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How Weed Control Affects *Eucalyptus globulus* Labill. Productivity: Results from Two Long-Term Trials

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Abstract: Weed control is considered a critical management operation for the establishment and growth of *Eucalyptus globulus* and is often performed during the first two years following planting. However, no information has been found related to the effects of weed management on the long-term growth of *E. globulus*. This study aims to better understand how adjusting the timing of weed control, beyond tree establishment, affects the productivity of eucalypts on two commercial plantations in Central Portugal. Two treatments were considered: weed control when vegetation cover occupied at least 50% of the area with a mean height of at least 50 cm, and no weed control. At the northernmost site, weed control operations were performed during the first 3 years following planting. At the southernmost site, weed control interventions occurred between 1.5 and 8.2 years. Weed control demonstrated to be effective at diminishing vegetation cover density to a maximum of 79% and 94% in the northmost and southmost sites, respectively. Weed control significantly increased *E. globulus* productivity by the end of the study, demonstrating that the timing of weed management must be adjusted in accordance with the understory competing vegetation cover (weeds) and during the entire rotation, not only during tree establishment.

Keywords: forest management; understory vegetation; wood production; tree growth

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1. Introduction

Eucalyptus globulus Labill. is a highly relevant forest species widely planted around the world, providing raw material for the pulp and paper industry because of its rapid growth and high cellulose production [1–6]. *E. globulus* plantations in Portugal account for 26% of the total forest area, occupying 812,000 ha in 2015, with a mean productivity of 10 m^3 ha^{-1} yr^{-1} [7].

Considerable efforts have been made to increase the productivity of *E. globulus* plantations and, thereby, provide guarantees for economic rentability [6]. In general, productivity is a crucial topic in forest management [8]. It is of particular relevance in areas where low rentability easily leads to land abandonment and, in turn, to the encroachment of invasive species and the intensification of rural fire regimes [9,10]. Forest managers and producers have been investing in the implementation of efficient silviculture practices, such as adequate soil tillage, genotype selection, weed control, and fertilization, to increase forest productivity [11].

Among forestry practices, special attention has been given to weed management operations, as weeds may significantly affect the establishment and productivity of forest species [12,13]. Weeds can interfere with tree growth directly through competition for light, water, and nutrients [13–15], but also indirectly by increasing fire hazards due to their contribution to the accumulation of biomass as fuel load [16]. The negative effects of weeds on *E. globulus* establishment and growth also depend on vegetation cover and composition [15]. Herbaceous species have a greater direct effect during planting and establishment, whereas shrub species have a stronger impact after canopy closure [17].

The impact of weeds during the early phases of *E. globulus* establishment is well documented [13–15,18]. The initial timing of weed control operations is essential for its effectiveness during the so-called critical weed-free period [19], as at that stage, vegetation usually grows faster than young trees [15]. Although in the case of *E. globulus*, the critical weed-free period was reported to be 20 months after planting [14], in Portugal, weed control on *E. globulus* plantations typically involves mechanical and/or chemical operations during the first year following planting and, if needed, again between the third and fifth years [6].

Few studies have monitored the impact of weed control on the productivity of *E. globulus* for a whole rotation [15,20], and even in those, vegetation management operations were only performed during the first two years following planting. A gap of knowledge was found in how varying the timing of weed control interventions beyond the critical weed-free period may affect the long-term growth of *E. globulus*. This knowledge is highly relevant, not only to the productivity of *E. globulus* but also to the sustainability of plantations. Sustainable forest management must be based on procedures that raise forest productivity without endangering the ecosystems or the ecosystem services provided by the forests [21]. To achieve this balance, forest managers need to have a thorough understanding of how to adjust management practices to local physical and environmental conditions, thus minimizing the environmental impacts of their interventions.

This study was conceived under the hypothesis that we can potentiate the productivity of *E. globulus* throughout the whole rotation by adjusting the timing of weed management according to site conditions. Thus, the goal of this study was to determine how weed control, scheduled according to the understory vegetation development, can affect the long-term productivity of E. globulus. Under this context, two field trials were installed on plantations of *E. globulus* located in Central Portugal: one in the province of Beira Litoral, and another further south in the province of Estremadura.

