



Short-term effects of prescribed fire for *Eucalyptus globulus* Labill. slash management in Portugal

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Abstract Effective fuel management is a priority in Mediterranean *Eucalyptus globulus* plantations due to wildfire risk, but the short-term ecological effects of prescribed fire remain unclear. We hypothesized that PF would reduce post-harvest fuel loads without negatively affecting short-term soil properties or stump resprouting in *E. globulus* plantations. The main objectives were to determine the short-term effectiveness of PF in reducing fuel load and to evaluate its impacts on soil properties and on stump survival and resprouting height. A field experiment was carried out in two recently harvested blue gum stands under contrasting climates in northern and central Portugal during January 2023. Each site was divided into two plots (approximately 0.5 ha each): one prescribed fire treatment and one control, with three parallel transects per plot. Fuel loads, soil properties

and stump resprouting were assessed pre-PF and 45–60 d after PF. Soil impacts were evaluated using temperature recordings at 0–2 cm depth and visual soil burn severity. Stump resprouting heights were measured post-fire in both regions. Statistical analyses were used to assess differences between treatments. PF significantly reduced fine fuel loads by 73.5% in Póvoa de Varzim and 60.3% in Nisa compared to the control ($p < 0.05$). Soil burn severity was low, with peak temperatures of 117.5 °C and 107.5 °C at a 2-cm depth in Póvoa de Varzim and Nisa, respectively. PF increased soil pH (from 4.0 to 5.0 in Póvoa and 5.7 to 7.1 in Nisa) and phosphorus content. Organic matter levels were unaffected in Nisa and slightly reduced in Póvoa. Stump survival rates were high ($> 87\%$) in both sites, with PF showing no statistically significant difference from control. However, while similar in Póvoa (0.37 m), resprouting heights in Nisa were lower in PF plots (0.50 m) than in controls (0.91 m). Overall, this study provides field evidence that PF can be used to effectively reduce fire hazard without significant negative effects on soil chemical properties or on the short-term survival and sprouting of *E. globulus* stumps.

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Introduction

Southern Europe is characterized by fire-prone ecosystems (Moreira et al. 2011; Rodrigues et al. 2023). Climate change, due to higher temperatures, prolonged droughts, and altered precipitation patterns (Resco de Dios and Nolan 2021; Wasserman and Mueller 2023) as well as land use alterations, namely the decline of agricultural practices, abandonment of land and rural spaces, urbanization and afforestation (Moreira et al. 2011; Pausas and Fernández-Muñoz 2012) are expected to lead to an increase in the wildfire incidence and severity (Pausas and Fernández-Muñoz 2012; Russo et al. 2017; Turco et al. 2019; Ruffault et al. 2020; Benali et al. 2021; Rodrigues et al. 2023). The increasing frequency and intensity of wildfires has detrimental consequences to the environment, society and economy (Paveglio et al. 2016; Gao et al. 2023; Meier et al. 2023).

In this context, sustainable forest management is essential for maintaining healthy and productive ecosystems, reducing fire hazard, and ensuring the continued provision of forest resources (Siry et al. 2005; Corticeiro et al. 2023; Rangra and Xu 2024). One of the primary requisites of forest management in fire-prone regions is to reduce fuel hazard in forest plantations (Corona et al. 2015; Benali et al. 2021; Nocentini et al. 2022; Maia et al. 2024). Leaving harvest residues in place contributes to soil fertility and conservation, increasing soil surface filtration and water retention (Zhu et al. 2020). Nevertheless, high fuel loads specially if combined with a complex vertical forest structure increases the risk of upward and horizontal flame spread lead to intense and uncontrollable wildfires, causing severe environmental damage, including to soil conservation and fertility (Fernandes and Botelho 2003; Shakesby 2011; Caon et al. 2014; Ferreira et al. 2016) and human assets (Xanthopoulos et al. 2006; Pausas and Fernández-Muñoz 2012). Fuel-reduction and weed control treatments include mechanical thinning, pruning, understory mastication, application of chemicals and controlled grazing (Xanthopoulos et al. 2006; Masiero et al. 2015; Corticeiro et al. 2023). Among these techniques, prescribed fire (PF) stands out as an efficient and cost-effective method to reducing fuel loads, by diminishing the accumulation of leaf litter and downed dead woody fuels on the forest floor, and of understory vegetation, thus lowering the risk of uncontrollable and severe wildfires (Fernandes and Botelho 2003; Fernandes et al. 2013; Fernandes 2022; Fernández-Guisuraga and Fernandes 2024). PF involves the intentional ignition of vegetation under conditions conducive to meet specific management objectives (Fernandes

and Botelho 2003; Fernandes et al. 2013; Hmielowski et al. 2016; Fernández-Guisuraga and Fernandes 2024). When planned and implemented appropriately, PF can be used to manage large areas efficiently, with relatively few but specialized technicians (Hmielowski et al. 2016; Davim et al. 2022; Fernández-Guisuraga and Fernandes 2024).

Numerous studies have documented the benefits of PF in various forest ecosystems (Fernandes and Botelho 2003; Ascoli and Bovio 2013; Aponte et al. 2014; Hmielowski et al. 2016; Francos and Úbeda 2021; Fernández-Guisuraga and Fernandes 2024). In Mediterranean regions, PF has been successfully used to manage shrublands and pine forests, reducing fire hazards and maintaining ecosystem health (Fernandes et al. 2013; Fernández-Guisuraga and Fernandes 2024). However, the operational application of PF in Europe has been limited and predominantly focused on shrublands (Fernandes 2022).

Within plantation forestry, timber harvesting may increase dead fuel load by adding slash fuels and changing the local microclimate, exacerbating ignition potential and fire behavior (Berg 2003; Calviño-Cancela et al. 2016; Burton et al. 2022; Kulmann et al. 2023; González et al. 2023). In South Europe, where *Eucalyptus globulus* Labill. (blue gum) plantations constitute a significant proportion of forest cover and are subject to frequent harvesting due to their fast growth and economic value (Barreiro and Tomé 2012; ICNF 2019; Tomé et al. 2021). The large amounts of residual biomass after harvesting eucalypt plantations may thus be a fire-hazard concern (Mirra et al. 2017).

While PF is recognized as a viable post-harvest management tool for fuel reduction in blue gum plantations (Aponte et al. 2014; Davim et al. 2022; Fernández-Guisuraga and Fernandes 2024) there are still knowledge gaps regarding its immediate and short-term effects on soil chemical and physical properties, stump survival and coppice regrowth, especially under Mediterranean conditions. Previous studies determined the technical basis for prescribed fire in Portuguese blue gum stands, concerning fire behavior, fuel consumption and tree damage (Pinto et al. 2013; Davim et al. 2022) or post-wildfire regeneration and mortality (Catry et al. 2013), but comprehensive field studies on post-harvest prescribed fire in *E. globulus* plantations remain scarce.

This study investigates the viability of prescribed fire as a fuel management tool in post-harvest blue gum (*E. globulus*) plantations in Portugal. Specifically, the objectives of this work are (1) quantify the reduction in fuel loads from PF; and (2) assess its short-term effects on soil chemical and physical properties, stump survival and resprouting height. By addressing these objectives in two biogeographically contrasting sites, our work seeks to fill important gaps and inform best practices for sustainable blue gum plantation management in fire-prone Mediterranean landscape.

Materials and methods

Study area and experimental design

The two study areas were located in Portugal (Póvoa do Varzim—Minho and Amieira do Tejo—Alentejo), in the districts of Porto and Portalegre, respectively (Fig. 1). The Póvoa de Varzim has a Mediterranean Csb Köppen climate (Koppen and Geiger 1936), with an average annual temperature of 14.8 °C and average annual rainfall of 1092 mm, and the Nisa has a Mediterranean Csa Köppen climate, with an average annual temperature of 15.1 °C and an average annual rainfall of 1092 mm, based on actual data recorded by nearby automatic meteorological stations, for the period 1982–2021 (IPMA 2024).

