Universidade de Aveiro
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Uso de fogo prescrito numa plantação após exploração de *Eucalyptus globulus* - primeiros efeitos

Using prescribed fire in a post harvesting *Eucalyptus globulus* plantation – first effects

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Ecologia Aplicada, realizada sob a orientação científica da Doutora Sofia Corticeiro Investigador CESAM e do Departamento de Biologia da Universidade de Aveiro co-orientação científica de Doutora Ana Quintela, Investigadora do RAIZ.

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o júri

Presidente	Professora Doutora Maria Helena Abreu Silva, Professora Auxiliar, Departamento de Biologia, Universidade de Aveiro
Vogal - arguente	Doutor Oscar González Pelayo, Investigador, MED - Instituto Mediterrâneo para a Agricultura, Ambiente e Desenvolvimento, Universidade de Évora
Vogal - orientadora	Doutora Sofia Caçoilo Corticeiro, CESAM & Departamento de Biologia, Universidade de Aveiro

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palavras-chave

Fogo de baixa severidade, eucalipto, gestão florestal, impactos no solo, regeneração de cepos

resumo

O fogo prescrito pode ser uma boa técnica para a gestão de resíduos de colheita em plantações de *Eucalyptus globulus*, no entanto o conhecimento dos impactos desta técnica no solo e nas plantações florestais é um pouco escasso, devido à grande variedade de resultados obtidos por estudos anteriores. O principal objetivo deste trabalho foi determinar os efeitos do fogo prescrito como ferramenta de gestão de resíduos da colheita nas propriedades físicas e químicas do solo. Foi estabelecida uma área de estudo, uma plantação de 10 anos em primeira rotação, colhida durante o mês de setembro de 2021, em Quintarrei, Valongo, Porto, Portugal. Após uma primeira caracterização física e química do solo e avaliação da acumulação de biomassa, o tratamento (fogo prescrito) foi realizado a 16 de dezembro de 2021. A severidade do fogo no solo foi avaliada através da avaliação visual das alterações do solo e do solo florestal e através da monitorização das temperaturas do solo superficial com termopares. Como demonstrado pelos resultados, o fogo prescrito foi eficiente, diminuindo as cargas de biomassa e o risco de incêndio, ao mesmo tempo que tinha uma baixa severidade de 1. Os parâmetros físicos (diâmetro de peso médio, pedregosidade, granulometria e densidade aparente) e químicos (pH, condutividade eléctrica, matéria orgânica, catiões permutáveis (Ca^{2+}, Mg^{2+}, K^+ e Na^+), acidez permutável, capacidade de permuta catiónica (ECC), saturação catiónica (EBSl), fósforo extraível, e micronutrientes (Zn, Cu, Mn, Fe)) foram monitorizados em fevereiro, um mês e meio depois. A regeneração dos cepos foi avaliada 4 meses e meio após a instalação do fogo prescrito e o tamanho das varas foi medido nesse mesmo tempo e novamente em setembro de 2022, 10 meses após a instalação do fogo prescrito. Enquanto todos os parâmetros físicos permaneceram inalterados, o pH, capacidade de troca de catiões, saturação de catiões, fósforo extraível, Mg^{2+}, Ca^{2+}, K^+ e Mn aumentaram nos tratamentos de fogo prescrito, e a acidez permutável, Al e Fe diminuíram. O aumento de nutrientes no solo e os parâmetros físicos inalterados indicam que o fogo prescrito pode ser uma boa técnica para a gestão dos resíduos de colheita nas plantações de eucalipto. Esta hipótese é também suportada pela regeneração de cepos e pelo crescimento das varas, que foi muito semelhante no tratamento controlo e no tratamento com o fogo prescrito de ambos os blocos, contudo é necessária uma maior monitorização para compreender a sua viabilidade.

keywords Low severity fire, eucalypt, forest management, soil impacts, stump resprouting

abstract

Prescribed fire may be a good technique for the management of harvest residues in *Eucalyptus globulus* plantations, however the knowledge of the impacts of this technique on the soil and the forest plantations is a little scarce, due to the high variety of results obtained by previous studies. The main objective of this work was to determine the effects of the prescribed fire to manage harvest residues on the soil physical and chemical properties. A study area was established, a 10 years old first rotation plantation harvested during September of 2021, in Quintarrei, Valongo, Oporto, Portugal. After initial soil physical and chemical characterization and biomass accumulation assessment, the prescribed fire treatment was performed on December 16th of 2021. Soil burn severity was evaluated by visual assessment soil and forest floor changes and by monitoring the topsoil temperatures with thermocouples. As shown by the results, prescribed fire was efficient decreasing the biomass loads and fire risk, while having a low fire severity of 1. Soil physical (mean weight diameter, stoniness, granulometry and bulk density) and chemical parameters (pH, electric conductivity, organic matter, exchangeable cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+), exchangeable acidity, cation exchange capacity (ECC), cation saturation (EBSI), extractable phosphorus, and micronutrients (Zn, Cu, Mn, Fe)) were monitored in February, a month and a half later. Stump resprouting was assessed 4.5 months after prescribed fire installation and stem size was measured at that same time and again in September 2022, 10 months after prescribed fire installation. While all of the physical parameters remained unaltered, pH, cations exchange capacity, cation saturation, extractable phosphorus, Mg^{2+}, Ca^{2+}, K^+ and Mn increased in the prescribed fire treatments, and exchangeable acidity, Al and Fe decreased. The increased nutrients in the soil and the unchanged physical parameters indicate that prescribed fire can be a good technique for the management of harvest residues in eucalyptus globulus plantations. This hypothesis is also supported by stump resprouting and stem growth, which was very similar in the control and prescribed fire treatment of both blocks however, further monitorization is necessary to understand its viability.

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1. Introduction

1.1. Mediterranean Region

The Mediterranean Region is home to a large number of species and endemisms, as well as exceptional genetic diversity between and within populations (Médail & Myers, 2004). This biological richness results from the wide range of local climates in the region due to its distinctive geographical and topographical diversity, with high mountain ranges, peninsulas, and archipelagos (Médail & Myers, 2004). Despite fire being a natural component in the Mediterranean Region, the fire-prone landscape of this region often favours the occurrence of high-severity wildfires that spread quickly and are difficult to extinguish (Alcañiz et al., 2016). Aggravating forest degradation and deforestation, in southern and eastern European countries most forest areas are public, making little incentive for conservation and management (Palahi et al., 2008). Due to climate alterations, it is predicted that in southern Europe the temperature will rise and that precipitation in summer will decrease (Dupuy et al., 2020). The Mediterranean Basin is particularly vulnerable to climate change, due to its location in a transition zone between arid and temperate regions (Gaol & Giorgi, 2008), which, combined with the manipulated landscapes, complex vegetation, and land use mosaics, results in a significant increase in wildfire risk in this region (Fernandes, 2013b). Higher risk could lead to more frequent and more severe wildfires, aggravating even more the already high environmental, economic, and social impacts of the wildfires (Figueiredo et al., 2013; Feurdean et al., 2020; Moreira et al., 2020).

1.2. Portuguese forests

In the last 20 years, Portugal has been highly affected by the dryer climate and recurrent wildfires, transforming several forested areas into shrublands (Acácio et al., 2009). In Portugal 70% of the national continental territory is occupied by forests, mainly by pine, broad-leaved deciduous, deciduous and forests with industrial purpose (ICNF, 2015). In the last National Forest Inventory (ICNF, 2015) it was assessed that the cork and holm oaks forests are the main forest occupation, with about 1 million hectares. Pine forests also have an area of almost 1 million hectares, being the forest ecosystem with the greatest reduction of occupied area, when compared to data from previous years. Bush and pasture represent 31% of the land use, having continuously increased since 1995. *Eucalyptus* forests have increased in area for the last 50 years, occupying 845 thousand hectares of mainland Portugal's forests. Deciduous hardwoods are the least representative forest formation, occupying about 17% of the area. The soil occupation distribution of continental Portugal is represented in figure 1.

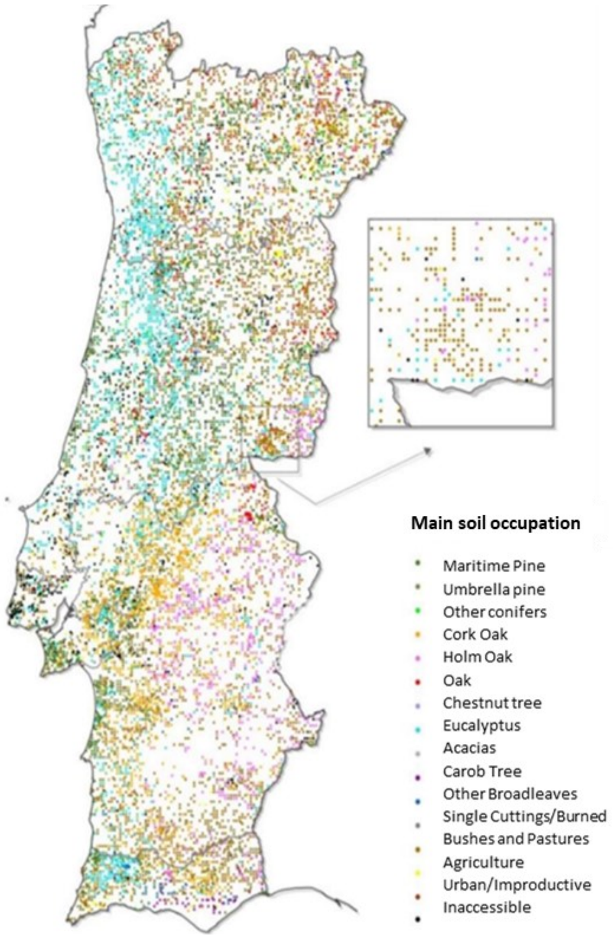

Figure 1- Map of the main soil occupations and forest species of Portugal, adapted from ICNF, 2015

1.3. Eucalyptus globulus

Despite eucalypts species being native to Australia, New Guinea, Indonesia and Philippines (Florence, 1986), *Eucalyptus globulus* is one of the most widely planted hardwood species in temperate regions of the world (Potts et al., 2004). *Eucalyptus* species in Europe remote to the 19th century (Goes, 1977) and are among the most important hardwood species, especially in Portugal and Spain, for the pulp and paper industry sector and contribute to national economies. In Portugal particularly, one of the most relevant tree species is *Eucalyptus globulus* accounting for 4,4% of the Portuguese GDP (Fernandes et al., 2019), raising some concerns about the environmental impacts of the plantations, such as fire, pests and diseases (Tomé et al., 2021).

Although the increment of eucalyptus plantations in Portugal, in a study developed by Fernandes et al. (2019) no relationship was found between the expansion of *Eucalyptus globulus* plantations and the increase of the burned area in Portugal. Mixed stands of *Eucalyptus globulus* and *Pinus pinaster*, are very common as a consequence of land abandonment and represent the highest fire hazard among all forest types in Portugal (Moreira et al., 2009). This risk is minimized through preventive measures that can be applied at tree level (by selecting species), at stand level (reducing shrub layer vegetation) and at landscape level (organizing the territory) (Fonseca et al., 2021).

1.4. Forest management for wildfire prevention

Forest fuel management can be an useful tool to mitigate fire risk, particularly in fire-prone regions as the Mediterranean Region (Fernandes, 2013a). Fire reduction treatments related to fuel management can include the control of the understory vegetation during the establishment and growth of forest plantations or the reducing of the forest residues following the harvesting of a plantation. In Portugal, understory vegetation control in forest management is usually done by manual and mechanical operations, by using herbicides or, in less extent, by applying prescribed fire. The main treatments corresponded to the removal of the residual biomass or control of understory vegetation either keeping them on the surface or incorporating it into the soil (Madeira et al., 2007). In eucalyptus, it is common to manage between plantation lines with a disc harrow or other type of mechanical intervention or less common applying herbicide (Fonseca et al., 2020). It is also standard procedure to remove residues and transport them to a bioenergy facility, masticate or ground them and disperse them across the harvest site, or pile and burn them (Page-Dumroese et al., 2017). In Portugal the reduction of the harvest residues is commonly done by pile burning or prescribed fire.

1.5. Prescribed fire

Prescribed fire is the planned use of fire under recognized meteorological conditions, and recognized fuel, and topographic parameters with defined goals (Alcañiz et al., 2018). The low intensity fire, usually done in the winter, aims to reduce the quantity of fuel and modify the structural arrangement of vegetation to avoid large fires during summer periods (Alcañiz et al., 2016; Figueiredo et al., 2013). This has been found to be a good tool to manage large forest areas with limited economic resources, especially in fire-dependent ecosystems since its impact is always lower than in the case of a wildfire (Francos & Úbeda, 2021). Although prescribed fire is usually used to decrease fire hazard, it can help achieve other goals, such as preparing sites for seeding or planting of forest species, controlling the competing vegetation, improving habitat and creating diversity, controlling insects and diseases, improving pasture quality for cattle, improving access into forest stands, contributing to preserve fire-dependent plant species, and fertilizing the soil (Alcañiz et al., 2016; Fonseca et al., 2017).

In previous studies related to the use of prescribed fire in forest areas it has been found that in the medium- to long-term, prescribed fire does not change vegetation communities (Boensch, 2016). Although some harmful effects on the soil, water and vegetation were documented these are few and transitory, whereas the benefits are long-term and much greater than the damage (Francos & Úbeda, 2021).

Prescribed fire in Portugal is mostly used in shrubland and maritime pine trees (Pinto et al., 2013), however few studies have focused on the effects that prescribed fire has on soil quality, especially in eucalypts plantations. Prescribed fire has been studied has a possible fire hazard reduction tool in pine stands (Fernandes & Botelho, 2004). In NW Portugal, Meira Castro et al. (2015) demonstrates, in a *Pinus pinaster* plantation, that prescribed fire can be a useful tool to reduced litter without affecting the soil quality. Although it is necessary to assess the long-term effects that prescribed fire may cause on the soil in the Mediterranean Region, the results of studies done so far have shown no significant impact of an individual prescribed fire on soil quality (Shakesby et al., 2015).

1.6. Soil

Geologically, Portugal can be divided into 2 large units: the Hesperian Massif and the Epi-Hercynian cover. The Hesperian Massif is of Precambrian and Palaeozoic age, which include granitoids and a flysh-type series of schists and graywackes. The Epi-

Hercynian cover includes the western and southern Meso-cenozoic, including limestones, marls, shales, sandstones and conglomerates (Inácio et al., 2008).