2. Materials and Methods

2.1. Site Selection and Characterization

The present study was conducted in two *E. globulus* plantations in the Central Region of Portugal managed by The Navigator Company (Figure 1). The southernmost trial was established in 2009 at Torres Vedras, district of Lisbon (39°05′11.56″ N, 9°10′31.78″ O, 242 m above sea level (ASL)). The northernmost trial was established in 2015 at Soure, district of Coimbra (40°05′11.56″ N, 8°35′45.96″ O, 80 m ASL). Both study areas are located in the Mediterranean Csb climate zone, temperate climate with dry and mild summers, according to the Köppen classification [22,23], with an annual mean precipitation (1971 to 2000) of 638 mm in Torres Vedras [22] and of 741 mm in Soure [23]. In Torres Vedras, the annual mean temperature was 15.8 °C, with a mean monthly minimum temperature of 9.2 °C and a mean monthly maximum temperature of 24.1 °C [22]. In Soure, the annual mean temperature recorded was 15 °C, with mean monthly temperatures ranging from 4.4 °C to 28.6 °C [23]. Soils in both study areas are mainly epileptic and endoletic arenic Regosols [24] (Table 1).

These *E. globulus* plantations were being managed for wood. The establishment and development of both plantations were performed as previously defined in the forest company's management planning: clear-cut harvesting of the preceding *E. globulus* planting followed by soil tillage with a single iron plough and planting of young cuttings. *E. globulus* clones were planted with 4.0 × 2.0 m spacing (1250 trees ha^{-1}) at both sites.

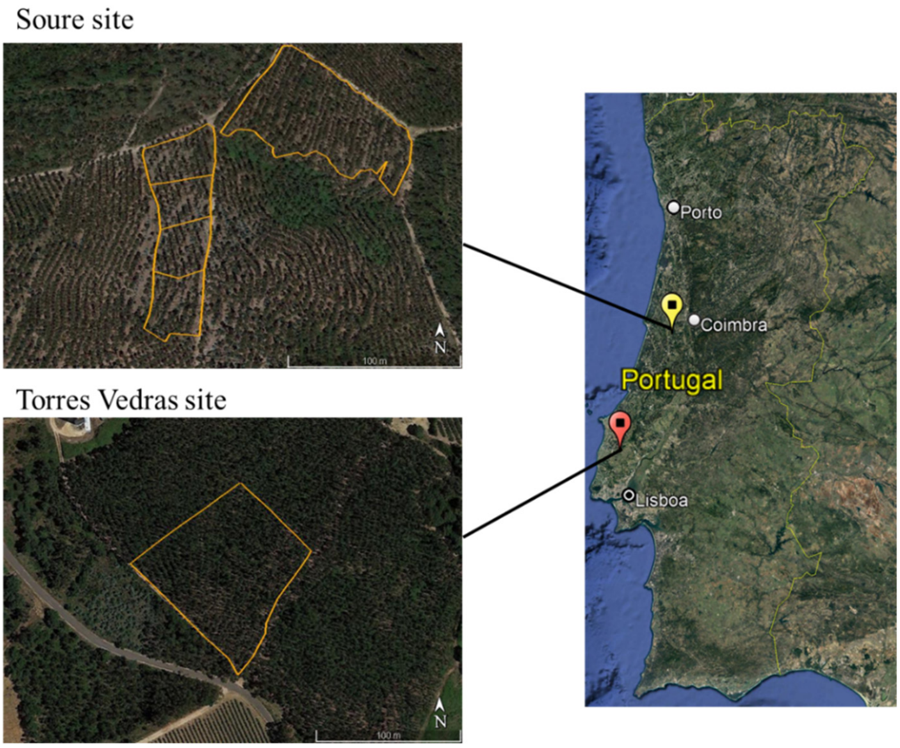

Figure 1. Location of the commercial plantations of *E. globulus* selected for the establishment of the two study areas: Soure, in Coimbra district, and Torres Vedras, in Lisbon district.

Table 1. General characteristics of the two study areas, including information on the weed control treatment application: Torres Vedras (Lisbon) and Soure (Coimbra).