According to specialized technical reports provided by the forest managers, prior to trials establishment revealed that in the northern location, Póvoa de Varzim, the soil

had little profile differentiation, was classified as *Skeletal Regosol* (Humic), derived from schist greywacke bedrock and silt texture whereas in Nisa. The southern location was identified as *Fluvic Arenosol* with clay schists and graywackes bedrock and silt sand textured. Póvoa de Varzim and Nisa presented soils with an AC horizon and a maximum depth of 60 cm. As expected for mediterranean soils, the stoniness of soils was high revealing in Póvoa de Varzim around 45%, slightly lower than the Nisa's 50%. Both regions exhibited weak soil structure and a humus-rich silty loam texture, indicating the presence of organic matter. Soil compaction was absent to weak in both areas (Table 1).

The selected *E. globulus* plantations were 11-year-old (Póvoa de Varzim) and 14-year-old (Nisa), first rotation stands, both harvested during January of 2023. The site preparation technique for the first rotation was ripping. Planting spacing was 2 m × 4 m, with an average of



Fig. 1 Map of the two study sites in north and central Portugal and their respective climate types, and maps delineating the respective forest management units and the sub-areas where the PF were and were not carried out

Table 1 Soil physical characteristics for the study areas of Póvoa de Varzim and Nisa

Characteristics		Póvoa de Varzim	Nisa
Typology		<i>Skeletal regosol</i> (Humic)	<i>Fluvic arenosol</i>
Parent material		Schists and graywackes and related rocks	Clay schists, graywackes, sandstones and rolled pebbles
Horizons		AC	AC
Depth		45 cm	60 cm
Stoniness		45%	50%
Structure		Weak	Weak
Compaction		Absent to weak	Absent to weak
Color		Brown	Light brown
Topsoil properties (0–2 cm)	Texture	Silty	Silty sand
Particle size distribution (< 2 mm)	Fine fraction (< 2 mm) (%)	45.7 ± 6.5	61.1 ± 6.7
	Sand fraction (%)	62.7 ± 3.2	85.9 ± 5.9
	Silt fraction (%)	20.1 ± 2.0	9.0 ± 1.5
	Clay fraction (%)	17.3 ± 2.0	5.1 ± 2.3

1250 ind ha⁻¹. No weed control operations were performed during the two years prior to harvesting.

Experimental design

In each study area, two plots of approximately 0.5 ha each were established: one control plot, where post-harvest slash was left undisturbed, and one prescribed fire (PF) treatment plot, where post-harvest slash was managed with prescribed fire. The PF was applied following harvesting, in the blue gum coppice plantation, according to established safety and operational guidelines. Fuel distribution after harvesting was homogenous (Fig. 2). The control and PF treatment plots

were comparable in terms of soil profile, aspect, topography, spacing and fuel distribution.

Within each plot, three parallel transects were established, each ranging from 25 to 40 m in length (depending on the site), and 1 m wide, positioned perpendicular to contour lines, and located in areas representative of the site characteristics and post-harvest slash deposition. In each plot, three parallel transects (25–40 m) were established, perpendicular to contour lines, on areas representative of the site characteristics and post-harvest slash deposition.

In each plot, a complete inventory was conducted to assess stump survival and the height of the tallest shoot or tree at monitoring intervals. Transects were used for detailed

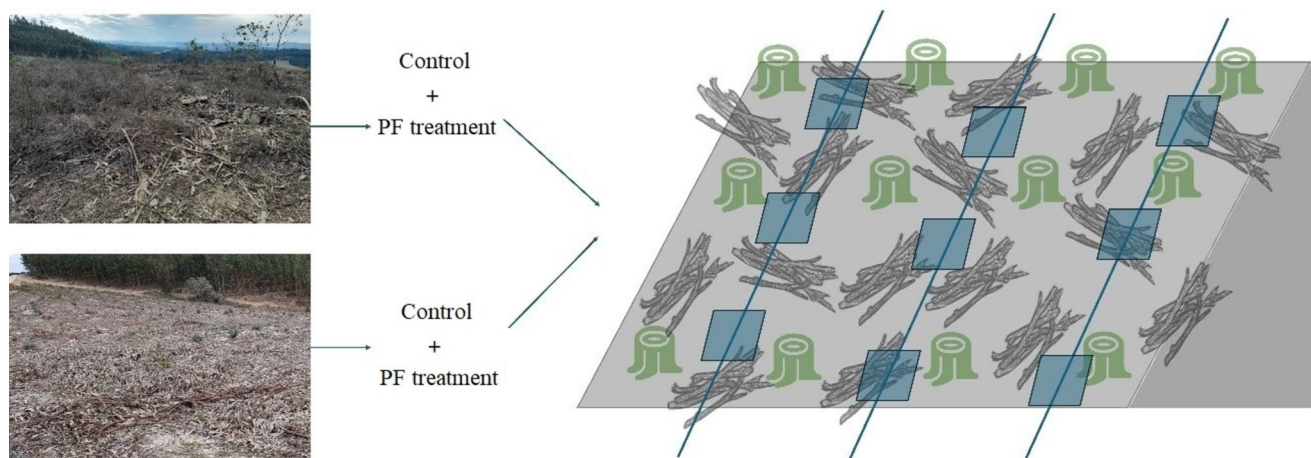


Fig. 2 Fuel distribution after harvesting in the two study areas: Póvoa de Varzim (left top) and Nisa (left bottom). Schematic representation of the experimental design in the control and PF treatment plots, in both study areas (right)

fuel and vegetation sampling both before and after the application of treatments.

Pre-prescribed fire slash, litter and soil moisture content

Prior to PF, samples of slash, litter and soil were collected in each plot (between transects) at both study sites for assessing moisture content, and therefore the initial conditions for PF. The moisture content was determined in the laboratory following the gravimetric method (Schunk et al. 2016). Five composite samples of fine and coarse fuels, five soil samples were randomly collected on each plot near the transects. Litter samples were gathered by carefully removing the litter layer (e.g., dead leaves) by hand. Samples of the mineral topsoil were collected at a depth of 0–2 cm at the same location as the litter sampling plots. All samples were placed into plastic hermetic bags and weighed promptly in the laboratory to obtain fresh weight. Samples were then oven-dried at 65 °C for 24 h and weighed again for dry weight. Water content was calculated as the difference between the fresh weight and the dry weight, and moisture content was computed as the water content per dry weight of each sample (slash, litter or soil) (Burton et al. 2022).

Canadian forest fire weather index system (FWI) and prescribed fire

To assess fire risk and potential fire behavior during PF, the Canadian Forest Fire Weather Index System (FWI) was used (Table 2) (Van Wagner 1987). This system integrates six indices: three describing fuel moisture conditions and three representing fire behavior potential. Interpretation thresholds followed Fernandes and Palheiro (2015).

The Fine Fuel Moisture Code (FFMC) estimates the ignition potential of fine surface fuels and correlates with the probability of fire spread. The Duff Moisture Code

(DMC) represents the moisture content of the duff layer and informs predictions on the depth of litter consumption. The Drought Code (DC) reflects moisture conditions in deeper organic layers and is relevant for assessing subsurface fire risk and mop-up requirements. The Initial Spread Index (ISI) combines FFMC and wind speed to estimate the initial rate of fire spread. The Buildup Index (BUI), calculated from DMC and DC, indicates the amount of available fuel and its influence on fire intensity and suppression difficulty. The final index, Fire Weather Index (FWI), integrates ISI and BUI to provide an overall indication of fire intensity, control difficulty, and potential ecological severity. It is the most appropriate indicator for public fire danger communication and operational decision-making (Van Wagner 1987).