Since soils in Portugal with forest use are generally shallow, immature and with high spatial variability, depending on the local, the adoption of site-specific management systems is the better option for the conservation of forests and soil quality. These specific management plans require detailed knowledge of the distribution of soils across the landscape and their physical, chemical, and biological characteristics that affect productivity (Madeira et al., 2007).

Forests are considered the land use that is more preventive of erosion and physical degradation of the soil (Cerdan et al., 2010; Panagos et al., 2015), however the mechanical interventions, often used in the maintenance of planted forests, can affect the physical characteristics of the soil (Fabres et al., 2021). Harvest residues management can also have impacts on the soil, since the cover of slash or litter reduces soil erosion (Vega et al., 2004). The effects of forest management on soil conservation depend on topography, morphological, and physical characteristics of the soil and the silvicultural or forestry practices adopted (Madeira & Araújo, 2015).

Forest species have a high efficiency in the use of resources, requiring less nutrients than agriculture (Pereira et al., 2007). Since planted forests usually occupy soils with lower natural fertility, mineral fertilization in forest plantations is often of great relevance (Fabres et al., 2021). In forests, soil nutrients are supplied by the biomass, the organic layer, and the mineral soil fraction, however nutrients can also enter the ecosystem through atmospheric precipitation and fertilizer application (Akselsson et al., 2007; Ali et al., 2017; Ranger & Turpault, 1999). Dead leaves are important for the inflow of nutrients to the soil due to the very high nutrient content, improving its fertility throughout the forest development cycle (Shammas et al., 2003; O´Connell et al., 2003).

Nutrients are essential for the growth and productivity of plants, as thoroughly explained in Dechen & Nachtigall (2007). While calcium (Ca) is of most importance for the cellular wall function and for the cellular division (being essential for the plants growth), magnesium (Mg) is a component of the chlorophyll molecule, and it is also a part of essential processes as photosynthesis, respiration, macromolecular synthesis and ionic absorption. Potassium (K) regulates the osmotic pressure of the plant and activates the enzymes for the ionic absorption process, phosphorus (P) is essential for the plant’s growth, since it is incorporated in metabolic processes in ATP form. Iron (Fe), copper (Cu), manganese (Mn) and zinc (Zn) are essential for enzymes activity, Cu and Fe is an activator or component of enzymes that participate in oxi-reduction reactions, Mn forms the bridges between the ATP and phosphokinases and phosphotransferases and activates decarboxylases and dehydrogenases in the Krebs cycle, Zn is a prime component of RNA polymerase, being essential to RNA synthesis, and is also a component of ribosomes, which actuates in the maintenance of the structural integrity of the organelles.

1.7. Objectives

Most studies related to prescribed fire in Portugal have been conducted in pine forests or shrubland areas. However, the use of prescribed fire to manage post-harvest residues in *E. globulus* plantations has not been extensively studied, and there is a lack of relevant information related to the impacts of this operation on the soil and on the survival and viability of the coppice of *E. globulus*. The present work was delineated under the hypothesis that prescribed fire, when performed under adequate operational conditions, can be an efficient tool to reduce biomass loads with low impact on soil quality and on the survival and growth of *Eucalyptus globulus*.

Under this context, the main objectives of the present work were to determine the short-term effects of the prescribed fire:

a) on reducing the post-harvest biomass load under specific conditions of biomass, litter and soil moisture;
b) on physical and physico-chemical parameters of the soil;
c) on the survival and growth of the coppice of *Eucalyptus globulus*.

To accomplish those aims, a working plan was formulated, and main framework was provided (chapter 1 – Introduction). Detailing, an experimental trial focused on the use of prescribed fire for management of harvest residues was established in a recently harvested *E. globulus* plantation in the North of Portugal. The monitoring of biomass load and soil parameters was performed before and immediately after the prescribed fire (one and a half months after). The parameters related to the survival and growth of *E. globulus* were evaluated four and a half months and ten months after the fire as described in chapter 2 of Materials and Methods. It is also presented a chapter of results (chapter 3) and discussion (chapter 4) where main results of fire severity, soil and plant impacts in study area are revealed and discussed. Finalizing this thesis, it is presented the final considerations, study limitations and next steps (chapter 5 – Conclusion).

2. Materials and methods

2.1. Study area: location and edaphoclimatic characterization

The area of study was a *Eucalyptus globulus* plantation located in Valongo (41˚ 12´54N 8˚ 29´55W) in the city of Oporto, Portugal (figure 2). The soil was Humic Epileptic Regosol, according to a field survey carried out in the study area before the implementation of the experiment, derived from schist and graywacke as bedrock.

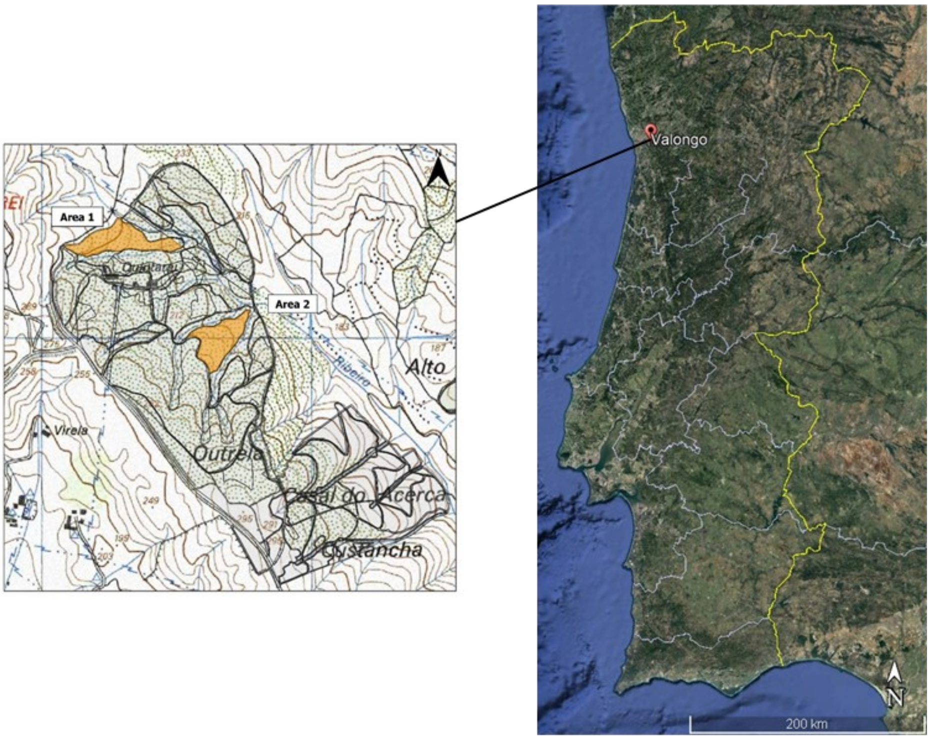

Figure 2 - Localization of the selected study area, an adult *Eucalyptus globulus* plantation in Valongo, Portugal.

The climate of the study area is Mediterranean and registers an average annual precipitation of about 1140 mm and a median temperature of 14.9˚C (1981 – 2000) with a dry warm summer and a mild winter and can be classified as humid mesothermal with moderate but prolonged warm dry summers (Köppen; Csb) (AEmet & I. P. M. A., 2011). This area has good productive potential. The first rotation *E. globulus* stand was harvested in September 2021 (stocking density around 1250 plants/ha; 4m between line x 2 m between plants in plantation line). This plantation is going to be managed under coppice regime.

2.2. Experimental design

After mechanic harvesting, the residues were deposited in lines/strings between former line plantations in the area (figure 3). This distribution of harvesting residues was not homogeneous originating, therefore, regions within the area with less biomass residues load, and others with much more.

Figure 3 - Distribution of *Eucalyptus globulus* biomass residues in the study area after harvesting, in Valongo (December 2021).

Survey trials considered 2 blocks (figure 4). Each block was then divided in two contiguous areas, T0 (control) and T1 (prescribed fire) that were considered in comparable conditions (e.g. soil typology, exposition, number of stumps, condition of cutting leftovers deposition) during preliminary field evaluation. In the T0 there was no management of the harvest residues, while T1 had the prescribed fire treatment applied. Block 1 has 2.35 ha and East exposition. The eucalypt stand was 9.7 years old and was harvested in September 2021. Block 2 with 2.14 ha has North-east exposition and the plantation was 10.8 years old when it was also harvested in September 2021. The treatments, the prescribed fire, were applied on the T1 of both block 1 and block 2 on the 16th of December 2021.

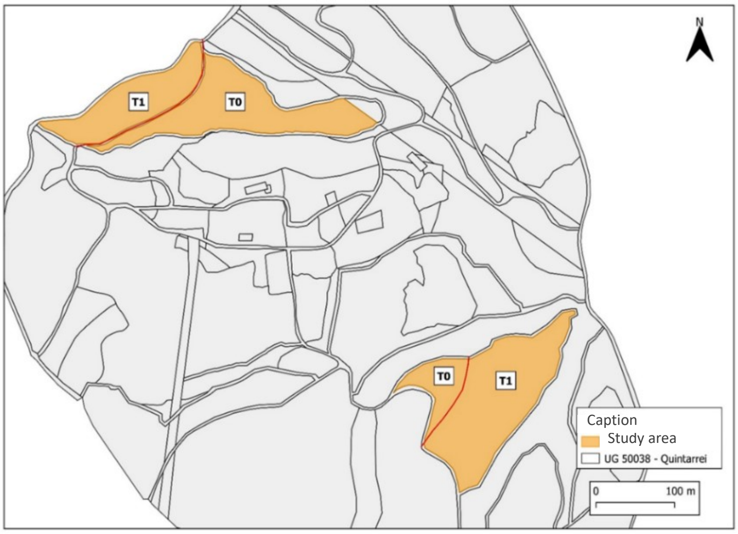

Figure 4 - Location of block 1 (upper yellow area) and block 2 (downer yellow area) under study of the *Eucalyptus globulus* plantation in Quintarrei, Valongo, and identification of the treatments; T0 - without fire (control); T1 - with prescribed fire for harvest residues management.

In each treatment and block, three transects of approximately 25 meters were set up, from the bottom to the top of the slopes, and equidistant three sampling points per transect were established for subsequent soil and biomass monitorization. The sampling points were the same to biomass and soil sampling. The transects were marked in the field allowing to shift slightly their location on the subsequent monitorizations in order to avoid sampling points previously evaluated.

2.3. The prescribed fire operation implementation

The prescribed fire was done by a specialized team from AFOCELCA. AFOCELCA is a company specialized in firefighting, created in 2002, that is closely related to The Navigator Company and to ALTRI group. It is a reference of good practices in forest fires prevention and fighting integrating the Portuguese national system for the defence of forests against forest fires and it is a founding member of “Aliança para Acções em Manejo do Fogo”, established in 2007 in Sevilla, Spain.

Since the meteorological parameters, such as temperature, wind, and precipitation, are important for the safe practice of this technique, these were assessed before the implementation of the fire (table 1). According to Fernandes & Botelho, 2004 the optimal conditions to the application of a prescribed fire are temperature inferior to 13 ˚C, wind speed of 3 km/h to 6 km/h and fuel moisture of 15% to 21%. When these parameters were analysed, not optimal, they were all within the acceptable ranges to the safe and effective application of the prescribed fire.

Table 1 - Meteorological information (precipitation, temperature, and wind speed) on the day of the prescribed fire application (16th of December of 2021).

Date	16th December 2021
Precipitation	< 0,25 mm; without rain
Temperature	Min: 9 ˚C Max: 14 ˚C
Wind speed	10 km/h direction prevalence: East

The fire conduction technique (figure 5) used was upwind and downhill, with ignition in the lines of greater accumulation of fuel, and it was performed on December 16th of 2021, at 10:30 AM.

Figure 5 - Application of the prescribed fire by the AFOCELCA team on the harvest residues of the *Eucalyptus globulus* plantation in Quintarrei, Valongo, on December 16th of 2021.

2.4. Biomass, litter and soil moisture content estimation

Samples of biomass, litter (the layer of dead plant material present on the soil surface (Krishna & Mohan, 2017)) and soil were collected prior to treatments implementation in T1 of each block in order to assess their moisture content. Five sampling points were chosen by transect, totalizing 15 samples collected per block. Samples were carried to lab in the same day and fresh weight was obtained. These samples were then dried in an oven at 60°C for 24h to 48h, until constant weight, obtaining the dry weight. The moisture content was calculated by the difference between the dry weight and the fresh weight.

2.5. Fire severity evaluation

The fire severity was assessed with two methods: visual indicators of fire severity assessment on the soil, based on Vega et al. (2013), and measuring the soil temperature prior, during and after fire with thermocouples. The use of visual indicators of soil severity infers the alterations on soil chemical and microbiological properties, reflecting the changes in soil quality. This method has good agreement between the levels, based on visual signs, and those indicated by changes in relevant chemical and microbial properties.

2.5.1. Topsoil temperature assessment

To measure the superficial soil temperature reached during fire implementation, thermocouples were installed in soil at the depth of 2 cm (figure 6) in the T1 of each block (block 1 and block 2) before the prescribed fire implementation.

Figure 6 - Thermocouple being installed on the topsoil, at a depth of 2 cm, prior to the prescribed fire installation.

Three thermocouples were implemented along each transect, making a total of 9 thermocouples per block. They were collected right after fire extinguishment. The temperatures were registered every 5 minutes, obtaining the soil temperature before, during and after the prescribed fire. The average and maximum temperature of each point was obtained, as well as the time during which the temperature was higher than 100˚C.

2.5.2. Visual Indicators of fire severity

The soil impact of the prescribed fire was assessed by visual indicators, in table 2.

Table 2 – Visual indicators of severity assessment of fire on the soil, based on Vega et al. (2013).

Level	Forest floor	Mineral soil
0	No evidence of fire.	No evidence of fire.
1	Oa layer partially or totally intact.	Undisturbed.
2	Oa layer totally charred and covering mineral soil. There may be ash.	Undisturbed.
3	Forest floor completely consumed (bare soil). There may be ash.	Undisturbed. Soil structure unaffected. Soil organic matter not consumed. Surface fine roots not consumed.
4	Forest floor completely consumed (bare soil). Thick layer of ash.	Soil structure affected. SOM consumed in the upper layer. Surface soil colour altered (grey). Surface fine roots burned.
5	Forest floor completely consumed (bare soil). There is no charred residue.	Soil structure affected. SOM consumed in the upper layer. Surface soil colour altered (reddish). Surface fine roots burned.