Site	Plantation	Monitoring Period	Weed Control Operations (*n*)	Lithology	Soil Type (FAO) [24]
Torres Vedras	March 2008	2009–2017 (tree age 1.5–9 years)	3 (1.5, 5.2, and 8.2 years)	Conglomerates, sandstones, and limestones	Epileptic and endoleptic arenic Regosols
Soure	May 2014	2015–2019 (tree age 1.6–5.2 years)	3 (1.6, 1.9, and 3.1 years)	Sandstones and pebble	Epileptic and endoleptic arenic Regosols

2.2. Experimental Design

At both sites, plots were randomly established following plantation lines. A plot consisted of a group of three or four measurable consecutive trees in the same plantation line, at Torres Vedras and Soure, respectively. The first plot was installed in the second line of the plantation after the road. Successive plots were separated by at least one tree, with a minimum distance of 4 m between the nearest trees of plots of the same plantation line. No plots were installed in consecutive plantation lines. A plantation line with control and herbicide plots was separated from the following by a line of trees with no plots installed, with a minimum distance of 8 m between the nearest trees of plots of different plantation lines (Figure 2). Two to ten plots were established on each plantation line, depending on the local site conditions and the number of viable trees within a line. Overall, at Torres Vedras 55 plots (165 trees) were distributed along 9 plantation lines. At Soure, a total of 32 plots were established, 16 plots by treatment, corresponding to a total of 120 measured trees. One of the following treatments was applied to each plot: no weed control or chemical weed control. The treatment applied to each plot was defined following a random sampling strategy to account for differences in vegetation characteristics and/or soil characteristics.

In each plot and along the plantation line, herbicide was applied from 1 m before the first tree to 1 m after the last tree of the plot. Plots with different treatments were separated by a minimum of 3 m between the last point where herbicide was applied until the first tree of the following control plot. Between plantation lines, the herbicide was applied up to 2 m on each side of the trees in the plot.

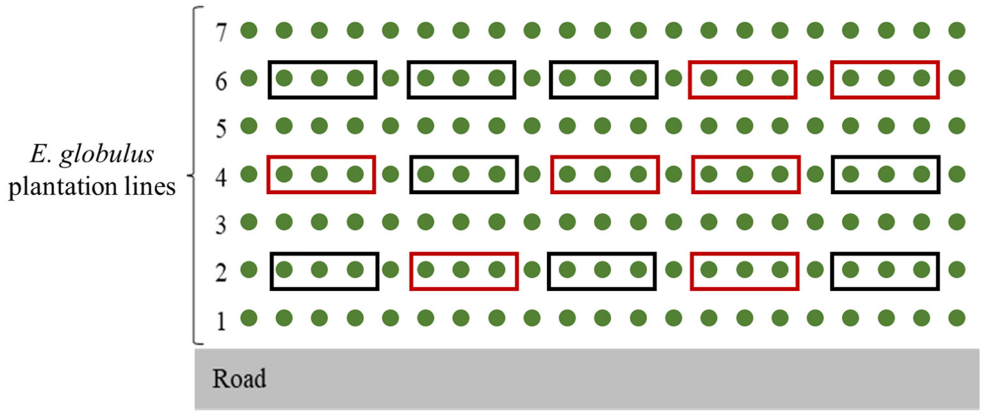

Figure 2. Representative scheme of the experimental design at the study sites. Individual trees are represented by green circles, herbicide-treated plots are delimited by black rectangles, and control plots (no weed control) are delimited by red rectangles. The numbers indicate the respective plantation line.

2.3. Weed Control Treatments

The plots with no weed control treatment, hereby denominated as control plots, did not suffer any intervention related to the understory vegetation. In the plots subjected to weed control, hereby denominated as herbicide plots, vegetation control was carried out in the designated areas with the herbicides Roundup UltraMax, 360 g/L glyphosate (1% to 5%), or Garlon, 480 g/L triclopyr (0.3%). Glyphosate (Roundup UltraMax) was used for the broad-spectrum control of weeds, while triclopyr herbicide (Garlon) was only used for selective control of brambles (*Rubus* spp.). The weed control interventions and their timing were defined following internal guidelines of best practices and forest certification standards (FSC 2016; PEFC 2018). The treatment was repeated when the understory vegetation cover developed to a percentage of 40% to 60% of the plot area, with a mean height of at least 50 cm. Following these criteria, in Torres Vedras, the vegetation development required weed control operations to be conducted at 1.5 years (T0), 5.2 years (T1), and 8.2 years (T2). The final evaluation of trees (height (H) and diameter at breast height (DBH) (1.30 m from the ground)) was performed at 8.8 years (T3), only 0.6 years after the last herbicide application. In Soure, herbicide applications were performed at 1.6 years (T0), at 1.9 years (T1), and at 3.1 years (T2). The interval in herbicide application between T0 (fall) and T1 (spring) was due to the considerable increase in herbaceous plant cover during early spring. These were mainly graminoids and short-lived species that could, nonetheless, compete with the young, recently planted eucalyptus. The final measurement of trees in the Soure site was considered as 5.2 years after planting (T4), since a windstorm that occurred after that period caused considerable and unexpected damaged to the plantation, due to the high number of trees that fell in the experimental area.