The PF in Póvoa de Varzim was carried out by the Forest Association Portucalea in collaboration with forest hand-crews from Vila do Conde and the Volunteer Firefighter Department of Póvoa de Varzim on the 2nd of March of 2023 (Fig. 3). During the burning window, wind speed ranged from 0 to 0.8 m s⁻¹ (measured at the IPMA Vila Chã station), and air temperature varied between 5.3 and 13.6 °C (according to hourly data from the IPMA Barcelos station, the nearest station with temperature sensors). In Nisa, the PF was carried out by AFOCELCA fire-fighting hand-crews in collaboration with The Navigator Company on the 16th of March 2023 (Fig. 3). Meteorological observations from the nearby Abrantes station indicated that, during burning window, wind speed varied from 0 to 0.4 m s⁻¹, and hourly air temperature increased from 13 to a maximum of 19 °C. Both fires were conducted downslope, against the wind under low fire danger conditions as per the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987), in Póvoa de Varzim and Nisa, indicating similar fire prescription characteristics in both areas (Table 2).

Table 2 Estimated values and meaning for the Canadian forest fire weather index system on the PF days in Póvoa de Varzim and Nisa (Cease-fire; Government of Canada)

Canadian forest fire weather index system	Póvoa Varzim	Nisa	Interpretation (Fernandes and Palheiro 2015)
FWI (Fire weather index)	6.8	6.2	Low fire intensity
ISI (Initial spread index)	4.2	4.4	Moderately slow fire
BUI (Buildup index)	20.2	15.9	Most fine fuel is eliminated. Approximately half of the decomposing litter is consumed. The consumption of coarse dead fuel is substantial
FFMC (Fine fuel moisture code)	86.4	87.5	Moderate- to high-intensity fire is possible
DMC (Duff moisture code)	16.6	10.5	Duff moisture content is moderately high
DC (Drought code)	64.7	81.2	The potential for sub-surface or underground fire is minimal. The need for mop-up is limited to occasional hot spots at the fire edge



Fig. 3 Prescribed fire operations, conducted downslope and against the wind, performed at Póvoa de Varzim (top image) and at Nisa (bottom images)

Fire behavior

To assess fire behavior during PF, a series of metal stakes, each of sufficient length to remain visible above the fuel layer, were positioned within the experimental plots. These stakes were spaced 10 m apart, with parallel reference markers such as stones, lines or branches placed along a lateral path to facilitate identification and ensure alignment with the stakes. Fire behavior characteristics were measured during the burns: flame height, flame depth, flame angle and rate of fire spread (Pinto et al. 2013). Flame height was estimated visually by assessing the vertical distance, in meters, between the ground and the average tip of the flame. Observations were recorded at the start and end of each segment of the burn to ensure accurate representation. Flame depth, defined as the width of the combustion zone, was determined by measuring the horizontal distance from the front of the flame base upon reaching the initial stake to the rear of the flame at the final stake. To enhance precision, this measurement was repeated five times for each segment of the experimental area. The angle of the flame, relative to the vertical, was observed visually as the flame passed each stake, and its inclination was measured against a perpendicular to the terrain.

The rate of fire spread was calculated as the distance covered by the flame front between stakes divided by the time it took for the fire to propagate that distance, yielding a value in m min^{-1} . These primary measurements allowed for the subsequent derivation of key fire behavior metrics (Table 3). Flame length was determined by dividing the flame height by the cosine of the flame angle, providing a geometric estimate of flame extension. Residence time, or the duration of active combustion at a point, was calculated as the ratio of flame depth to the rate of fire spread.

Fireline intensity, representing the energy release rate per unit length of the flame front, was estimated employing a formula that relates flame length to intensity through a squared relationship. The second method applied Byram's equation, which is the product of rate of fire spread, fuel consumption per unit area, and the heat of combustion. For the latter, a constant of $18,000 \text{ kJ kg}^{-1}$ was used, a standard assumption in fire behavior studies. These calculations enabled a comprehensive characterization of fire

behavior within the experimental plots, adhering to established methodologies in wildfire research.

Soil burn severity

Soil burn severity (SBS) was visually assessed immediately after the fire in the burnt treatment, following Vega et al. (2013). The top-soil temperature during PF was recorded with thermocouples installed in the soil (2-cm depth). The thermocouple probes employed in this study were Type-K thermocouples (model KA02/RS PRO), determining instantaneous heating temperatures up to 450°C . The Type-K thermocouple probes were connected to EL-USB-TC/Lascar dataloggers. Three thermocouples were installed along each transect (one at the top, one in the middle, and one at the bottom), totaling nine thermocouples per plot. At each location, the dataloggers were individually placed in bags and buried, placing thermocouple probes just below the soil surface (2-cm depth). The HOBO dataloggers were programmed to detect temperature on a 5 min interval prior and during the PF with the software HOBO BoxCar Pro 4.3 (Onset Computer Corporation). For each location, the peak burning temperature was determined, as well as the duration of heating, determining the soil temperature prior, during and after PF (Coates et al. 2018).

The visual assessment of SBS was based on a 6-level system from no evidence of fire occurrence on soil surface or on forest floor, level 0, to being highly affected by fire, with the forest floor completely consumed (bare soil) and the soil structure altered, level 5 (Vega et al. 2013).

Fuel load and distribution

Slash height was determined by nondestructive point sampling at 1-m intervals along each transect (Fig. 2). At each sampling point, a measuring rod was inserted perpendicular to the ground and the type and height of the first (top) cover feature intersected by the rod was recorded plant (and species), slash fuel (coarse if $> 6 \text{ mm}$ or fine—leaves, bark or woody debris $< 6 \text{ mm}$). Along each transect, three sampling points were selected on representative patches, to collect all the aboveground biomass over an area of $50 \text{ cm} \times 50 \text{ cm}$ (Santana et al. 2016). The collected biomass was transported to the laboratory, where it was sorted by size class,

Table 3 Characteristics of fire behavior (average and range of variation) in the study locations and their classification

Fire behavior metrics	Flame height (m)	Flame length (m)	Rate of spread (m min^{-1})	Residence time (min)	Fine fuel consumption (kg m^{-2})	Fireline intensity, visual (kW m^{-1})
Póvoa Varzim	2.7 (1–4)	4.1 (1–7.6)	2.21 (1–4.29)	2.1 (0.9–3.7)	4.089	6326 (300–17394)
Nisa	0.9 (0.4–1.5)	1.4 (0.4–2.9)	1.15 (0.62–1.86)	2.3 (0.5–4.8)	2.806	821 (8–2446)

respectively fine and coarse (Burton et al. 2022). The fuel fractions were then oven-dried for 48 h at 65 °C, or until the weight stabilized, to obtain their dry weights. The fuel load of a plot was then computed as the sum of the dry weights of the fine and coarse fractions per m². Fuels were assessed on the day before burning and 45 to 60 d after PF in Póvoa de Varzim and Nisa, respectively.