The visual evaluation of soil impact of the prescribed fire was performed immediately after the fire was extinguished, as soon as the AFOCELCA team cleared that it was safe to walk along the transects. The soil assessment was done along the transects, and the visual indicators, described in table 2, were searched.

2.6. Biomass distribution and sampling

Biomass height was determined by nondestructive point sampling at 1 m intervals on each transect. The beginning and end of the transect defined the first and last sampling points, respectively. At each sampling point, a 2-m measuring road (cm) was inserted perpendicular to the ground and the type and height of the cover were registered.

Along the transects, 3 sampling points were established per treatment in each block for biomass sampling and characterization. In each sampling point, a 0.25 m^2 square (50x50 cm) was delimited and the biomass that was inside the square area was collected (figure 7), in order to be characterized in the lab.

Figure 7 - Sampling of biomass (harvest residues) of the *Eucalyptus globulus* plantation in Quintarrei, Valongo, within the 50x50 cm square.

Fuel load was characterized each meter of the transects into fine (< 6 mm) and coarse (> 6 mm) biomass based on the diameter of the biomass present. Biomass load was also assessed per treatment by measuring the biomass height each meter of the transects. Since the transects were around 25 meters long, 75 annotations were taken per treatment, comprising 150 per block.

2.7. Topsoil sampling and characterization

To evaluate the prescribed fire impact on soil quality, topsoil samples, 0-2 cm depth, were collected (in the same squares where biomass was collected, figure 8). The sampling was done per block (block 1 and 2) and treatment (T0 and T1) before the trial's implementation, on the 16th of December, and approximately one and a half months after, on the 1st of February.

For soil bulk density assessment, metallic rings with 3 cm height (about 199 cm^3) were used following the Campbell, 1994 method. Due to the high stoniness of this area, the volume of the soil particles with size superior to 2 mm was removed, to know the soil volume.

Figure 8 - Representation of the soil sampling done in both blocks (block 1 and block 2) of the *Eucalyptus globulus* plantation in Quintarrei, Valongo with the 25x25 cm square inside the 50x50 cm square.

To evaluate the prescribed fire impact on topsoil fertility and physical properties, samples 0-2 cm deep were collected (in a 25x25 cm square where biomass was prior collected (figure 8)). The sampling was done per block (block 1 and 2) and treatment (T0 and T1) before the trials implementation, on the 16th of December, and approximately one and a half months after, on the 1st of February. All the soil samples collected in the field (n=9 per treatment totalizing 18 per block) were air dried at room temperature in laboratory for 3 weeks. Then, they were dried sieved allowing to assess soil particle size distribution (according to the international method of mechanical analysis as defined by Guitián and Carballas (1976)): superior to 2 mm, between 2 mm and 1 mm, between 1 mm and 0.5 mm, between 0.5 mm and 0.25 mm and inferior to 0.25 mm. The mechanic sieving last for 2 minutes. The stones were then separated from the 2 mm aggregates, by grinding the soil at top of the 2 mm sieve.

Table 3 - Parameters analysed, method used and their unit.

Parameter	Method	Unit
pH (H_2O)	ISO 10390:2005	Esc. Sor.
OM	ISO 10694:1995	% (air-dried basis)
EC (25ºC)	CEN/TS 15937:2013 - Internal Method	dS/m
Exchangeable Ca^{2+}	Extraction with ammonium acetate and ICP-OES determination	$cmol_c$/kg (air-dried basis)
Exchangeable Mg^{2+}	Extraction with ammonium acetate and ICP-OES determination	$cmol_c$/kg (air-dried basis)
Exchangeable K^+	Extraction with ammonium acetate and ICP-OES determination	$cmol_c$/kg (air-dried basis)
Exchangeable Na^+	Extraction with ammonium acetate and ICP-OES determination	$cmol_c$/kg (air-dried basis)
Exchangeable acidity	KCl extraction and volumetric determination	$cmol_c$/kg (air-dried basis)
CEC	Calculation	$cmol_c$/kg (air-dried basis)
EBSI	Calculation	%
Al saturation	Calculation	%
Extractable P	Internal Method - Egner-Rhiem extraction and EAM dosage	mg/kg (air-dried basis)
Zn	ISO 14870:2001 or Internal Method: Lakanen-Ervio extraction, ICP-OES determination	mg/kg (air-dried basis)
Cu	ISO 14870:2001 or Internal Method: Lakanen-Ervio extraction, ICP-OES determination	mg/kg (air-dried basis)
Mn	ISO 14870:2001 or Internal Method: Lakanen-Ervio extraction, ICP-OES determination	mg/kg (air-dried basis)
Fe	ISO 14870:2001 or Internal Method: Lakanen-Ervio extraction, ICP-OES determination	mg/kg (air-dried basis)

These steps allowed the assessment of mean weight diameter (MWD), calculated by adding the product of the proportion of each aggregate size fraction, and median diameter of each aggregate size class in soil, stoniness (of rock fragments larger than 2 mm in diameter (Tetegan et al., 2011)), particle size distribution, and bulk density (BD).

For physico-chemical and chemical characterization of each topsoil sample the capacity of the plant to obtain the required nutrients from the soil was considered. Having this in consideration the assessed parameters were: pH, electric conductivity, organic matter, exchangeable cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+), exchangeable acidity, cation exchange capacity (CEC), cation saturation (EBSI), extractable phosphorus, and micronutrients (Zn, Cu, Mn, Fe). These analyses were performed in RAIZ laboratory following the methods presented in table 3.

2.8. Stumps resprouting and stems growth

After prescribed fire implementation (T1), the resprouting of stumps and stems growth (figure 9) were evaluated in order to assess the effect of this practice in the viability and productivity of a eucalyptus plantation in second rotation (coppice regime).

Figure 9 - Stump of *Eucalyptus globulus* in a plantation in Quintarrei, Valongo, after cutting (a) and after resprouting (b) in May 2022.

The number of resprouted stumps was counted on May 2022, 4 and a half months after the prescribed fire installation, in each treatment (T0 and T1) per block. Along with this counting, the stems height per stump was measured, which was repeated in September 2022, 10 months after the prescribed fire operation, seen in figure 10.

Figure 10 - Stems growth in September 2022, 10 months after the application of the prescribed fire, in a *Eucalyptus globulus* plantation in Quintarrei, Valongo.

2.9. Statistical analysis

To each variable the averages and corresponding standard deviations were calculated, by treatment and sampling timing. The normality of the data was determined by performing a Shapiro–Wilk test. Depending on these results, to normal data distribution the One-Way ANOVA test was performed and to not normal data distribution the non-parametric Kruskal Wallis test was used (table 4). All statistical analysis was conducted in the program R version 4.2.0. The significance value used, to all parameters, was $p<0.05$.

Table 4 - List of statistical tests performed in each analysis, comparing treatments (T0 and T1 within the same sampling timing, pre-installation and post-installation) and sampling timings, pre-installation and post-installation, (comparing the same treatment in both sampling timings). Each analysis had different statistical tests performed, according to the Shapiro–Wilk tests results. The same parameter can have different statistical tests performed in the different sampling timings analysed.

Statistical test	**Kruskal-Wallis**	**One-way ANOVA**
Parameters		
BD	X	X
MWD	X	X
Stoniness	X	
Granulometry	X	X
pH	X	X
OM	X	X
EC	X	X
Ca^{2+}	X	X
Mg^{2+}	X	X
K^{+}	X	X
Na^{+}	X	X
Exchangeable acidity	X	X
Extractable P	X	X
CEC	X	X
ESBI	X	X
Al	X	X
Zn	X	
Cu	X	X
Mn	X	X
Fe	X	X

3. Results

3.1. Biomass, litter and soil moisture content

The moisture content of biomass, litter, and soil was assessed immediately prior the prescribed fire implementation (T1). In block 1, litter presented the higher moisture content, with an average value of 128%, while biomass and soil had the lower moisture content, with 22% and 15%, respectively (figure 11).

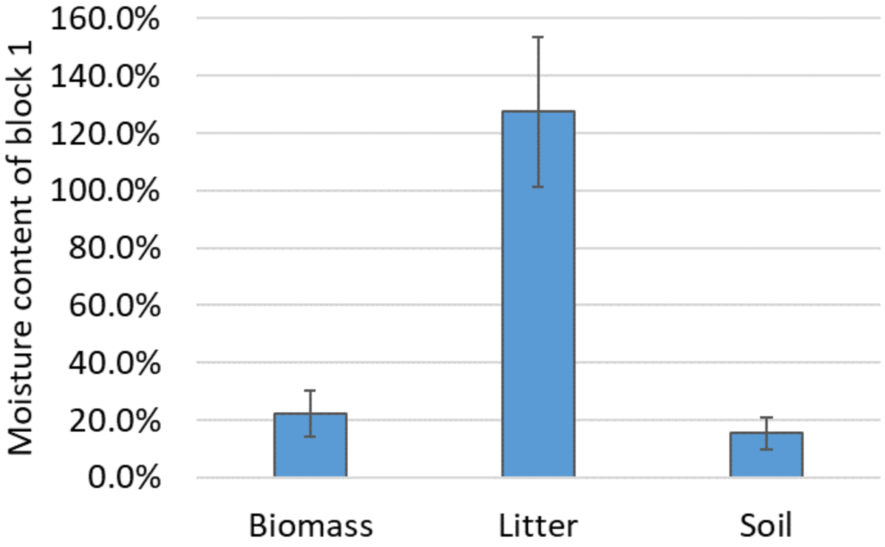

Figure 11. Moisture content (in percentage) of biomass, litter, and soil of block 1 obtained immediately prior to the prescribed fire installation in the *Eucalyptus globulus* plantation in Valongo, in December 2021 and the corresponding standard deviations.

The moisture content of biomass, litter and soil on block 2 followed the same tendency of block 1 (figure 12). The moisture content of the litter was the highest, around 71%, while biomass and soil had values of 42% and 16%, respectively.

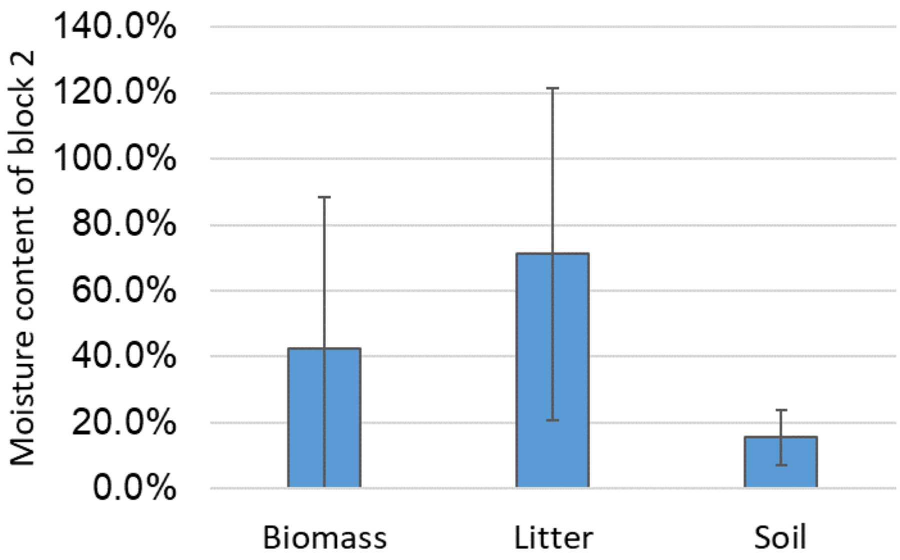

Figure 12 – Moisture content (in percentage) of biomass, litter, and soil of block 2 obtained immediately prior to the prescribed fire installation in the *Eucalyptus globulus* plantation in Valongo, in December 2021 and the corresponding standard deviations.

3.2. Fire severity evaluation

Regarding the assessment of fire severity by visual evaluation on block 1, all the monitored points presented the organic horizon (dead layer) practically intact, with no presence of ashes and no changes at the level of mineral soil structure. Therefore, according to Vega et al. (2013) method, the fire severity on block 1 was considered low, with the median value of 1 (figure 13), and the impact of the fire on the soil surface was considered negligible.

The median severity class in block 2 was also 1 (the organic horizon of the soil was partially or fully intact, with no disturbance of the mineral soil). Nevertheless, differences were observed between sampling points: four sampling points were classified with a fire severity value of 2 (the organic horizon totally charred and presence of some ash), two sampling points were classified with fire severity of class 1 and the remaining three sampling points were of fire severity class 0, with no evidence of fire (figure 14).

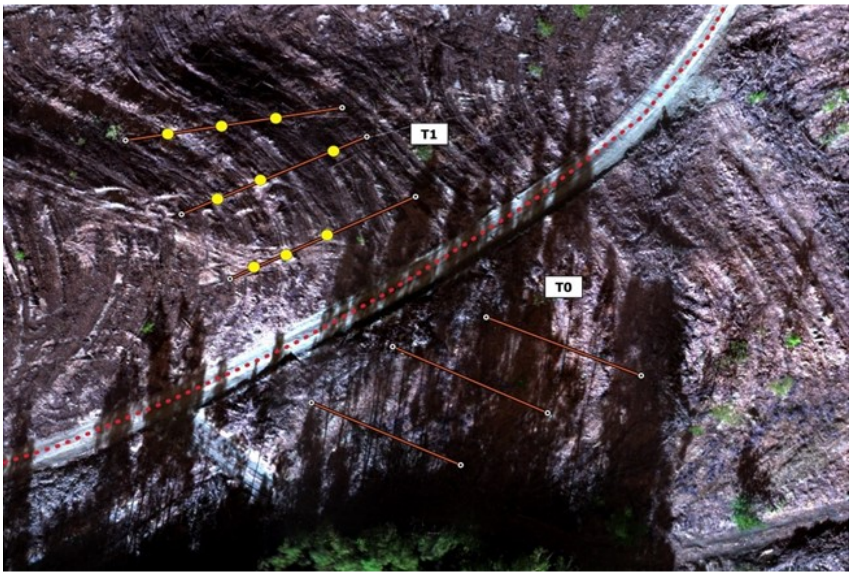

Figure 13 - Image of the block 1 with the schematic location of the transects of T0 and T1 (red lines) in *Eucalyptus globulus* plantation in Valongo. Full dots indicate the points of fire severity evaluation through visual indicators and the location of thermocouples on T1. The yellow dots represent fire severity of class 1.

