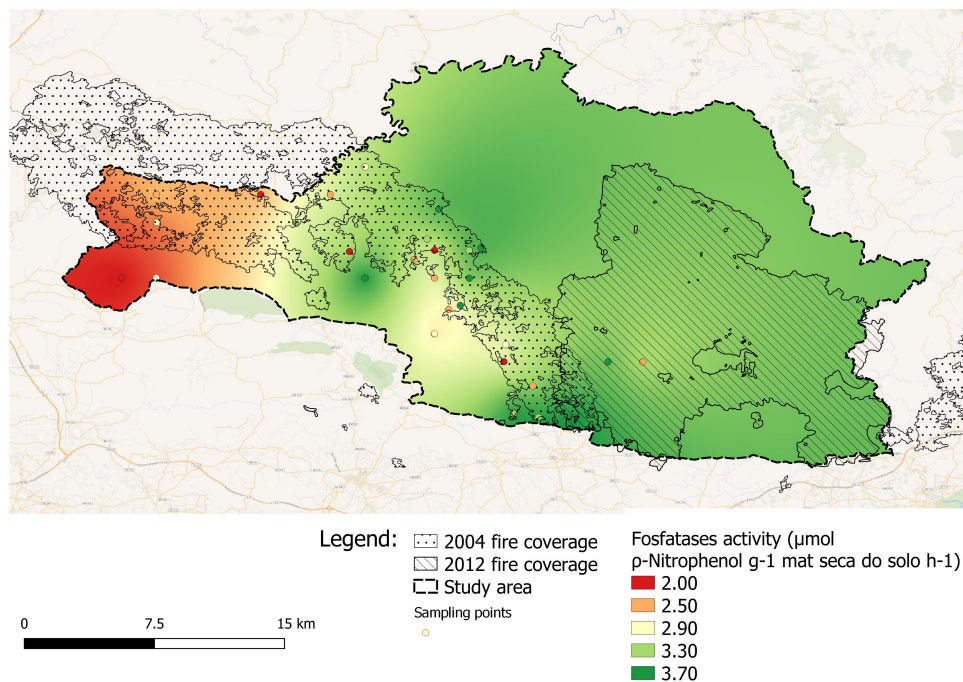


Figure 3.22: Spatial distribution of Phosphatase activity over the study area

Ureases

No difference is noticeable on the 3 study groups as regards to the Ureases activities. We observe the same results on the map presented in figure 3.24. Probably this absence in terms of difference is due to the study time scale that is too long to observe changes that may be occurring over months instead.

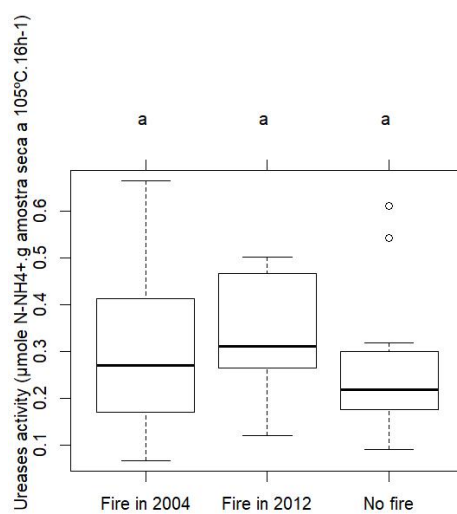


Figure 3.23: Comparison of box-plots of Ureases activity
Groups identified by the same letter are not significantly different regarding the mean
($\alpha = 0.05$, Tukey-HSD)