Soil chemical and physical analysis

The day before the PF operation, 45 (Póvoa de Varzim) and 60 (Nisa) d after the PF, soil samples were collected in 25 cm side squares for chemical and physical analysis and with 233 cm³ diameter soil rings for soil bulk density. Soil samples were collected at the depth of 0–2 cm, to obtain the most superficial topsoil, most likely to be affected by the fire (Badía et al. 2014; Zavala et al. 2014). Soil bulk density was calculated as the ratio between the soil dry weight and the volume of the core soil sample after oven drying the soil in the laboratory at 65° ± 5 for 48 h (Santana et al. 2016). After weighing the dried samples, they were sieved at 2-mm to separate gravels, charcoal particles and the larger roots from the finer sediments (Santana et al. 2016). Soil samples were also analyzed for: (i) soil particle size assessment following Gee and Or method (Gee and Or 2002), and (ii) physico-chemical elements: pH (ISO 10390:2005), extractable phosphorus (Egner-Rhiem method), exchangeable cations (Ammonium acetate method), micronutrients—Mn, Fe, Zn (ISO 14870: 2001- ICP-OES) and organic matter content (ISO 10694: 1995).

Blue gum stump survival and sprouts height

Post-fire vegetative response in terms of survival and height of the sprouts was assessed for all stumps included within the area delineated by the outer transects (Fig. 2). More specifically, survival was determined as the presence of live sprouts, while height was assessed as the vertical length of the tallest living sprout of each stump 45 to 60 d after PF.

Data analysis

The “runs test above and below the median” and, for the critical values at $\alpha = 0.05$, Sokal and Rohlf (1981) was used to test the independence of the tree height, biomass and soil data collected along the transects at both study sites in each study area prior to the prescribed burning. This involved ordering the data following the number of the site and, within each site, the number of the transect and, within each transect, the number of the transect point. Whenever the resulting series of values differed in a statically significant manner from a random sequence, the average values of the transects were considered as the individual values and

used in further data analysis. Such lack of independence was detected in only three cases, i.e.: (i) litter biomass at the Póvoa de Varzim site (runs = 3; ≤ 5 critical runs ≥ 15); (ii) Manganese at the Póvoa de Varzim site (runs = 5; ≤ 5 critical runs ≥ 15); (iii) exchangeable Na+ at the Nisa site (runs = 2; ≤ 3 critical runs ≥ 11). In four further cases, however, the test could not be applied, as there were too few runs or, on other words too many values that were equal to the median and, ultimately, too little variability among the measurements. All four cases concerned soil data, three at the Nisa site (Total Nitrogen, Zinc and Copper) and one at the Póvoa de Varzim site (Boron). Also in these four cases, the average values of the transects were used in further data analysis, as also evidenced by the respective numbers of observations.

The Shapiro–Wilk test was used to assess the normality of the data for each variable and treatment group. Non-parametric tests were chosen when the sample size was too small and/or the distribution of the data did not meet the assumptions for the student's *t*-test or the ANOVA, including normality and homogeneity of variances. The Kruskal–Wallis test was applied to compare moisture content among different sample types (slash, litter, soil) within each site. The Mann–Whitney *U* test was used to compare moisture content between sites for each sample type and to compare the fine and coarse fractions between the Control and Burnt treatments within each location (Póvoa de Varzim and Nisa) and for the same treatment between different locations (Póvoa de Varzim vs. Nisa). In relation to sprout growth, an independent two-sample *t*-test was performed to determine if there was a statistically significant difference in the mean plant heights between the control and PF treatment. Except for the soil results, all statistical analyses were performed using the software R version 4.3.1, particularly the packages *dplyr*, *ggplot2*, *car*, *ggpubr* and *rstatix*. Soil results statistical analyses were performed using Statistica, TIBCO software Inc. (Santa Clara, CA, USA), version 13.5.0.17. To check the significance of the results ($p \leq 0.05$) the Tukey test (HSD) or Mann–Whitney *U* Test were applied, according to the normality of the data.

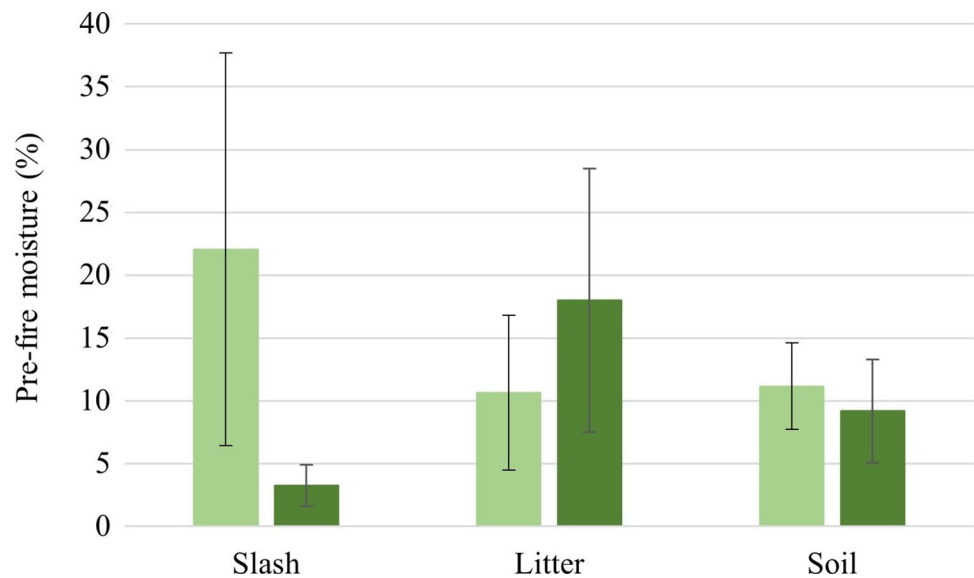
Results

Pre-fire moisture contents of slash, litter and topsoil

In Póvoa de Varzim, moisture contents of slash fuel leaf litter and soil were not statistically different. The slash fuel had the highest average moisture content ($22.0\% \pm 15.6\%$), while the soil and litter had lower average moisture contents ($11.2\% \pm 3.4\%$ and $10.7\% \pm 6.2\%$, respectively) (Fig. 4).

In Nisa, the moisture content was not significantly different between components but showed a tendency to be

Fig. 4 Average moisture content in slash, litter and soil samples collected immediately prior to burning in Póvoa de Varzim (light green) and in Nisa (dark green). No statistical differences were detected between samples for the same study area, and between areas for the same component (slash, soil and litter, $p \leq 0.05$)



higher in the litter layer with $18.0\% \pm 10.5\%$, followed by the soil with a mean moisture content of $9.2\% \pm 4.1\%$, and the biomass presented the lowest average moisture value of $3.3\% \pm 1.6\%$ ($p = 5.804$; $p\text{-value} \leq 0.05$) (Fig. 4).

Effect of prescribed fire on fuel load and distribution

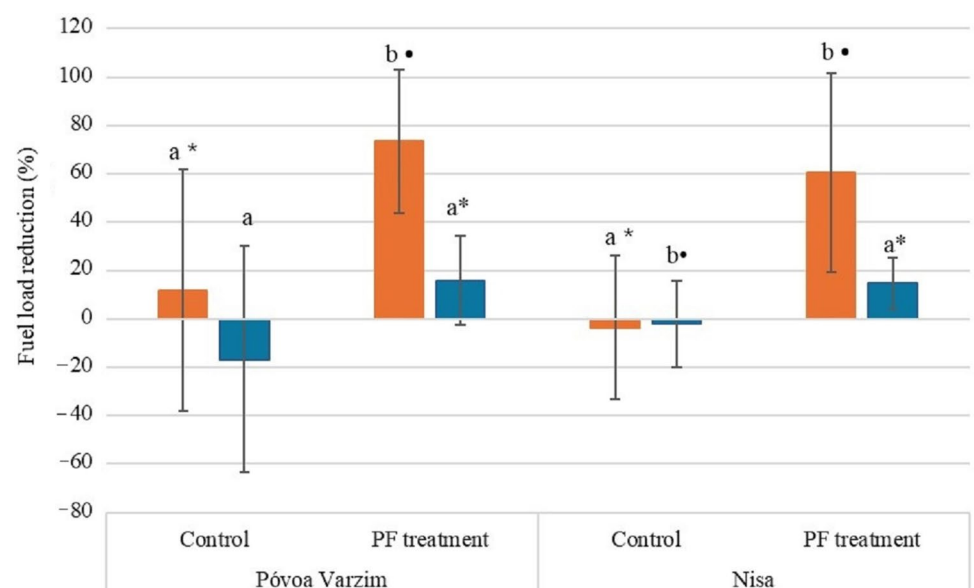
Fine fuel decreased between pre-fire and 45 to 60 d after PF averaged 11.8% in the control plot, while in the PF treatment plots the fine fuels load was 73.5% lower in the second sampling period (after PF). In Nisa, the fine load variation followed the same tendency. The reduction in fine fuel load was significantly higher in the PF treatment (60.3%) than in the control (-3.7%) (Fig. 5).