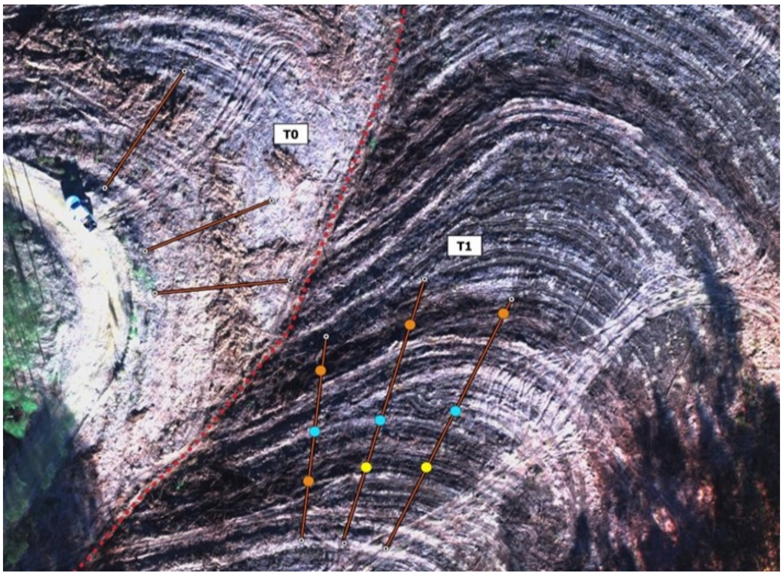

Figure 14 – Image of the block 2 with the schematic location of the transects of T0 and T1 (red lines) in *Eucalyptus globulus* plantation in Valongo. Full dots indicate the points of fire severity evaluation through visual indicators and the location of thermocouples on T1. The blue dots represent fire severity of class 0, the yellow dots represent fire severity of class 1, and the orange dots represent fire severity of class 2.

In the complementary method for fire severity estimation using thermocouples at the soil surface, it was registered soil temperatures (0-2 cm depth) ranging between 20 °C and 76 °C. Analysing thermocouples records in block 2, the temperatures varied between 16°C and 40°C, with a single record of 168°C in one of the thermocouples.

3.3. Effect on biomass height

On the T1 of block 1 the average biomass height reduction was much greater than on T0, having a difference of around 60% (figures 15 and 16). Block 2 had similar results to block 1, although the difference was not so accentuated. Despite T1 having a reduction of 60% as observed in block 1, the T0 had a reduction of 30% (figures 17 and 18).

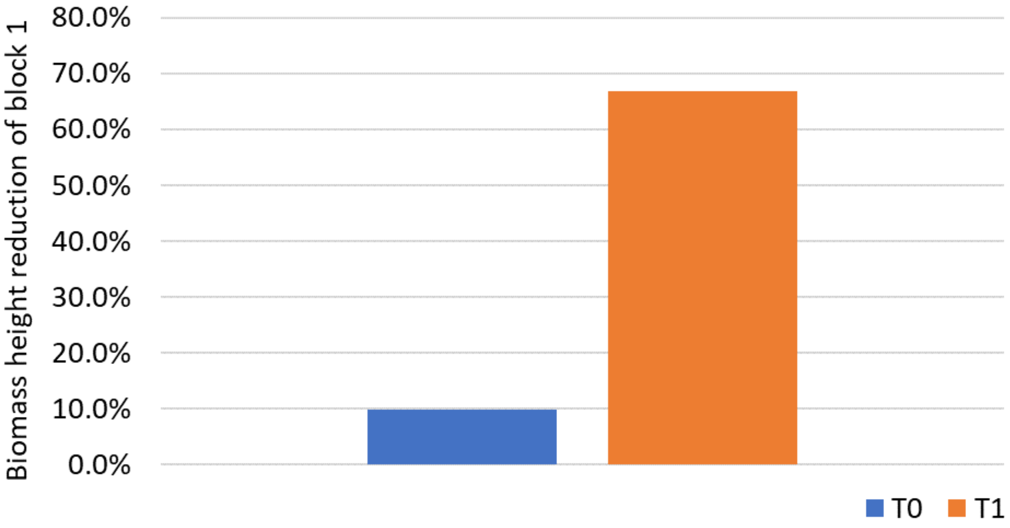

Figure 15 - Biomass height reduction on block 1, between the pre-installation of the prescribed fire (December 2021) and a month and a half after the installation of the prescribed fire (February) in the *Eucalyptus globulus* plantation in Valongo.

Figure 16 - Evidence of the biomass reduction with the image of before (left) and immediately after (right) the prescribed fire application on block 1 of the *Eucalyptus globulus* plantation in Valongo.

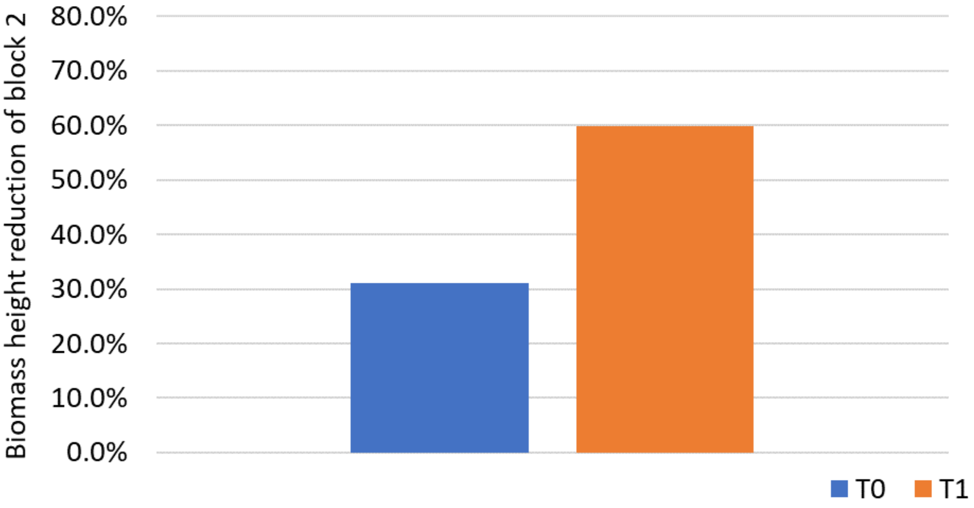

Figure 17 - Biomass height reduction on block 2, between the pre-installation of the prescribed fire (December 2021) and a month and a half after the installation of the prescribed fire (February) in the *Eucalyptus globulus* plantation in Valongo.

Figure 18 - Evidence of the biomass reduction with the image of before (left) and right after (right) the prescribed fire application on block 2 the *Eucalyptus globulus* plantation in Valongo.

3.4. Impacts in topsoil

3.4.1. Block 1

In block 1, results from soil samples (0 – 2 cm depth) showed that both treatments had no significant differences in BD, MWD, stoniness, and granulometry (table 5).

The parameter BD in December, pre-trail, was 0.72 g/cm^3 and 0.68 g/cm^3 in T0 and T1 respectively. One and a half months after the prescribed fire implementation (in February), neither treatment suffered significant changes. It varied 0.01 g/cm^3, the BD of the T0 was 0.73 g/cm^3 and the T1 was 0.67 g/cm^3.

MWD also had small variances. In December it was 0.70 mm in T0 and 0.65 mm in T1. In February the T0 increased slightly to 0.71 mm, while the T1 remained similar.

The stoniness was confirmed to be higher than 50%, which agreed with soil classification attributed in the field survey. In February, the stoniness had no statistically significant changes, being 53.34% on the T0 and 57.52% on the T1.

Table 5 - Resume of the results of the soil bulk density (BD), mean weigh diameter (MWD) and stoniness of block 1 of the *Eucalyptus globulus* plantation in Valongo

Area	Treatment	Sampling time	BD (g/cm^3)	MWD (mm)	Stoniness (%)
B1	T0	December	0.72	0.70	52.60
		February	0.73	0.71	53.30
	T1	December	0.68	0.65	54.50
		February	0.67	0.65	57.50

On block 1, topsoil samples revealed that the coarser fraction (> 2mm) represented more than 50%, followed by < 0,25 mm (15% – 20%) and 1-2 mm particle size (10%). After separating this fraction into stoniness and aggregates, it was possible to verify that represented more than 50% of the soil, while the aggregates represented a much smaller fraction. No statistically significant differences (p<0.05) was observed between treatments or between sampling time (figure 19).

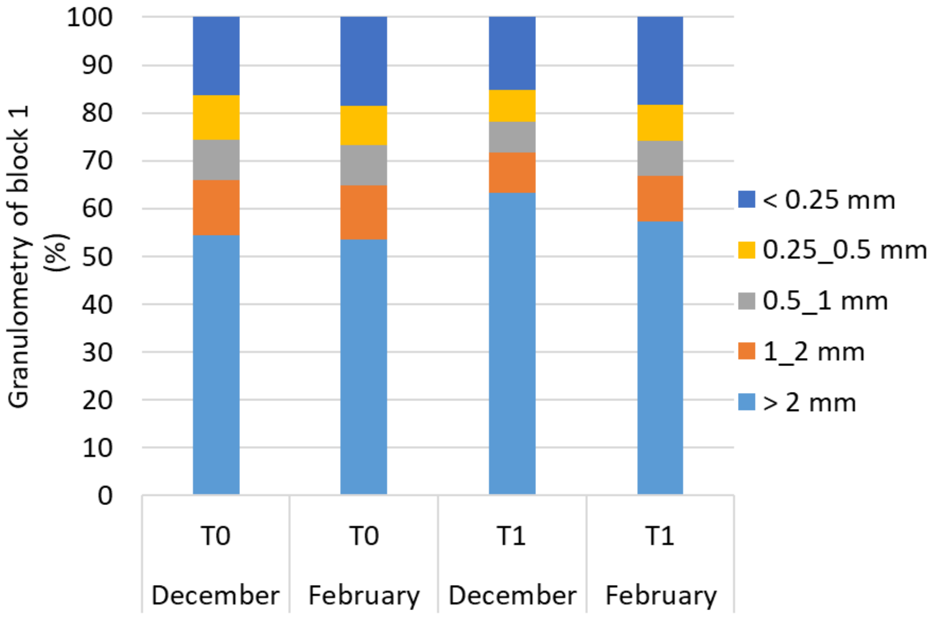

Figure 19 – Particle size distribution of soil samples (0-2 cm depth) collected on the *Eucalyptus globulus* plantation in Valongo in December 2021 (before trial implementation) and February 2022 (after trial implementation). on block 1 of the *Eucalyptus globulus* plantation in Valongo with the corresponding standard deviations; the treatments T0 - control and T1 – prescribed fire treatment.

On table 6 the average results from the parameters EC, OM, exchangeable acidity, CEC and micronutrients Fe, Zn, Cu and Mn are presented.

Table 6 - Results of the electric conductivity (EC), organic matter content (OM), exchangeable acidity, cation exchange capacity (CEC) and micronutrients iron (Fe), zinc (Zn), copper (Cu) and manganese (Mn) of the topsoil of block 1 of the *Eucalyptus globulus* plantation in Valongo.

	Block 1			
Treatment	T0		T1	
Timing	December	February	December	February
Parameters				
EC (25˚) (dS/m)	0.10	0.06	0.09	0.09
OM (%)	11.47	10.63	11.54	12.07
Exchangeable acidity ($cmol_c$/kg)	2.88	3.23	2.81	1.29
CEC ($cmol_c$/kg)	5.26	4.77	4.72	7.10
Fe (mg/kg)	414.44	410.00	356.67	309.00
Zn (mg/kg)	8.40	8.07	8.50	9.21
Cu (mg/kg)	2.06	0.81	1.09	1.32
Mn (mg/kg)	58.23	36.26	66.00	133.89

The EC of the initial topsoil was bellow ≤ 0.1 dS/m and similar on both T0 and T1 (table 6). On T1 samples, where the prescribed fire was applied, this parameter remained similar before and after the fire. However, on T0 EC decreased significantly to 0.06 dS/m ($p<0.05$). The OM on the soil prior to the experiment establishment was around 11.5% on both treatments, supporting the humic attribute on soil classification. On the month of February neither T0 nor T1 had statistically significant changes (table 6). The exchangeable acidity before trail installation was of 2.87 $cmol_c$/kg and 2.80 $cmol_c$/kg, on T0 and T1 respectively (table 6). On T0, one and a half months after, there was a slight increase to 3.23 $cmol_c$/kg, however it was not statistically significant. On T1 the exchangeable acidity decreased significantly to 1.29 cmol_c/kg ($p<0,05$). The CEC on the initial sampling was similar on both treatments, 4.72 cmol_c/kg (T1) to 5.26 cmol_c/kg (T0). No significant differences were observed one and a half months after trial implementation for both treatments (table 6). The micronutrients Fe, Zn and Cu had similar profiles (table 6). Fe, on the initial characterization, had similar values on both treatments (414.4 mg/kg and 356.7 mg/kg) but T0 had slightly higher values than T1. One month and a half later, in February, this tendency maintained. Zn content on soil was similar on both treatments, varying between 8.4 mg/kg and 8.5 mg/kg. In February this value decreased slightly to 8.07 mg/kg on T0 and increased slightly to 9.21 mg/kg on T1. The Cu content on soil initially was higher on T0 than on T1, varying between 2.06 mg/kg and 1.09 mg/kg. On the month of February, the control treatment was lower, although this difference was not statistically significant. On the prescribed fire treatment there was a slight increase to 1.32 mg/kg. While on the initial characterization the micronutrient Mn had similar values on both treatments, having differences of 5 mg/kg between T0 and T1. In T1, Mn content increased significantly to 133.9 mg/kg ($p<0.05$) one and a half months after the fire.

On the initial sampling, the soil pH was very similar on both T0 and T1, 4.2 and 4.3 correspondingly (figure 20). When comparing the pH results from both sampling moments, it revealed that on T0 the pH had a slight decrease, although it was not significant. However, on T1 the soil pH showed a statistically significant increase from 4.3 to 5.4 ($p<0.05$).