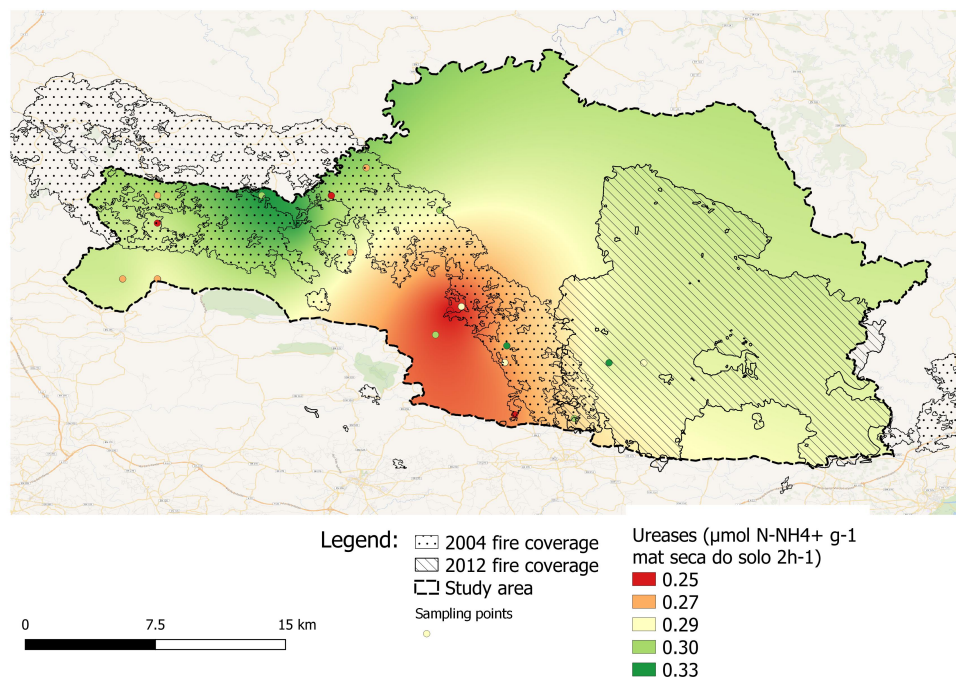


Figure 3.24: Spatial distribution of Ureases activity over the study area

3.4 Discussion

The analyses of the soil samples collected all over the study area give interesting results and insights about the soil recuperation after a forest fire. Some of the results we obtain allow us to verify behaviors already well described in the scientific literature. Firstly, it is possible to notice on the analyses made both on the layers 0-5cm and 5-30cm that fire affects more the first centimeters of the soil. In effect, for several results where we observe differences between the groups on the first layer, there is no significant difference deeper. For the Carbon stock, we globally observe, in comparison to the control group, an increase 9 years after the fire, with levels that keep rising up to 17 years after the fire. Even though Carbon concentrations in forest soils tend to decrease immediately after the fire, it is important to notice the scale of time of our study. The time difference between the fire groups is around 8 years. On this time scale, some studies observe an increase in forest soils organic matter. For instance Page-Dumroese et al. mention controlled fires where increases

around 20% of the Carbon pool were observed [29]. In our case, for the Total Carbon, we observe for the layer 0-5cm an increase of 18% after 9 years, and 44% after 17 years of recuperation. Those values are high but coherent as it seems that wildfires induce, on a medium-term time period, an increase in the soil Carbon concentrations. The observed Phosphorus reaction to the fire also appears to be normal, as we expected it to rise after the fire. Concerning NO_3^- and NH_4^+ , we notice that they are present in very low concentrations and we cannot observe any significant difference between the groups. It is not surprising for those forms of Nitrogen to be found in low concentrations because, as mentioned in introduction, they tend to be evacuated from the environment if there is no plant uptake.

The Cations Exchange Capacity for instance is higher on the 2012 fire group and reaching back initial level for the 2004 group. This results is odd because we expected a drop of CEC directly after the event. Concerning Dehydrogenase and Cellulase, we also observe an increase in activity, when the previous works tend to mention a decrease in activity, linked to the loss of microbial biomass. However, since the sampling happened a relatively long time after the fire probably the microbial reconquest of the area already happened. Considering that we also observed an increase in Organic Carbon concentrations, this result and hypothesis seem acceptable.

Finally, several parameters give odd results that are difficult to analyze. Concerning the enzymes, Phosphatase, Urease and Glucosidases activity data do not allow us to discern any groups and to make any conclusions concerning soil recuperation. The patterns observed cannot be linked with any of the fires areas. It is probable that the time scale chosen for the experiment is not allowing us to notice any clear change in those activities, as most of the change occurs on a time scale of months and several years. It is also probable that it is linked to the natural heterogeneity of the soils. For the Labile Carbon, the concentrations are also very close to each other between the groups and we cannot observe any specific behavior relatively to fire.

4. Conclusion

The experiment that was conducted for the REMAS project during my internship gave interesting results. We produced first quantification of several soil parameters that will give interesting insights to the REMAS project team. In particular, we noticed a significant increase in Carbon concentrations approximately one and two decades after the wildfires.

However, some results didn't allow us to discern any recuperation pattern. The use of another time-scale might be interesting in order to detect changes at every step of the recuperation process. However, it might also be linked to the natural heterogeneity of the soils.

The study of soil response to a forest fire is a crucial step in understanding how to reduce Carbon emissions during forest fire and mitigate Global Warming.

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