The variation in coarse biomass was not statistically different between treatments in Póvoa do Varzim ($U = 22.0$, $p\text{-value} \geq 0.05$) (Fig. 5). However, in Nisa, the reduction in coarse biomass load was significantly higher in the PF treatment ($14.56\% \pm 10.58\%$) than in the control ($-2.00\% \pm 17.96\%$; $U = 39.0$; $p\text{-value} \leq 0.05$) (Fig. 5).

Soil burn severity and effect on soil fertility

The maximum soil temperature at 2-cm depth during the fire reached 117.5°C in Póvoa de Varzim, and 107.5°C in the Nisa. Most temperature records above 100°C had a residence time of 5 s except for the temperature range

Fig. 5 Reduction of fine (orange) and coarse (blue) slash verified 45 and 60 d after the fire in the study areas of Póvoa de Varzim and Nisa, respectively



102–116.5 °C that had a longer residence time of 15 s during the PF of Póvoa de Varzim (Table 4).

As for the visual assessment immediately after the fire, mineral soil was not exposed and the lower duff was partially to totally intact, which corresponds to class 1 of soil burn severity (Vega et al. 2013).

Soil bulk density measured in the initial monitoring in each treatment by study area revealed no significant differences between treatments within each study area. However, differences were found between study areas being higher in Nisa (T0—1.22 g cm⁻³, T1—1.28 g cm⁻³) than in Póvoa de Varzim (T0—0.76 g cm⁻³, T1—0.83 g cm⁻³).

For the control and PF treatment in Póvoa de Varzim, the variations in pH between pre-fire and 45 d after the fire were similar, increasing from 4.0 in pre-fire (both treatments) to 5.1 and 5.0 in control and PF treatment, respectively. In Nisa, pH values pre-fire and 60 d after the fire were higher, with treatments presenting different tendencies: in control, no variation in pH was observed between the 45 d

monitoring period, being 5.7. In the PF treatment there was an increase in pH from 5.7 (pre-fire) to 7.1, in the post-fire monitoring (Fig. 6).

Regarding organic matter (OM), no significant differences were found between treatments in both areas (Fig. 7). The study area of Póvoa de Varzim had higher OM in the topsoil than Nisa. In Póvoa, OM decreased in both treatments between the pre-fire and post-fire monitoring, from 21.9 to 15.6% in the control and from 18.1 to 15.8% in the PF treatment. In Nisa, the OM content was around 4% in both treatments with no differences between initial sampling and soil sampling after 60 d.

The P concentration was significantly higher in topsoil after PF in both areas than those of initial monitoring or control without residues removal (Table 5). The exchangeable cations Ca, Mg and K were increased by PF in Nisa while in Póvoa only an increment in Ca was recorded. Regarding soil microelements, a significant increment in Mn concentration was revealed in Póvoa after PF.

Table 4 Maximum temperatures and temperatures above 100 °C and their residence time recorded by the thermocouples during prescribed fire in Póvoa de Varzim and Nisa

Study area	Maximum temperature recorded by device (°C)	Records of temperature higher than 100 °C (°C)	Residence time of the temperatures higher than 100 °C (s)
Póvoa de varzim	41–117.5	100.5	5
		106.5	5
		102–116.5	15
		117.5	5
Nisa	63.5–107.5	107.5	5

Fig. 6 pH values in control (in green) and PF treatment (in orange), prior to and 45 and 60 d after the fire in the study areas of Póvoa de Varzim (left) and Nisa (right), respectively. Different letters present statistical differences within each treatment before and after trial implementation ($p \leq 0.05$)

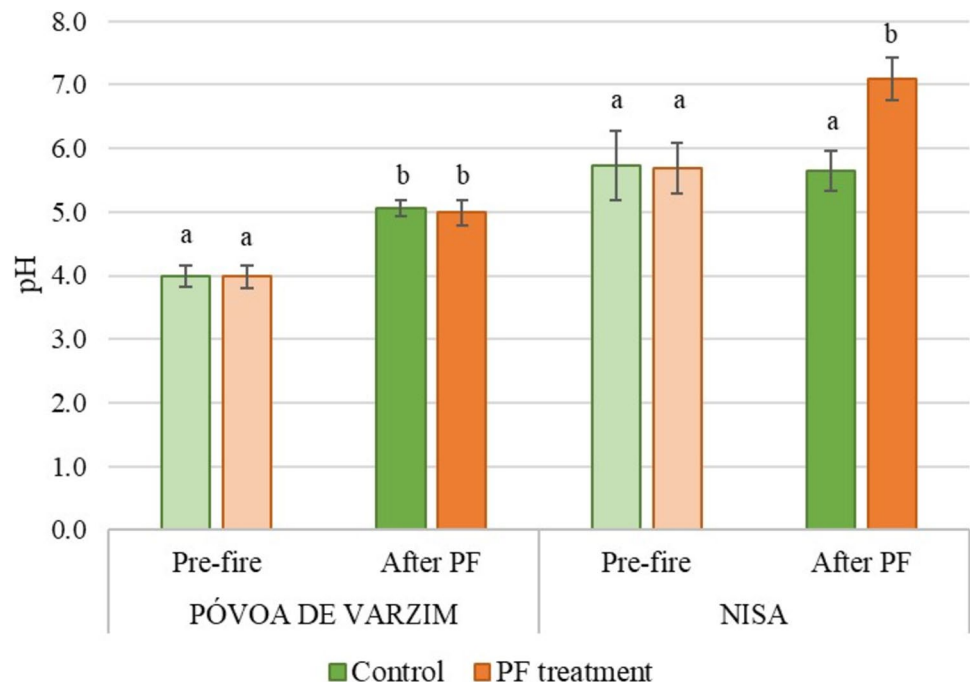
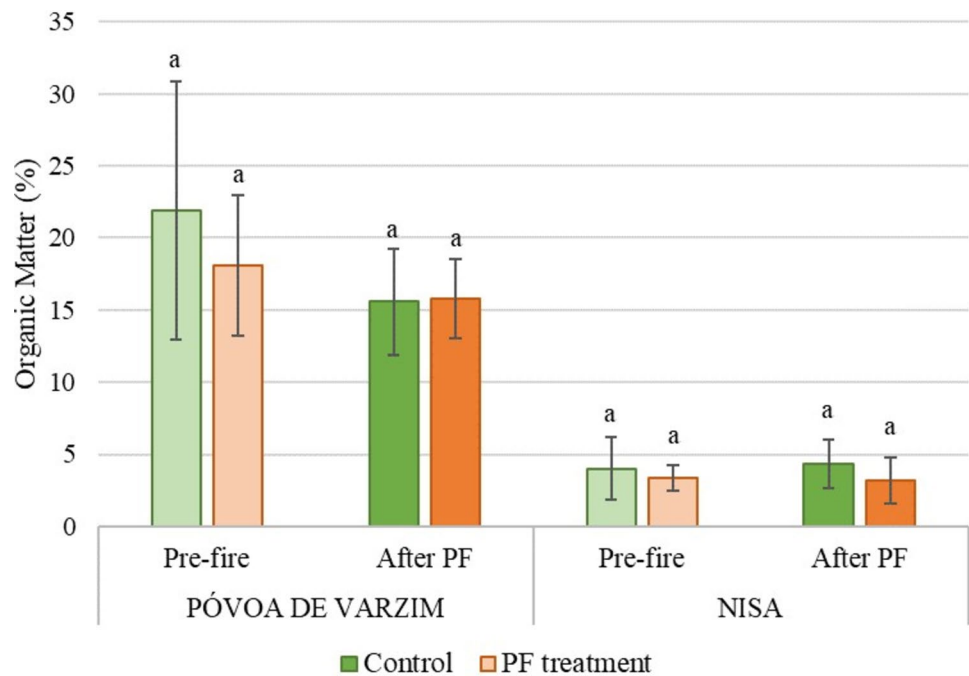