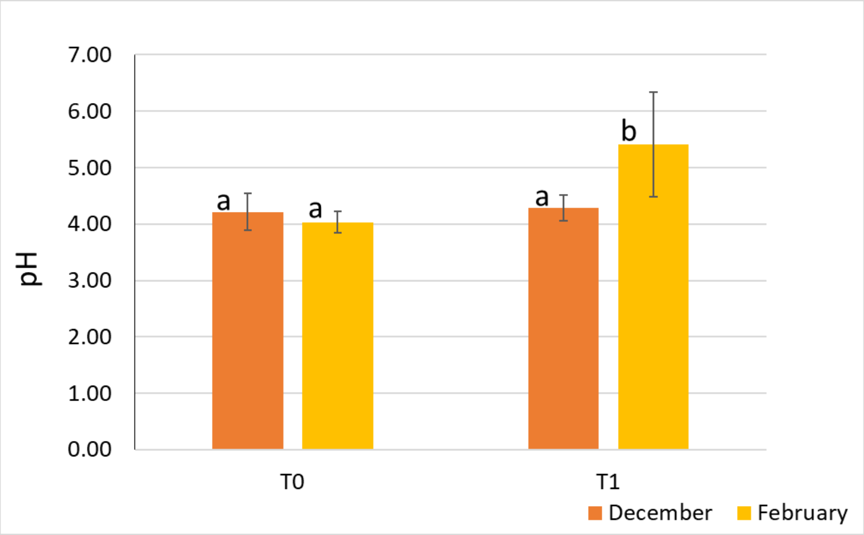

Figure 20 – pH values of topsoil samples (0-2 cm depth) collected in December 2021 (before trial implementation) and in February 2022 (1,5 months after) on block 1 of the *Eucalyptus globulus* plantation in Valongo with the corresponding standard deviations; the treatments T0 - control and T1 – prescribed fire treatment; different letters correspond to statistically significant differences ($p<0.05$).

Concerning the exchangeable cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+), in topsoil samples collected in December, before trial installation, the values of Ca^{2+} were of 1.47 $cmol_c/kg$ in T0 and 1.20 $cmol_c/kg$ in T1 (figure 21). One and a half months after the experiment, no differences were observed in the levels of Ca^{2+} in T0, while the value in T1 increased significantly ($p<0.05$) to 4.5 $cmol_c/kg$.

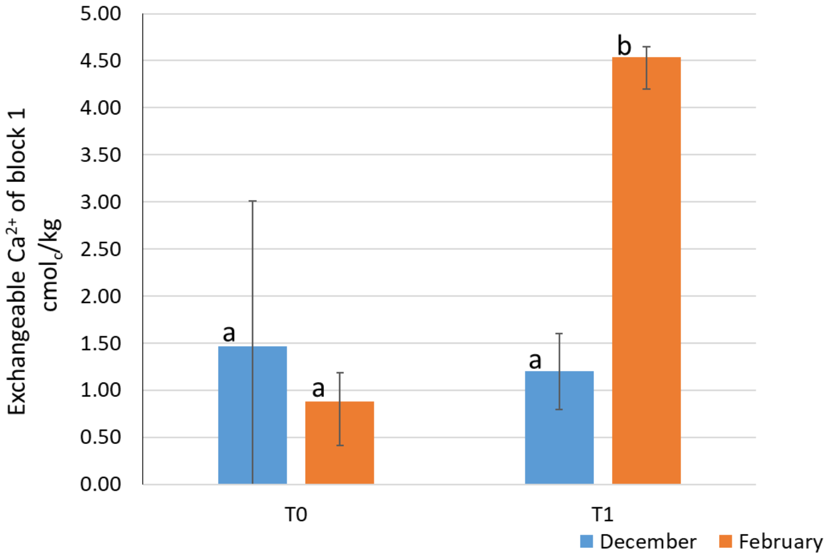

Figure 21 - Exchangeable cation Ca^{2+} of topsoil samples (0-2 cm depth) collected in December 2021 (before trial implementation) and February 2022 (after trial implementation) on block 1 of the *Eucalyptus globulus* plantation in Valongo with the corresponding standard deviations; the treatments T0 - control and T1 – prescribed fire treatment; different letters correspond to statistically significant differences ($p<0.05$).

Also prior to the trial installation, the levels of Mg^{2+} were 0.47 $cmol_c/kg$ in T0 and 0.33 $cmol_c/kg$ in T1 (figure 22), the levels of K were 0.25 $cmol_c/kg$ in T0 and 0.20 $cmol_c/kg$ in T1 (figure 23), and Na cation values were of 0.19 $cmol_c/kg$ in both T0 and T1 (figure 24). In February, similar results were achieved for control treatment. However, on T1 Na^+ was the only cation that had no statistically significant change, while Mg^{2+} and K^+ all increased significantly ($p<0.05$).

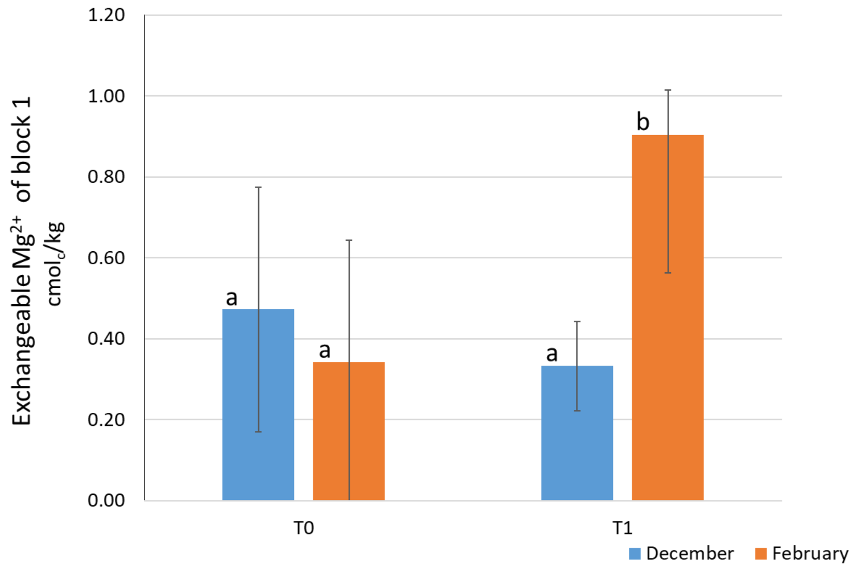

Figure 22 - Exchangeable cation Mg^{2+} of topsoil samples (0-2 cm depth) collected in December 2021 (before trial implementation) and February 2022 (after trial implementation) on block 1 of the *Eucalyptus globulus* plantation in Valongo with the corresponding standard deviations; the treatments T0 - control and T1 – prescribed fire treatment; different letters correspond to statistically significant differences ($p<0.05$).

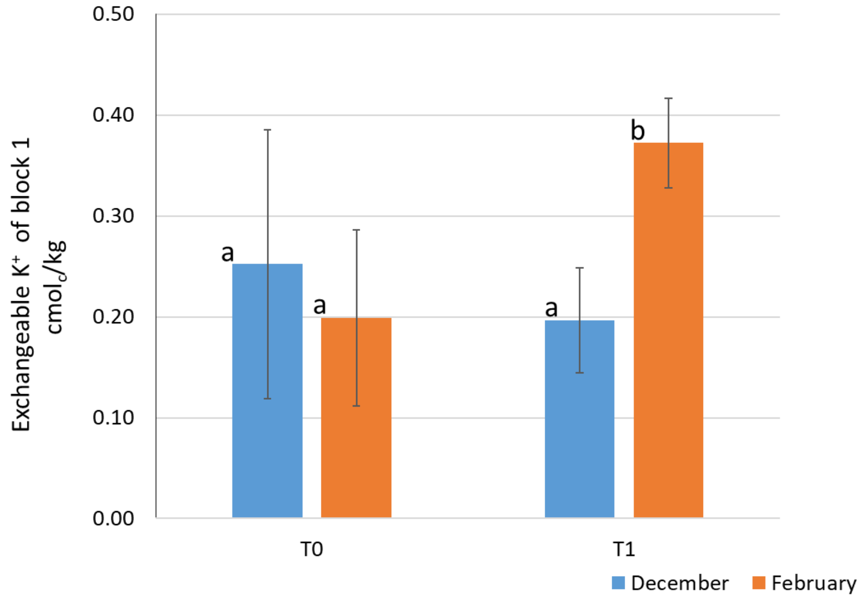

Figure 23 - Exchangeable cation K^{+} of topsoil samples (0-2 cm depth) collected in December 2021 (before trial implementation) and February 2022 (after trial implementation) on block 1 of the *Eucalyptus globulus* plantation in Valongo with the corresponding standard deviations; the treatments T0 - control and T1 – prescribed fire treatment; different letters correspond to statistically significant differences ($p<0.05$).

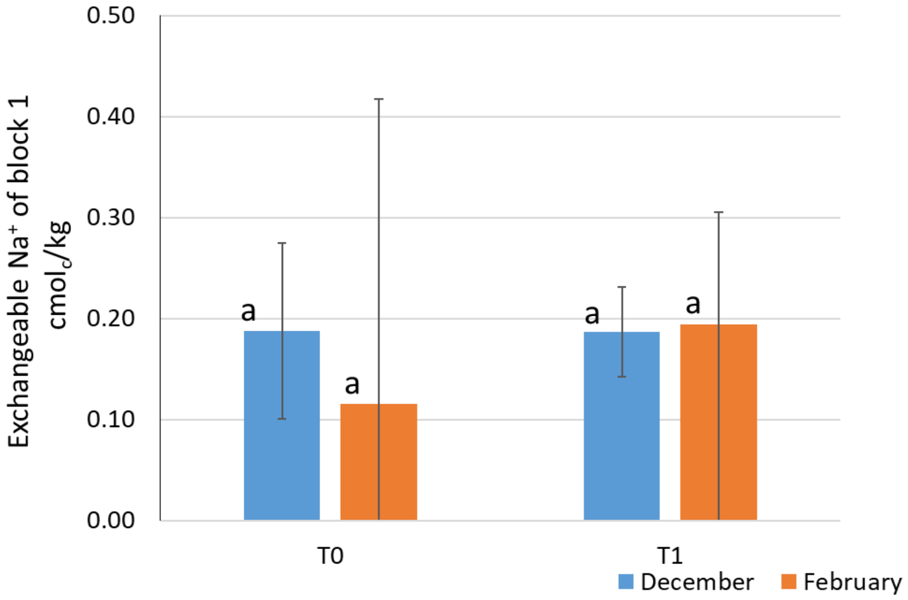

Figure 24 - Exchangeable cation Na^+ of topsoil samples (0-2 cm depth) collected in December 2021 (before trial implementation) and February 2022 (after trial implementation) on block 1 of the *Eucalyptus globulus* plantation in Valongo with the corresponding standard deviations; the treatments T0 - control and T1 – prescribed fire treatment; different letters correspond to statistically significant differences ($p<0.05$).

On the initial sampling, the ESBI initially was around 40%, on both blocks (figure 25). While on the T0 this parameter had no significant changes one and a half months later, on the T1 it increased almost 40%, to 78% ($p<0.05$). The AI initially was around 60%, and one and a half months later the T0 had no significant changes (figure 25). However, the T1 decreased significantly to 23% ($p<0.05$).

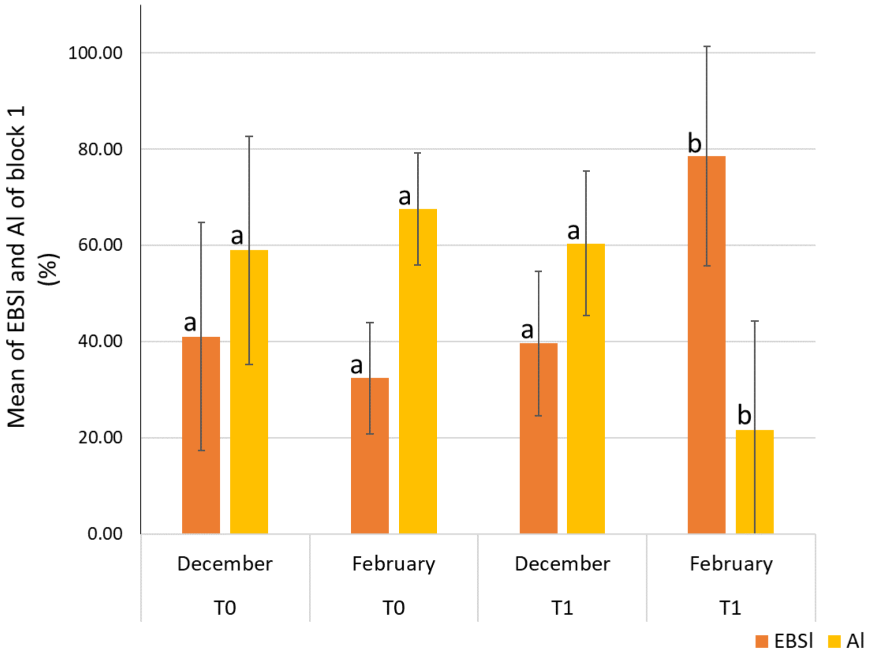

Figure 25 - Mean of the ESBI and AI content in topsoil samples (0-2 cm depth) collected in December 2021 (before trial implementation) and February 2022 (after trial implementation) on block 1 of the *Eucalyptus globulus* plantation in Valongo with the corresponding standard deviations; the treatments T0 - control and T1 – prescribed fire treatment; different letters correspond to statistically significant differences (p<0.05) per parameter.

The extractable P initially, in December, was around 10 mg/kg (10.3 mg/kg on T0 and 10.2 mg/kg on T1) (figure 26). On the control treatment, in February, this value remained similar, however, on T1 it was an increased to 62.7 mg/kg. Although this increase was substantial, was not statistically significant, probably due to the high variability between samples.

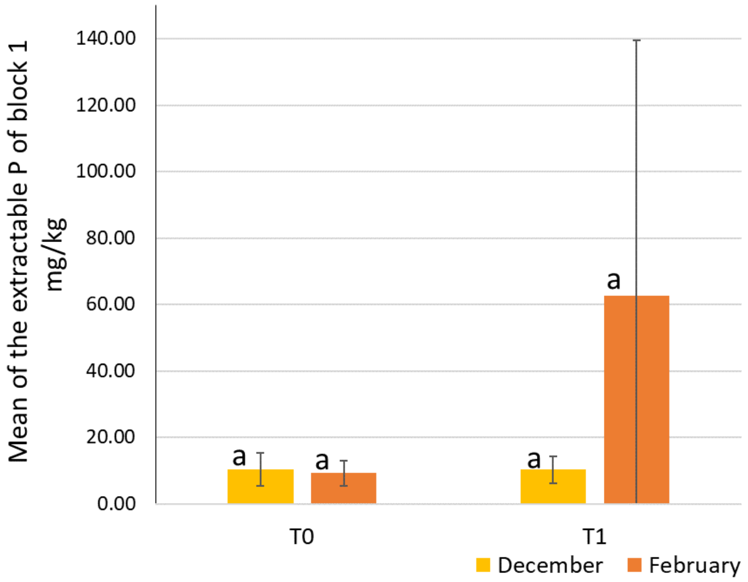

Figure 26 - Mean of the extractable phosphorus (P) in topsoil samples (0-2 cm depth) collected in December 2021 (before trial implementation) and February 2022 (after trial implementation) on block 1 of the *Eucalyptus globulus* plantation in Valongo with the corresponding standard deviations; the treatments T0 - control and T1 – prescribed fire treatment; different letters correspond to statistically significant differences ($p<0.05$).

3.4.2. Block 2

Similar to block 1, also in block 2 an initial characterization was done in December, previous to trial implementation, in order to characterize the area and allow the comparison between treatments. Results showed that both treatments had comparable BD, MWD, stoniness and granulometry, since they were not statistically different. When comparing both sampling timings, no significant difference was found on either of the physical parameters analysed (table 7).

Table 7 - Resume of the results of the soil bulk density (BD), mean weigh diameter (MWD) and stoniness of block 2 of the *Eucalyptus globulus* plantation in Valongo.

Area	Treatment	Sampling time	BD (g/cm^3)	MWD (mm)	Stoniness (%)
B2	T0	December	0.74	0.62	58.47
		February	0.67	0.62	60.04
	T1	December	0.67	0.65	61.11
		February	0.64	0.66	60.14

In December BD varied between 0.74 g/cm^3 and 0.67 g/cm^3, in T0 and T1, respectively (table 7). In February these values had both decreased slightly, T0 had a BD of 0.67 g/cm^3 and T1 had a BD of 0.64 g/cm^3 although these changes were not statistically significant.

The MWD also had no statistically significant differences ($p<0.05$) between treatments or sampling timings (table 7). In December the MWD of T0 was 0.62 mm and of T1 was 0.65 mm, and in February the T0 remained at the same value, while T1 increased slightly to 0.66 mm, but these changes were not statistically significant.

The stoniness was confirmed to be higher than 50%, varying from 58% to 60%, which agreed with the soil classification attributed during the field survey. Initially, in December, the stoniness of the T0 soil was 58.47% and the T1 was 61.11% (table 7). In February both treatments (T0 and T1) had stoniness of 60%, varying 0.1% between treatments.

On block 2, topsoil samples revealed that the coarser fraction (> 2mm) represented more than 50% of the soil, followed by > 0.25 mm (20%) and 1-2 mm particle (9%) (figure 27). After separating this fraction into stoniness and aggregates, it is possible to understand that, in fact, it is the stoniness that represents more than 50% of the soil, while the aggregates represent a much smaller fraction. No statistically significant differences ($p<0.05$) was observed between treatments or sampling timings.

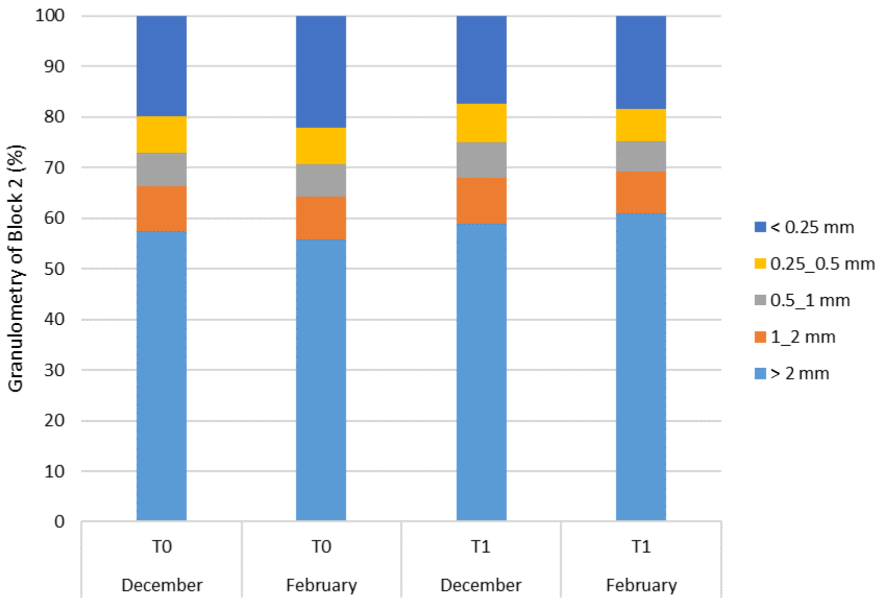

Figure 27 – Particle size distribution of soil samples (0-2 cm depth) collected in December 2021 (before trial implementation) and February 2022) on block 2 of the *Eucalyptus globulus* plantation in Valongo with the corresponding standard deviations; the treatments T0 - control and T1 – prescribed fire treatment.

The mean results from the parameters EC, OM, exchangeable acidity, CEC and micronutrients Fe, Zn, Cu and Mn are resumed in table 8. The EC of the initial topsoil was low (0.05 dS/m on block 1 and 0.13 dS/m on block 2). On T1 samples, where the prescribed fire was applied, this parameter remained similar before and after the fire. However, on T0, EC decreased significantly ($p<0.05$) to 0.08 dS/m. The OM on the soil on the month of December was 13.68% on T0 and 13.89% on T1, supporting the humic attribute on soil classification (table 8). On the month of February neither of the treatments, T0 and T1, had statistically significant changes.

The exchangeable acidity in December varied between 2.88 $cmol_c$/kg and 1.77 $cmol_c$/kg, on T0 and T1 respectively (table 8). On T0, in February, there was a slight decrease to 2.46 $cmol_c$/kg, however it was not statistically significant. On T1 the exchangeable acidity decreased significantly to 0.31 $cmol_c$/kg, with $p<0.05$.

The CEC on the initial sampling timing was similar on both treatments ranging from 4.33 (T1) $cmol_c$/kg to 4.61 $cmol_c$/kg (T0). On the control treatment this value decreased to 3.19 $cmol_c$/kg and on T1 the value was 9.04 $cmol_c$/kg, but this was not statistically significant (table 8).

Table 8 - Results of the electric conductivity (EC), organic matter content (OM), exchangeable acidity, cation exchange capacity (CEC) and micronutrients iron (Fe), zinc (Zn), copper (Cu) and manganese (Mn) of the soil of block 2 of the *Eucalyptus globulus* plantation in Valongo.

	Block 2			
Treatment	T0		T1	
Timing	December	February	December	February
EC (25˚) (dS/m)	0.05	0.08	0.13	0.08
OM (%)	13.68	9.97	13.89	13.56
Exchangeable acidity (cmol$_c$/kg)	2.87	2.46	1.77	0.31
CEC (cmol$_c$/kg)	4.33	3.19	4.61	9.04
Fe (mg/kg)	470.00	406.67	417.50	175.56
Zn (mg/kg)	5.74	4.02	8.20	7.09
Cu (mg/kg)	1.10	0.91	1.34	1.93
Mn (mg/kg)	11.77	6.64	33.35	155.33

Fe, on the initial characterization, had similar values on both treatments (470.00 mg/kg and 417.50 mg/kg) but T0 had slightly higher values than T1 (table 8). One month and a half later, in February, this tendency maintained, but with slightly smaller values. Zn content on soil was similar on both treatments, varying between 5.74 mg/kg and 8.20 mg/kg (table 8). In February this value decreased slightly to 4.02 mg/kg on T0 and to 7.09 mg/kg on T1. The Cu content on soil initially was 1.10 mg/kg on T0 and 1.34 mg/kg on T1. On the month of February (table 8), the control treatment was lower, although this difference was not statistically significant. On the prescribed fire treatment there was a slight increase to 1.93 mg/kg.

On the initial characterization the micronutrient Mn was 11.77 mg/kg on the T0 and 33.36 mg/kg on the T1(table 8). In February, on and a half months after the prescribed fire implementation, the T1 Mn content increased significantly to 155.33 mg/kg ($p<0.05$).

On the initial sampling timing, the soil pH was very similar on both T0 and T1, 4.2 and 4.3 correspondingly (figure 28). When comparing the pH results from both sampling moments, it revealed that on T0 the pH had a slight decrease, although it was not significant. However, on T1 the soil pH showed a statistically significant increase from 4.29 to 5.41, ($p<0.05$).

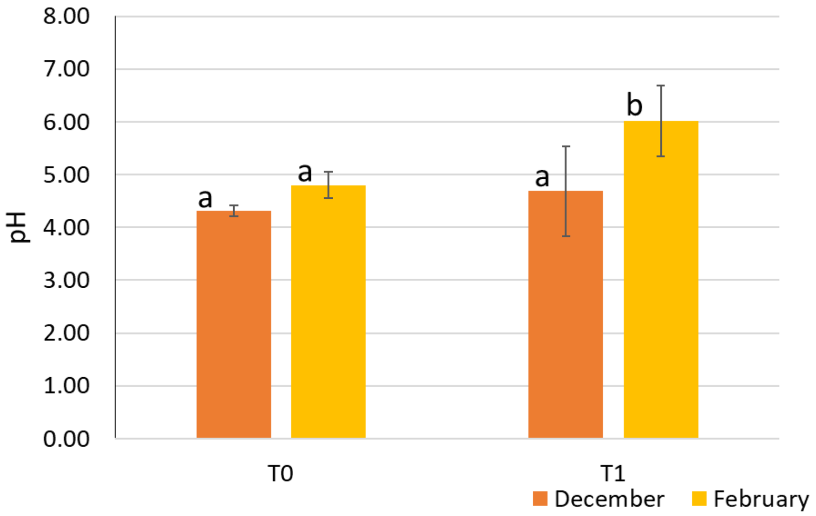

Figure 28 – pH values of topsoil samples (0-2 cm depth) collected in December 2021 (before trial implementation) and February 2022 (after trial implementation) on block 2 of the *Eucalyptus globulus* plantation in Valongo, with the corresponding standard deviations; the treatments T0 - control and T1 – prescribed fire treatment; different letters correspond to statistically significant differences ($p<0.05$).

Results from the samples collected in December, before trial installation, revealed that the values of the exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}) had no statistical differences (figures 29-32). In topsoil samples, before the experiment establishment, Ca^{2+} values were 0.81 $cmol_c/kg$ in T0 and 1.50 $cmol_c/kg$ in T1 (figure 29), Mg^{2+} levels were 0.30 $cmol_c/kg$ in T0 and 0.48 $cmol_c/kg$ in T1 (figure 30), K^{+} values were 0.22 $cmol_c/kg$ in T0 and 0.40 $cmol^{+}/kg$ in T1 (figure 31) and Na^{+} cation values were 0.13 $cmol_c/kg$ in T0 and 0.46 $cmol_c/kg$ in T1 (figure 32). On February, one and a half months after, similar results were achieved for T0. On T1, Na^{+} was the only cation that had no statistically significant change, while Ca^{2+}, Mg^{2+} and K^{+} all increased significantly.

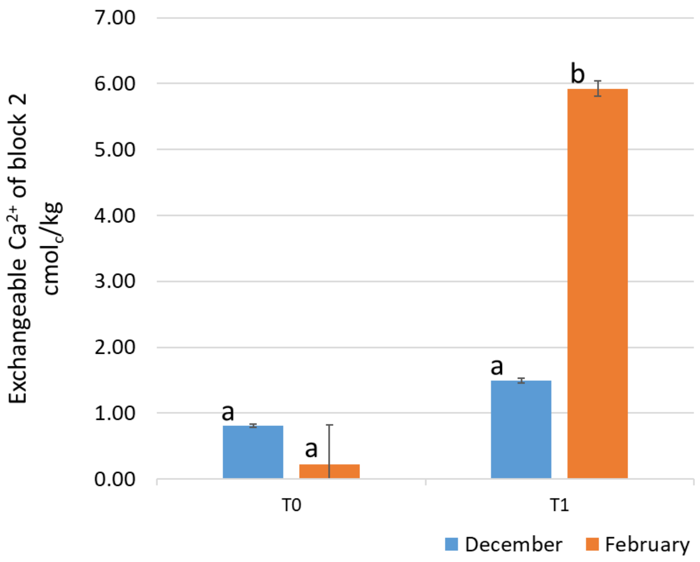

Figure 29 - Exchangeable cation Ca^{2+} of topsoil samples (0-2 cm depth) collected in December 2021 (before trial implementation) and February 2022 (after trial implementation) on block 2 of the *Eucalyptus globulus* plantation in Valongo, with the corresponding standard deviations; the treatments T0 - control and T1 – prescribed fire treatment; different letters correspond to statistically significant differences ($p<0.05$).

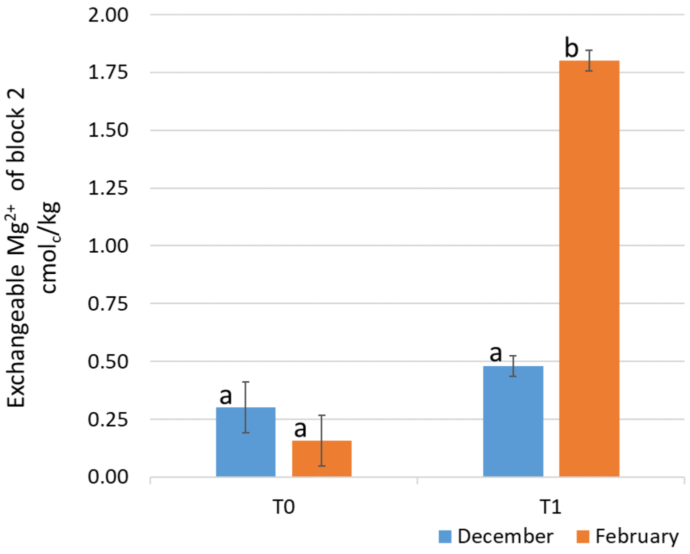

Figure 30 - Exchangeable cation Mg^{2+} of topsoil samples (0-2 cm depth) collected in December 2021 (before trial implementation) and February 2022 (after trial implementation) on block 2 of the *Eucalyptus globulus* plantation in Valongo, with the corresponding standard deviations; the treatments T0 - control and T1 – prescribed fire treatment; different letters correspond to statistically significant differences ($p<0.05$).