Fig. 7 Organic matter values obtained from soil samples (0–2 cm depth) in control (green) and PF treatment (orange) prior to and 45 and 60 d after the fire in the study areas of Póvoa de Varzim (left) and Nisa (right), respectively. Different letters present statistical differences within each treatment before and after trial implementation ($p \leq 0.05$)



Impact of prescribed fire in stump survival and sprouts height

Stump survival in Póvoa de Varzim was higher in the PF than in the control plot, while in Nisa, the survival rate of both treatments was very similar both treatments (Table 6).

In Póvoa de Varzim, the height of the shoots was 0.37 ± 0.24 m and 0.37 ± 0.23 m in PF treatment and control, respectively. No significant differences were detected between the two treatments ($t = -0.60$, $p \leq 0.05$, $df = 244$). Significant differences were observed between treatments in Nisa ($t = -4.91$, $p \geq 0.05$, $df = 337$). The average height of the shoots was 0.91 ± 0.29 m in the control and 0.50 ± 0.15 m in the PF treatment (Fig. 8).

Discussion

PF effectively decreased blue gum slash fuel with minimal impact on soil and no negative effect on tree regeneration and sprouting height in the short term. These findings are particularly relevant for regions where blue gum is one of the most relevant planted forest species (ICNF 2019) and wildfire hazard reduction is a significant concern (Corona et al. 2015; Meier et al. 2023). By substantially reducing fuel loads, PF helps to lower the intensity and spread of potential wildfires, thus protecting both forest ecosystems and local communities (Fernandes and Botelho 2003; Clode and Elgar 2014; Fernandes 2015).

Moisture content

The meteorological and fuel moisture conditions recorded during our prescribed fires indicate that both burns were conducted under low-intensity fire regimes. Air temperatures during PF were relatively low, ranging from 5.3 to 13.6 °C at Póvoa de Varzim and from 13 to 19 °C at Nisa. Wind speeds were also minimal ($0\text{--}0.8$ m s⁻¹ and $0\text{--}0.4$ m s⁻¹, respectively), and the Canadian Forest Fire Weather Index (FWI) values confirmed low fire danger at both sites. Furthermore, measurements of soil, litter and slash moisture contents taken before ignition showed elevated moisture levels, which are known to limit fire intensity and spread. The results aligned with previous findings that demonstrated that when conducted under specific climate and moisture conditions (Fernandes et al. 2013; Pinto et al. 2013), PFs are typically of low intensity, propagating through litter, woody debris and understory vegetation (Fernandes and Botelho 2003; Fernandes et al. 2013). When moisture levels in biomass, litter and soil are too low, the fire may become more intense, increasing the likelihood of tree mortality or soil damage (Pinto et al. 2013; Francos and Úbeda 2021). On the other hand, when moisture levels are excessive, the fire may not burn effectively, failing to succeed in reducing fuel hazard or accomplish other management purposes (Burrows and McCaw 2013; Fernandes et al. 2013; Francos and Úbeda 2021). Soil moisture has a major role in reducing the consequences of fire by preventing soil heating, therefore preserving soil microbial communities, and sustaining nutrient cycling (Pérez-Valera et al. 2019). Moisture in

Table 5 Soil fertility indicators obtained through chemical analysis of soil samples (0–2 cm depth) in both sites, under Control and PF treatments, at two sampling times: pre-fire and 45 and 60 d after the fire (post-PF), in Póvoa de Varzim and Nisa, respectively

Element	Exchangeable cations (cmol ⁺ kg ⁻¹)								Extractable phosphorus (mg kg ⁻¹)							
	Ca ²⁺				Mg ²⁺		K ⁺		Na ⁺		P					
	Pre-fire	Post-PF	Pre-fire	Post-PF	Pre-fire	Post-PF	Pre-fire	Post-PF	Pre-fire	Post-PF						
Sampling time	Site	Póvoa de Varzim	Control	0.13 ± 0.06 ^a	0.11 ± 0.07 ^a	0.44 ± 0.33 ^a	0.22 ± 0.11 ^a	0.23 ± 0.13 ^a	0.12 ± 0.03 ^b	0.31 ± 0.17 ^a	0.35 ± 0.26 ^a	7.17 ± 3.64 ^a	6.89 ± 1.54 ^a			
			PF treatment	0.07 ± 0.04 ^b	0.23 ± 0.27 ^a	0.21 ± 0.18 ^a	0.27 ± 0.25 ^a	0.16 ± 0.04 ^a	0.14 ± 0.05 ^a	0.22 ± 0.1 ^a	0.25 ± 0.08 ^a	4.50 ± 1.79 ^b	9.78 ± 4.47 ^a			
	Nisa	Control	1.48 ± 0.98 ^a	1.36 ± 0.72 ^a	0.50 ± 0.28 ^a	0.43 ± 0.2 ^a	0.21 ± 0.06 ^a	0.22 ± 0.07 ^a	0.05 ± 0.03 ^a	0.04 ± 0.02 ^a	12.33 ± 5.02 ^a	10.28 ± 3.18 ^a				
			PF treatment	1.59 ± 0.65 ^b	4.75 ± 2.6 ^a	0.57 ± 0.15 ^b	1.09 ± 0.46 ^a	0.22 ± 0.04 ^b	0.32 ± 0.05 ^a	0.04 ± 0.02 ^a	0.03 ± 0.01 ^a	10.22 ± 1.64 ^b	32.44 ± 11.07 ^a			
Element	Micronutrients (mg kg ⁻¹)															
	Zn				Cu				Mn				Fe			
	Pre-fire		Post-PF		Pre-fire		Post-PF		Pre-fire		Post-PF		Pre-fire		Post-PF	
Sampling time	Site	Póvoa de Varzim	Control	3.76 ± 2.6 ^a	2.80 ± 1.97 ^a	1.43 ± 0.4 ^a	1.38 ± 0.22 ^a	5.47 ± 2.44 ^a	4.49 ± 2.47 ^a	617.78 ± 189.92 ^a	516.25 ± 164.22 ^a					
			PF treatment	2.13 ± 1.52 ^a	2.54 ± 1.71 ^a	1.11 ± 0.15 ^a	2.40 ± 3.08 ^a	2.80 ± 0.95 ^b	7.71 ± 6.76 ^a	604.44 ± 292.92 ^a	586.25 ± 292.92 ^a					
	Nisa	Control	0.32 ± 0.22 ^a	0.32 ± 0.18 ^a	0.18 ± 0.09 ^a	0.13 ± 0.03 ^a	32.59 ± 21.5 ^a	43.94 ± 33.85 ^a	66.11 ± 29.27 ^b	105.67 ± 37.05 ^a						
			PF treatment	0.25 ± 0 ^a	0.46 ± 0.44 ^a	0.17 ± 0.07 ^a	0.15 ± 0.09 ^a	97.78 ± 83.85 ^a	95.44 ± 97.39 ^a	75.78 ± 27.46 ^a	44.67 ± 18.06 ^b					