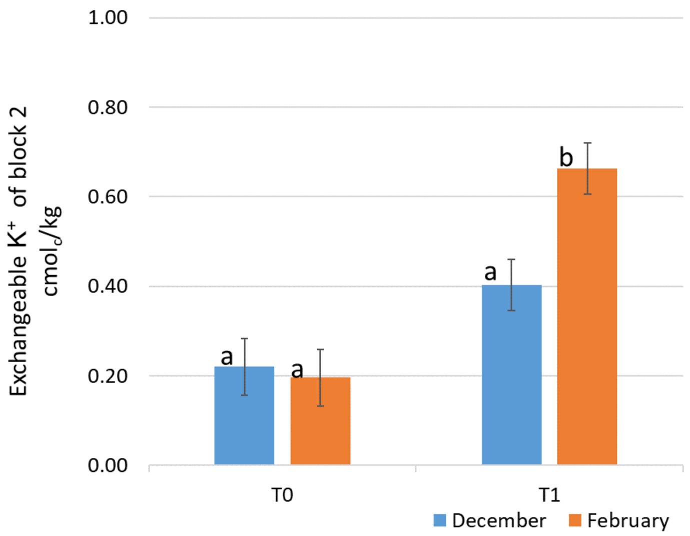

Figure 31 - Exchangeable cation K^+ of topsoil samples (0-2 cm depth) collected in December 2021 (before trial implementation) and February 2022 (after trial implementation) on block 2 of the *Eucalyptus globulus* plantation in Valongo, with the corresponding standard deviations; the treatments T0 - control and T1 – prescribed fire treatment; different letters correspond to statistically significant differences ($p<0.05$).

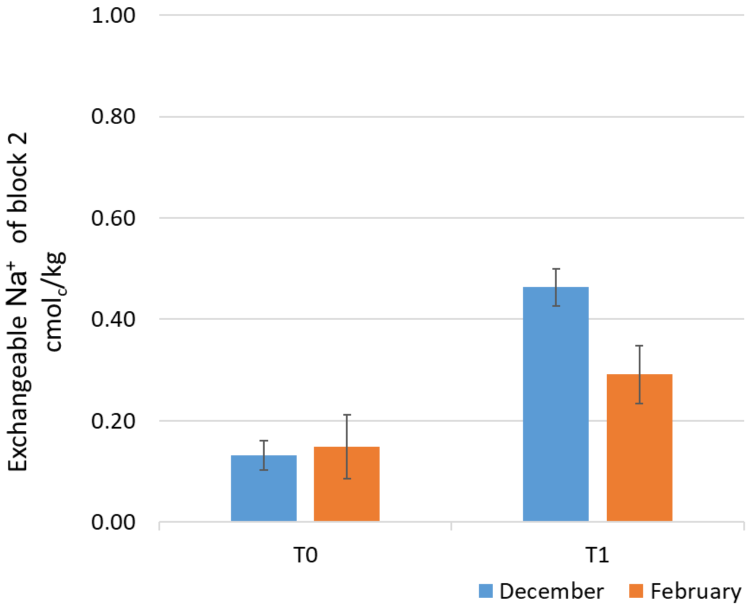

Figure 32 - Exchangeable cation Na^+ of topsoil samples (0-2 cm depth) collected in December 2021 (before trial implementation) and February 2022 (after trial implementation) on block 2 of the *Eucalyptus globulus* plantation in Valongo, with the corresponding standard deviations; the treatments T0 - control and T1 – prescribed fire treatment; different letters correspond to statistically significant differences ($p<0.05$).

On the initial sampling, the ESBI on the T0 was 33% and on the T1 it was 57%. On the following sampling, on T0, there was a slight decrease on the percentage of ESBI to 23%, although it was not statistically significant (figure 33). On the treatment where the prescribed fire was applied, T1, the ESBI increased significantly (around 40%) to 92%. Initially the AI was 67% on the T0 and 43% on the T1. On the next sampling timing, on T0, there was a slight increase in AI to 77%, although it was not statistically significant (figure 33). On the treatment where the prescribed fire was applied, T1, the AI decreased significantly (around 35%) to 9% ($p<0.05$).

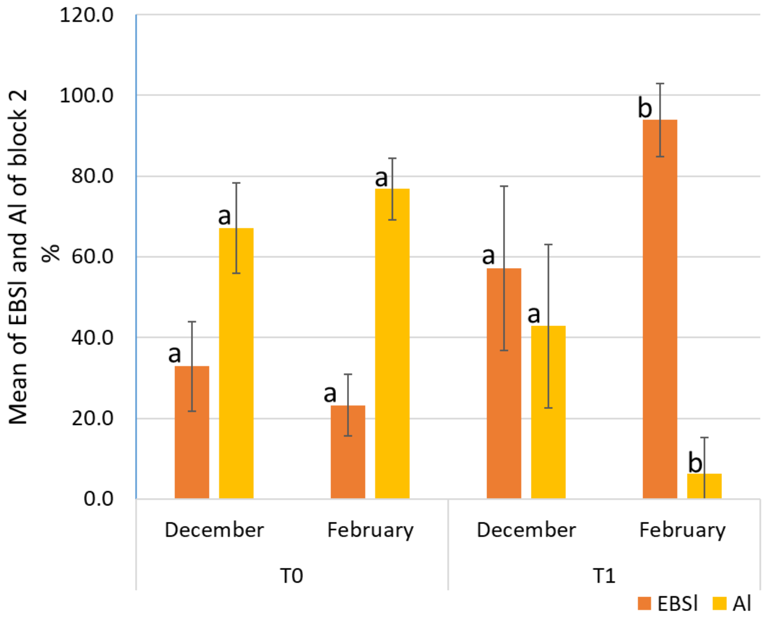

Figure 33 - Mean of the ESBI and AI topsoil samples (0-2 cm depth) collected in December 2021 (before trial implementation) and February 2022 (after trial implementation) on block 2 of the *Eucalyptus globulus* plantation in Valongo, with the corresponding standard deviations; the treatments T0 - control and T1 – prescribed fire treatment; different letters correspond to statistically significant differences ($p<0.05$) per parameter.

The extractable phosphorus initially, in December, was 10.22 mg/kg on T0 and 16.22 mg/kg on T1 (figure 34). On the control treatment, in February, this value remained similar, however, on T1 it increased to 62.67 mg/kg ($p<0.05$).

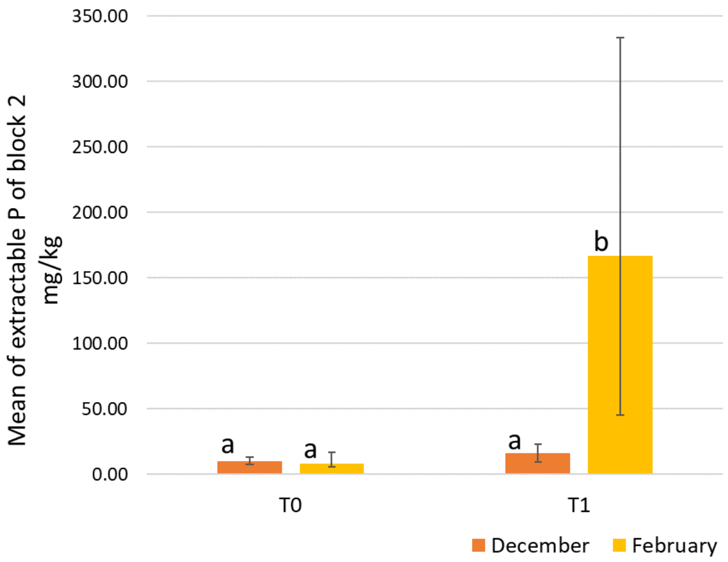

Figure 34 - Mean of the extractable phosphorus (P) topsoil samples (0-2 cm depth) collected in December 2021 (before trial implementation) and February 2022 (after trial implementation) on block 1 of the *Eucalyptus globulus* plantation in Valongo; the treatments T0- control and T1- prescribed fire treatment; different letters correspond to statistically significant differences ($p<0.05$).

3.4.3. Stumps resprouting and stems growth

Stump resprouting was assessed in May 2022, four and a half months after the prescribed fire operation, by counting the number of stumps that had resprouted per treatment (figure 35).

Figure 35 - Stump of *Eucalyptus globulus* in a plantation in Valongo, after cutting (left) and after resprouting in May 2022 (center) and in September 2022 (right).

In block 1, the stump resprouting had similar values on both treatments (T0 and T1). The percentage of resprouted stumps was superior to 90% in both treatments, around 91.3% in T0 and 94.7% in T1 (figure 36). In block 2, the resprouting percentage of the control treatment (T0) was higher than 93.3%, however the T1 treatment had a slightly smaller stump resprouting of 80.0% (figure 37).

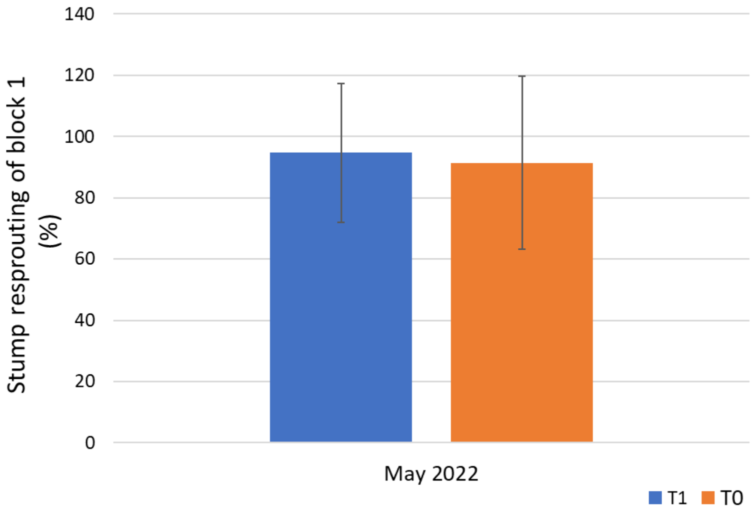

Figure 36 - Percentage of stump resprouting of block 1 of the *Eucalyptus globulus* plantation in Valongo, four and a half months after harvest and the prescribed fire installation with the corresponding standard deviations.

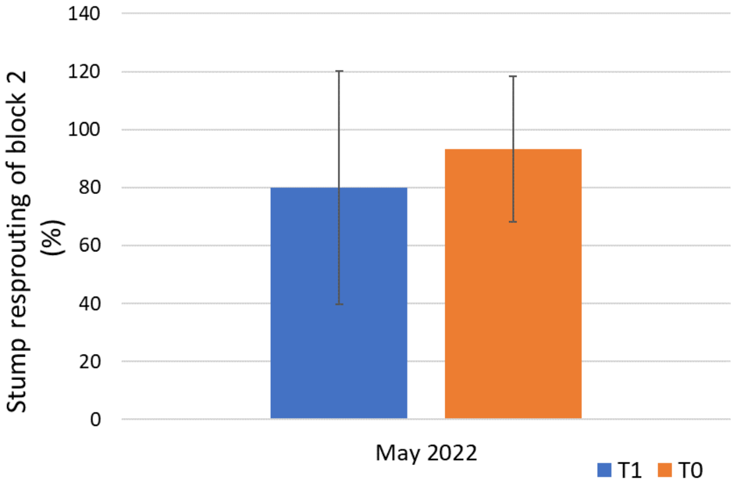

Figure 37 - Percentage of stump resprouting of block 2 of the *Eucalyptus globulus* plantation in Valongo, four and a half months after harvest and the prescribed fire installation with the corresponding standard deviations.

Regarding stems growth, on block 1, the height was similar between both treatments in both timings, May (four and a half months after the prescribed fire) and September (10 months after the prescribed fire). In May both treatments (T0 and T1) had stems with around 0.46 m of height, and in September the stems had an average height of 3.25 m (figure 38).

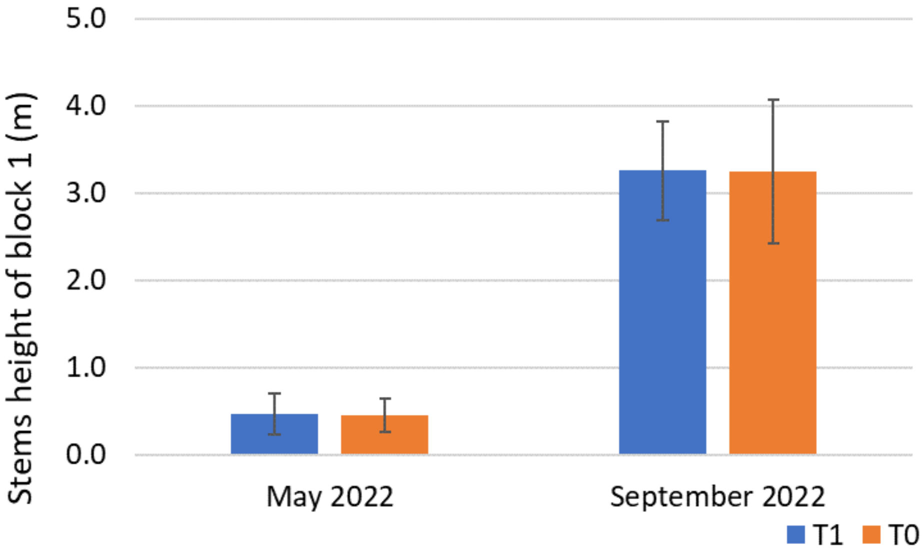

Figure 38 – Mean stems height (in meters) of *Eucalyptus globulus* trees of block 1 in the plantation in Valongo. The height was measured in May (four and a half months after the prescribed fire installation) and in September (10 months after the prescribed fire installation), with the corresponding standard deviations.

On block 2, in May the height of stems of in average 0.38 m in T0 and 0.29 cm in T1. In September, around 10 months after fire, the stems had an average height of 3.02 m in T0 and 2.80 m in T1 (figure 39). No significant differences ($p<0.05$) were found between treatments within the same monitoring timing.