Different letters signal statistical differences within each treatment before and after trial implementation by study area ($p \leq 0.05$)

Table 6 Blue gum stump survival in coppice in control and burnt treatments 1.5 to 2 months post PF in the study areas of Póvoa de Varzim and Nisa

Study area	Treatment	Resprouting stumps (% 1.5–2 months after fire)
Póvoa de Varzim	Control	74
	PF treatment	89
Nisa	Control	87
	PF treatment	89

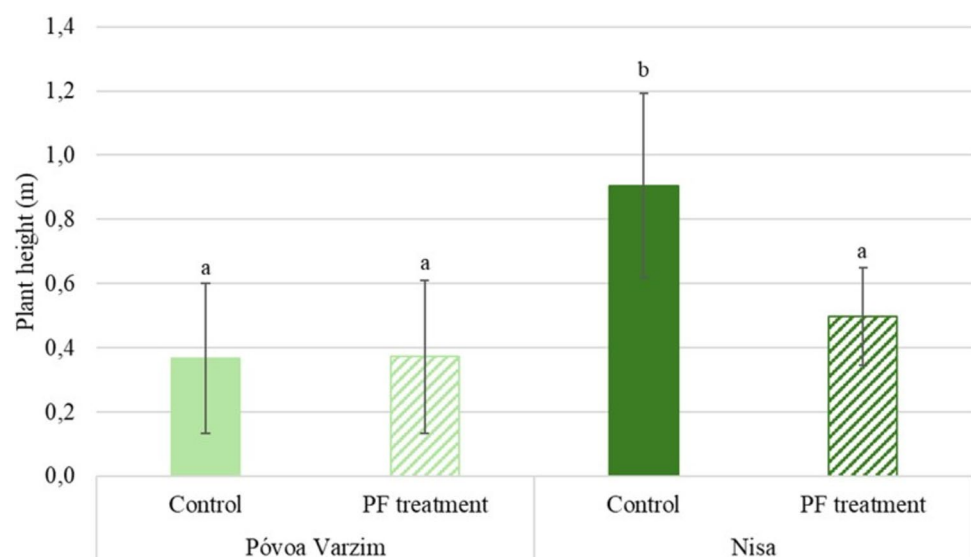
biomass and litter prevents full combustion, protecting soil organic layers and reducing nutrient volatilization, which in turn decreases fire intensity and spread (Fernandes 2009; Pinto et al. 2013). The mean moisture levels in soil, litter and biomass determined at both areas in this study were not higher than 22%. According to Pinto et al. (2013), when moisture content of blue gum litter is lower than 30%, the probability of sustained fire spread is more than 97%. This aligns with the FPMC values recorded on the PF days, which were 86.4 in Póvoa de Varzim and 87.5 in Nisa. Some variation was noted, however, due to local-scale factors such as altitude, exposure and slope, which are not captured by the spatial scale of fire weather indices (Van Wagner 1987). PF environmental and ecological effects do not depend exclusively on weather and moisture conditions, but on a complex interaction of these with other factors such as the method of fire ignition, fuel type and load and the topography (Bonner et al. 2021).

Soil burn severity

Soil temperatures recorded during PF exceeded 100 °C in both areas, Póvoa de Varzim and Nisa. In Póvoa de Varzim,

maximum temperatures varied in a narrow range, from 100.5 to 117.5 °C, with the residence times above 100 °C lasting predominantly 5 s. Nisa recorded a peak temperature of 107.5 °C with a 5-s residence time. Temperatures above 100 °C can disrupt soil properties, impacting microbial communities and seed banks, but the extent of these impacts is moderated by factors such as exposure duration, soil moisture and depth of thermal penetration (del Cacho et al. 2012; Zavala et al. 2014; Barreiro et al. 2020; Menges et al. 2021). However, our results demonstrated that in both areas the short residence times likely limited heat impact to surface layers, reducing potential ecological impacts. These findings indicate that the PF operations were generically consistent with good practices and under adequate meteorological and environmental conditions, achieving surface fuel reduction with limited adverse effects on soil related to increasing heat loads (Fernandes 2015).

Fireline intensity and soil heating can be decoupled, namely under PF conditions (Hartford and Frandsen 1992; Stoof et al. 2013). Hence, the observed fire behavior and measured temperatures only hint at potential soil damage. Conversely, soil burn severity is a good indicator of the effectiveness of PF as a sustainable management tool (Fernandes and Botelho 2003; Fernandes et al. 2013; Francos and Úbeda 2021). High soil burn severity indicates potential soil degradation, loss of organic matter, and negative impacts on post-fire recovery (Varela et al. 2015). In the current study, soil burn severity was low, since PF did not affect the mineral soil and the lower duff was partially or totally intact, which corresponds to class 1 of soil burn severity (Vega et al. 2013). These results align with the findings of several authors (Fernandes and Botelho 2003; Burrows and McCaw 2013; Fernandes et al. 2013; Meira Castro et al. 2015; Meira Castro and Meixedo 2017), that

Fig. 8 Mean maximum height (m) of the new blue gum shoots in coppice on the Control and PF treatments, 45 and 60 d after the PF at Póvoa de Varzim and Nisa, respectively. Different letters present statistical differences within each treatment before and after trial implementation ($p \leq 0.05$)

PF, when operated in suitable conditions, minimally disturbs the mineral soil layer.

Effect of prescribed fire on fuel load and distribution

A major indicator of PF effectiveness in hazard mitigation is fuel load reduction (Fernandes and Botelho 2003; Knapp et al. 2005; Mirra et al. 2017). The bulk of the fuels affected by PF are fine fuels (diameter < 6 mm), which control the behavior of the flaming fire front, including its rate of spread and flame size (Fernandes and Botelho 2003). Fine fuels are mostly responsible for allowing flames to spread vertically into the forest canopy, acting as a source of firebrands, which can spread spot fires ahead of the flame front (Fernandes and Loureiro 2013; Burton et al. 2022). As such, some harvested patches in temperate eucalypt forests are burned periodically (5 to 10 years) for the purpose of reducing fuel (Burrows and McCaw 2013; Burton et al. 2022).

While fuel consumption in surface fires is highly variable (Fernandes and Loureiro 2013), wildfires can consume all the existing biomass, whereas fuel consumption in PF should obey to burn objectives. This often calls for solely eliminating the hazardous fuel components, leading to substantial residual biomass, e.g. 35% to 40% (Hmielowski et al. 2016). The values are in line with our findings, where PF led to a fuel reduction of 74%, in the specific case of fine fuels in Póvoa de Varzim. PF in the present study aligns with previous research (Penman and York 2010), who highlighted the function of PF in reducing fuel accumulation and potentially modifying fire behavior. In relation to coarse biomass, no significant changes were found between treatments. The impact of PF is often more pronounced in fine biomass (Fernandes and Botelho 2003), which contrasts with results that found substantial reductions in coarse fuel following late season PF (Knapp et al. 2005). These discrepancies highlight the complexity of fire-fuel interactions and the influence of weather and local conditions on PF effects.

Effect on soil fertility

As in several other studies, the results of soil analyses showed that PF mobilizes elements important for plant nutrition and if well timed it can be a relevant source for plants to uptake nutrients at the start of growing season (Butnor et al. 2020). For instance, Ca and Mg that increased after PF probably derive from eucalypt biomass, particularly bark, that has a noticeable concentration in these elements.

Also, these are elements important to the forest plantation being, after PF, available for plant absorption at root system. It is known that elemental nutrients lost by volatilization are specific and temperature-dependent (DeBano 1991), Ca and Mg are resistant to volatilization, N can be volatile in temperatures between 200 to 375 °C (Hosking 1938), whereas

P and K are less sensitive than N (Raison et al. 1985). As in previous studies, a significant increase of P in topsoil after PF was recorded in both study areas, probably from the combustion of the harvest residues that were conducive to mineralize and release the inorganic P (Ferreira et al. 2016). Soil pH increased after PF because of the liming effect of biomass ash and Ca release which may influence the availability of some microelements particularly in acidic soils. It would be interesting to follow up the results for a longer time and compare interannual climate conditions to evaluate whether this response is ephemeral or extended in time.

Impact of prescribed fire in stump survival and sprouts height

The survival of eucalypt stumps in coppice systems after PF largely depends on the intensity and timing of the burn. Moderate intensity fires, which consume surface fuels and lightly scorch the lower canopy, tend to have minimal negative impacts on the survival of eucalyptus shoots. These conditions can even be beneficial, as the removal of competing vegetation and litter reduction can enhance light penetration and nutrient availability, thereby promoting the vigorous growth of new shoots (Watson et al. 2020; Burton et al. 2022). Moreover, the heat from the fire can stimulate the resprouting of new shoots from the lignotuber, a structure that provides a reserve of buds and carbohydrates, facilitating rapid recovery and growth after the disturbance (Whitlock et al. 2003; Clarke et al. 2013; Calviño-Cancela et al. 2018).

In relation to the impact of PF on blue gum in this study, PF did not negatively affect the survival of stumps, revealing a positive impact at Póvoa de Varzim trial. The short-term impact of PF on new shoots growth was less evident, as stumps from control treatments began to sprout earlier than those from PF treatments, as harvesting operations in Póvoa de Varzim and Nisa took place two months before PF. At the time of PF some stumps, particularly in Nisa, already showed evidence of new shoots, which were burned during the prescribed fire. As a result, only after the fire did the stumps from the PF treatment begin to resprout again, experiencing approximately a two-month delay compared to the control treatment in the same site. This suggests that, apart from differences in sprouting timing and the developmental stage of the buds, also the timing of the PF may have influenced growth responses, especially in Nisa.

Eucalyptus species are known for their fire resilience, often demonstrating vigorous regrowth post-burn due to their adaptation to fire (Catry et al. 2013). However, high-intensity fires can damage the cambium layer of the shoots and the lignotuber itself, potentially leading to increased mortality rates and reduced vigor in surviving shoots (Bär et al. 2019). This is particularly relevant in younger coppice

systems, where the lignotuber is less developed and more vulnerable to heat damage (Whittock et al. 2003; Clarke et al. 2013). Post-fire growth in eucalyptus coppice systems can also be influenced by changes in soil conditions induced by the fire (Alcañiz et al. 2018; Santín et al. 2018). Our findings demonstrated that PF can alter soil pH, increase nutrient availability through the release of minerals from ash, and reduce soil compaction, all of which can contribute to improved growth conditions for eucalyptus shoots (PF).

In a European context, the study supports the European Forest Strategy's emphasis on preventive wildfire management (European Commission 2018). PF has been used in several parts of Europe to manage forest fuel loads and reduce fire risk (Fernandes et al. 2013; Piqué and Domènech 2018). In the pine forests of Portugal and Spain, PF has been successfully used to manage underbrush and reduce fire hazards, demonstrating the broader applicability and effectiveness of such practices in different forest types and climates (Piqué and Domènech 2018). The findings of this study showed that PF had minimal impact on soil properties align with the EU Soil Thematic Strategy's goals of soil conservation. The preservation of soil organic and mineral layers post-fire suggests that PF, when properly managed, does not contribute to soil degradation, thereby supporting the sustainability of soil resources. This is crucial for maintaining the long-term productivity of eucalyptus plantations and the broader ecosystem services they provide, such as carbon sequestration and water regulation (Brockerhoff et al. 2013; Behera et al. 2020).

Overall, the results of the present work contribute to validate the use of PF as a management tool in post-harvesting eucalypt plantations. The analysis of the impacts of PF impacts on fuel load reduction, soil properties, and eucalypt survival and growth in coppice demonstrates its effectiveness and minimal adverse effects, thus reinforcing its role as a sustainable forest management practice. The Portuguese National Forest Programs (NFPs) prioritize wildfire risk management and the sustainable management of forest resources. The demonstrated benefits of PF in reducing fire hazards and promoting ecosystem resilience validate its continued use in post-harvest scenarios, aligning with national priorities and providing a practical tool to forest managers. This validation is also particularly relevant within the framework of European forest-related policies, such as the European Forest Strategy 2030 (European Commission 2018), which emphasizes sustainable forest management and wildfire risk reduction. The findings support the strategy's objectives by showing that PF effectively reduces fuel loads, a major factor to wildfire management in regions like Southern Europe where climate exacerbates fire hazards. The study also aligns with the EU Soil Thematic Strategy by demonstrating that PF does not significantly impact soil health, preserving the organic and mineral layers of the soil.

The study underscores the importance of continuous monitoring to evaluate the medium to long-term effects of PF on soil properties and the productivity of eucalyptus coppice. This monitoring is crucial for ensuring that PF remains a beneficial practice, as it allows for the adaptation of techniques and policies in response to observed outcomes. The long-term ecological and economic impacts of prescribed fire (PF), including its effects on soil health, biodiversity, and forest carbon dynamics, remains to be better investigated. This knowledge is crucial to ensure that PF not only effectively reduces wildfire risks but also promotes sustainable forest management and conservation. Additionally, understanding the social acceptance and economic viability of PF, along with adapting policies to account for climate change, is essential for integrating PF into broader forest management strategies and ensuring its responsible and beneficial use.

Conclusion

Main findings

This study demonstrates that prescribed fire (PF), when applied under controlled conditions in post-harvest *E. globulus* stands, can be a highly effective tool for fuel management with minimal ecological disruption. Specifically, PF achieved substantial reductions in fine fuel loads, significantly lowering fuel hazard. Despite these reductions, PF caused only minimal soil heating, resulting in low soil burn severity that preserved organic matter content and avoided soil degradation. PF led to immediate improvements in soil chemical properties, including increases in pH, extractable phosphorus, and exchangeable base cations (especially calcium and magnesium). Stump survival and resprouting rates remained high, confirming that PF did not negatively affect the coppicing capacity of the species, although a reduction in sprout height was observed in one site.

Interpretation and implications

These findings provide field-based evidence from two distinct biogeographic regions in Portugal, validating PF as a viable post-harvest management practice in blue gum plantations. The study demonstrates that PF can simultaneously achieve fire risk mitigation and promote soil fertility without compromising tree regeneration. The observed changes in soil properties suggest enhanced nutrient availability that could benefit initial vegetation growth, but the reduction in sprout height at one site highlights the importance of local conditions and fire timing for optimizing regeneration.

Limitations and future research

However, it is relevant to note that these results are based on short-term observations (45–60 d post-fire) at a very limited number of sites (two), not reflecting the longer-term or broader-scale ecological responses, including those affected by climatic variation. Overall, these results support the responsible integration of prescribed fire into fuel reduction protocols for eucalyptus plantations, particularly in fire-prone Mediterranean landscapes. Further research should include long-term monitoring and expanded replication to fully assess the sustainability and generalizability of this practice.

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