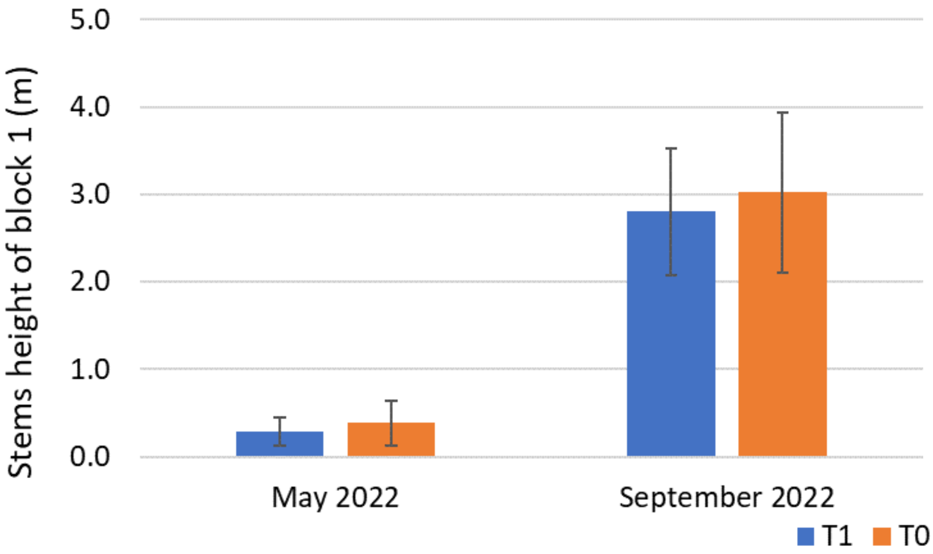

Figure 39 – Mean stems height (in meters) of *Eucalyptus globulus* trees of block 2 in the *E. globulus* plantation in Valongo. The height was measured in May (four and a half months after the prescribed fire installation) and in September (10 months after the prescribed fire installation) with the corresponding standard deviations.

4. Discussion

Before the prescribe fire operation, the weather conditions were assessed, to assure that the fuel load would be consumed, but the safety of the procedure would still be met. Since the temperature, precipitation and wind speed were all within the safe parameters, the AFOCELCA team installed the prescribed fire in the T1 of both blocks (block 1 and block 2). The prescribed fire was upwind and uphill.

In Molina et al (2021) the fine fuel moisture content was directly related to the total fuel load reduction of *Pinnus pinaster*, in Spain. This study showed that the optimal fine fuel moisture content was between 9% and 12%, to which the fuel reduction was around 91% and that for fuel moisture content > 14% had a fuel reduction of 38%. However, our results show higher biomass moisture content (22% and 42%) and the biomass reduction was greater than the predicted in Molina et al (2021).

The harvest residues of the eucalyptus were disposed heterogeneously in strings, due to the mechanization of the harvesting operation, being more accentuated in block 2. These areas within the treatments that had much fuel load and other with very little or even none. The moisture content of the biomass, litter and soil were analyzed, to understand how it influences the prescribed fire severity and effectiveness. The higher moisture content was present in the litter, in both blocks. Biomass had a moisture content of around 20% in block 1 and 40% in block 2. Soil moisture content was inferior to 20% in both blocks.

The fire severity, assessed by two methods (thought visual indicators related to forest floor evidence of fire and the impact on the topsoil following the method described by Vega et al. (2013) and measuring the soil temperature with thermocouples), was low in both blocks. The heterogeneous distribution and moisture content of the fuel load may have influenced fire severity. The fire severity of block 1 was the same (class 1) in all the assessed points, however, in block 2 it varied between classes 0 and 2. The fire severity and the effectiveness of the prescribed fire as a harvest residues management tool was highly influenced by the fuel load distribution and by the moisture content. Perrakis and Agee (2006) reported that in the areas where the harvest residues were more concentrated, the moisture content of the biomass was higher, making the biomass consumption by the fire harder since higher water content results often in less fuel consumed and lower intensity. Since the temperatures measured by the thermocouples were very low, and the biomass was displayed in the field with various concentrations, this may explain the low intensity fire in our study and the lower biomass consumption in block 2. However, since the biomass samples for moisture content were composed, for a moisture content representative of the area, and not punctual, this justification certainty cannot be validated.

Before and one and a half months after the prescribed fire, the biomass height was measured, to evaluate the effectiveness of the prescribed fire on the harvest residues management. The T1 (prescribed fire treatment) of both block 1 and block 2 had much higher reductions of fuel load, when compared to the T0 (control treatment), indicating that the prescribed fire was an effective tool.

Concerning the evaluation of the impacts of prescribed fire in soil properties, only the topsoil was analyzed (0-2 cm depth) because observations performed immediately after fire revealed a low severity, so possible effects would be more likely to be found on the most superficial layer of the soil in agreement with other studies (Badía et al., 2014; Zavala et al., 2014). Moreover, direct fire-induced changes in soils are mainly noticeable in the organic layer or in the most superficial centimetres of the mineral topsoil, as stated in literature (Vega et al., 2014).

In this study, none of the physical characteristics analysed (BD, MWD, stoniness and granulometry) had significant changes one and a half months after the implementation of the experiment that could be related to the prescribed fire operation. Therefore, results suggested that the use of prescribed fire to manage *E. globulus* residues after harvesting did not affect the physical features of topsoil, considering the specific weather conditions and moisture content of the biomass, litter and soil in which the procedure was conducted. In accordance, in the Mediterranean Region, topsoil bulk density has been reported to have no significant changes after prescribed fires (Meira-Castro et al., 2015) as well as the particle-size distribution (Oswald et al., 1998). On the other hand, under similar conditions, other authors have reported a continuously increase in bulk density for years (Granged et al., 2011).

The organic matter content of the topsoil of the blocks treated with prescribed fire (T1) remained similar to the initial characterization and to the control treatment (T0). This result was also registered by Fonseca et al. (2017) and Vega et al. (2000) in a low severity prescribed fire. Nonetheless, results may depend firstly on the fire severity, but also on the ecosystem affected and topography (Alcañiz et al., 2018).

The effects of a prescribed fire on the topsoil pH were also variable within the literature. However, in Alcañiz et al., 2016 this value increased immediately after the prescribed fire and continued to rise one year after the event, decreasing slightly afterwards. The pH increase observed immediately after the burning can be usually explained by the complete oxidation of the organic matter during the exposure of the soil surface to high temperatures and the release of cations by ashes, which can enter the exchange complex and expulse protons to the soil solution (Alcañiz et al., 2018). The pH increases generally because of the soluble inorganic ions that are released during the combustion of soil organic matter, as well as the formation of black carbon and the incorporation of ash and the soil enrichment with basic nutrients (Certini, 2005; Notario et al., 2004; Pereira et al., 2011; Terefe et al., 2008). Although the reliable justifications presented by other authors to the pH increment (Alcañiz et al., 2018, Certini, 2005; Notario et al., 2004; Pereira et al., 2011; Terefe et al., 2008), in the present study it seems that the contribution to the increase of pH may arise mainly from residual biomass combustion once there was not noticeable change in organic matter content of topsoil before and after prescribed fire.

Electrical conductivity tends to increase immediately after a prescribed fire (Certini, 2005; Khabarov et al., 2016), accompanied with the pH levels rise, due to the release of large amounts of soluble inorganic ions resulting from the combustion of the plants and litter layer (Alcañiz et al., 2016).

The ESBI increased significantly after prescribed fire and, although this parameter is not usually used to assess soil quality after this operation, it can be correlated to the increase in exchangeable cations (Ca^{2+}, Mg^{2+} and K^{+}), since it is the sum of base cations held onto the soil exchange sites divided by the total CEC. Available cations are expected to increase after low severity fire (Scharenbroch et al., 2012; Shakesby et al., 2015). In the study area, the increase of exchangeable cations in topsoil is probably the result of residual biomass contribution after fire. Further, it is known that particularly the eucalyptus bark is enriched in Ca and Mg.

Following a prescribed fire, it is normal to find an increase in P and other nutrients in the mineral soil (Alcañiz et al., 2016; Shakesby et al., 2015). However, the availability of macronutrients depends on the type of nutrient, vegetation, soil and the pathway of leaching processes (Kutiel & Shaviv, 1992). Phosphorus, mostly available in mineral form, is one of the essential nutrients for plants and is often a limiting factor in plant nutrition (Shakesby et al., 2015). Extractable P and cation levels tend to increase after a low severity fire due to the combustion of vegetation, the incorporation of ash into the soil (Alcañiz et al., 2016;

Úbeda et al., 2009) and the mineralization of organic phosphorus (Merino et al., 2019). Since the fire severity analysis showed that there was no formation of ashes in either of the blocks with prescribed fire, the increase in extractable P was likely due to the mineralization of the organic phosphorus as residual biomass combustion contribution, as seen in a pine forest in Spain by Merino (2019).

The micronutrient Fe became lower after the prescribed fire treatment, although not statistically significant in block 1, and Cu and Zn also had slight decreases in Block 2 this changes may have happened due to fire-induced depletion by convection in smoke columns, transport by wind, erosion and leaching or to conversion to insoluble oxidized forms in soils (García-Marco & González-Prieto, 2008). Both Cu and Zn of block 1 increased only a little after the treatment, however, Mn had a significant increment in both blocks. In Parraa et al. (1996) it was observed that there was a significant increase in the total content of Mn, but the content of exchangeable Mn didn't show any variation. Micronutrient availability in the soil varies due to fire-induced changes in the soil constituents (García-Marco & González-Prieto, 2008), since nutrient availability increase often happens due to nutrients added in ash, heating of organic matter, increased pH, and increased mineralization (Alcañiz et al., 2016).

The data of topsoil fertility evaluation post-fire revealed a great variability as noticed namely by the standard deviation values. This variability may be due to spatial heterogeneity of soil and biomass load, decomposition of charred residues, dynamics of burned biomass, hydrological processes or other factors as advanced by Khabarov et al (2016).

Despite these slight changes, soil nutrients tend to be ephemeral, lasting only a few months (Alcañiz et al., 2018), other studies and it is nine years after the prescribed fire when nutrient values had returned to their pre-fire levels (Alcañiz et al., 2016). When repeated fires are applied the nutrient values remain high (Scharenbroch et al., 2012). It would be, therefore, desirable to follow the evolution of soil fertility longer-term in the study area. In present study at least one expressive rainy event occurs days after prescribed fire establishment, even though, an increase in soil fertility was registered suggesting a minor exportation of nutrients from site which may also be related with the proper soil tillage of the plantation.

The stump resprouting was evaluated four and a half months after the prescribed fire installation, in May. In block 1, both treatments (T0 and T1) had more than 90% of the stumps resprouted, indicating that the prescribed fire did not affect the eucalyptus survival.

In block 2 the stump resprouting was also high, although the control treatment, T0, had around 10% more resprouts than T1. In addition to the resprouts, the stems height was measured, to understand if the prescribed fire, that had severity 1, had affected the *Eucalyptus globulus* plantation intended to be conducted in coppice regime.

The stems height was evaluated four and a half months after the prescribed fire installation, in May, and 10 months after the prescribed fire installation, in September. In block 1, the stems heights of T0 and T1 were very similar, however in block 2 the T1 stems were slightly smaller than the ones on T0. However, since the eucalyptus harvesting was done in September, and the prescribed fire installation was in December, the control treatments of both blocks had resprouts that were around 3 months older. However, the differences in stems height between both treatments were not statistically significant.

Since this three months' time difference is unnoticed in block 1, the increased nutrients availability may have improved the growth of the eucalypts. Additionally, fire is often related with eucalypt recruitment and establishment (Gill, 1997; Larcombe et al., 2013), due to increased light availability (Gill, 1997).

Despite the indication that the prescribed fire had no negative effects on the soil or in the productivity of eucalyptus plantation under coppice regime, it is of the most importance to continue to evaluate these parameters. The fire did not cause physical changes to the soil, however it did alter some physico-chemical properties and the monitorization of the quality of the soil, not only on the short-term, but also long-term, is of most importance for the monitorization of the plantation viability and production. Therefore, it is desirable to continue to monitor the evolution of the soil related parameters and the plant nutrition and growth, to fully understand the effect of the prescribed fire treatment on the *Eucalyptus globulus* plantation.

5. Conclusion

The prescribed fire was effective in reducing harvest residues of the *Eucalyptus globulus* plantation. Since it was a low intensity fire, the impacts on the soil and stumps were expected to be none or low (Shakesby et al., 2015). This study showed that, in short-term, the prescribed fire didn´t cause significant changes in the physical aspects of the soil, such as granulometry, mean weight diameter, bulk density and stoniness, however, it increased pH and nutrient availability (exchangeable Ca^{2+}, Mg^{2+}, and K^+ and extractable P) and it decreased Al. It also caused an increase in Mn, which may be a concern since it can become toxic for the eucalyptus plantation. Since the concentration of Mn that causes toxicity varies widely among plant species and varieties within species (El-Jaoual & Cox, 1998) it is of the most importance to continue to evaluate this parameter and the eucalyptus plantation growth. Despite causing significant changes, the increased nutrient availability of the soil may improve plant development, however, the time frame analysed was very small, and a continuous assessment of the effects of this management technique is essential to be able to estimate its viability.

The stump survival was very high (higher than 90%) in both the control treatment and the prescribed fire treatment. Despite the cutting operation and the prescribed fire having a 3 months' time difference, causing the control treatments eucalyptus trees have 3 months growth when the prescribed fire was applied to the T1. Despite this difference, the eucalyptus growth was similar in both the control treatment and the prescribed fire treatment, since the stems height was approximate in both blocks and treatments. The significant increase in nutrients availability could have contradicted the time difference, and the stems might have had better conditions for growth. It has been mentioned that post-fire monitoring should be done for at least five years to avoid the underestimation of delayed tree mortality or soil impacts (Van Mantgem et al., 2011) and due to this uncertainty, this study needs to be continued and further investigation is necessary.

Despite being necessary the continued assessment of this management tool on the soil and trees, this first evaluation indicates that it can be an alternative for manual and mechanical biomass control after harvesting for specific conditions. Prescribed fire is a technique that can be applied to a large area in a short period of time, with relatively low financial costs, and apparently low impacts on soil and on the *E. globulus* plantation, but the rigorous climatic parameters it needs to check causes a limited time frame to perform it.

Nonetheless, the evaluated effects are only on the short-term, and before the validation of this tool as a eucalyptus residues management tool it is necessary to fully understand the long-term effects of the prescribed fire on the soil and plantation. In this particular area, the Mn significant increase on the soil requires attention and a close monitorization, due to its toxicity. Soil physico-chemical parameters also should be continuingly evaluated along with the eucalyptus trees growth and productivity.

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