2.4. Vegetation Cover

The floristic inventory (weed cover) was recorded by sampling five control plots and five herbicide plots, randomly selected within each treatment. The main weed species identified in the Torres Vedras trial were *Cistus crispus*, *Rubus ulmifolius*, *Andryala integrifolia*, *Brisa maxima*, and *Holcus lanatus*. In the Soure experiment, *Juncus effusus* and *Rubus ulmifolius* were the dominant weed species found. Plant cover was visually estimated at the plot level, considering cover estimations of 10% intervals: 0%–10%, 10%–20% . . . 90%–100% [25,26].

To examine the influence of "weed" functional groups on *E. globulus* productivity, plant species were classified as herbaceous or woody plants. To evaluate the effectiveness of weed control treatments on weed cover, the cover of the understory vegetation was assessed at the ages of 2.5 (2010), 5.6 (2013), 6.2 (2014), 7.2 (2015), 8.2 (2016), and 9.2 years (2017) in Torres Vedras and at the ages of 2.1 (2016), 3.1 (2017), and 5.0 years (2019) after planting in Soure.

2.5. E. globulus Productivity

Tree height (H) and DBH were initially measured at the age of 1.5 (Torres Vedras) and 1.6 years (Soure), immediately prior to the first application of herbicide to determine the initial biometric variables of *E. globulus* and, therefore, for initial productivity assessment. H and DBH measurements were repeated once a year for growth monitoring until the ages of 8.8 and 5.2 years in Torres Vedras and Soure, respectively. The timber commercial volume of each individual tree (VOL) was calculated from DBH and H values, following the equation $Vol = (0.2105 \times (DHB/100)^{1.8191} \times H^{1.0703}) \times 1000$ [27].

E. globulus tree growth was also calculated according to the time intervals of herbicide application. In the Torres Vedras trial, the increment in H, DBH, and VOL was quantified from 1.5 years (T0) to 5.2 years (T1), from 5.2 years to 8.2 years (T3), and from 8.2 years to 8.8 years (T4). In Soure, the differences in H, DBH, and VOL were measured from 1.6 years (T0) to 1.9 years (T1), from 1.9 years to 3.1 years (T3), and from 3.1 years to 5.2 years (T4). The time frame between applications was not equal in both experiments due to the criteria defined for weed control (vegetation cover of 40% to 60% of the area around *E. globulus* trees with an average height equal to or over 50 cm). Thus, in order to standardize growth, the mean annual increment in tree volume (MAI) was calculated as the ratio between the increment in VOL and the corresponding period of time to which the increment was calculated (in years).

2.6. Statistical Analysis

The vegetation cover and height data were analyzed using generalized linear models (GLMs) created through a stepwise backward selection procedure, following a Gaussian error distribution and using the identity link function. The *E. globulus* H, DBH, and VOL data were analyzed using one-way ANOVA. Changes in DBH, H, and VOL between consecutive herbicide applications were analyzed using two-way ANOVA and ensuing least square difference (LSD) post hoc tests. ANOVA assumptions of normality of the errors and homoscedasticity were tested and validated prior to data analysis. All statistical analyses were carried out with the R software package, version 4.1.2, using routine stats (4.1.2), ggpubr (0.4.0), and dplyr (1.0.8), and using an α of 0.05.

3. Results

3.1. The Effect of Weed Control Treatment on Plant Cover

At both the Torres Vedras (Figure 2) and at Soure (Figure 3) study areas, vegetation cover was consistently lower in the herbicide plots, throughout the entire duration of the experiment. Overall, the plant cover registered in the herbicide plots was 21.9%, while the plant cover in the control plots was 44.6%. In relation to the control plots, the maximum vegetation cover reduction in the herbicide plots was 79% and 94% in Soure and in Torres Vedras, respectively.

Woody plant cover was consistently lower than herbaceous plant cover in both study areas (20% vs. 29% in Soure and 34% vs. 43% in Torres Vedras). Notwithstanding, the data suggest that the herbicide treatment produced a higher reduction on woody than on herbaceous cover, since the relative differences between control and herbicide plots were higher for the woody (87.8% in Soure and 52.1% in Torres Vedras) than for the herbaceous cover (69.5% in Soure and 23.8% in Torres Vedras) (Figures 3 and 4).

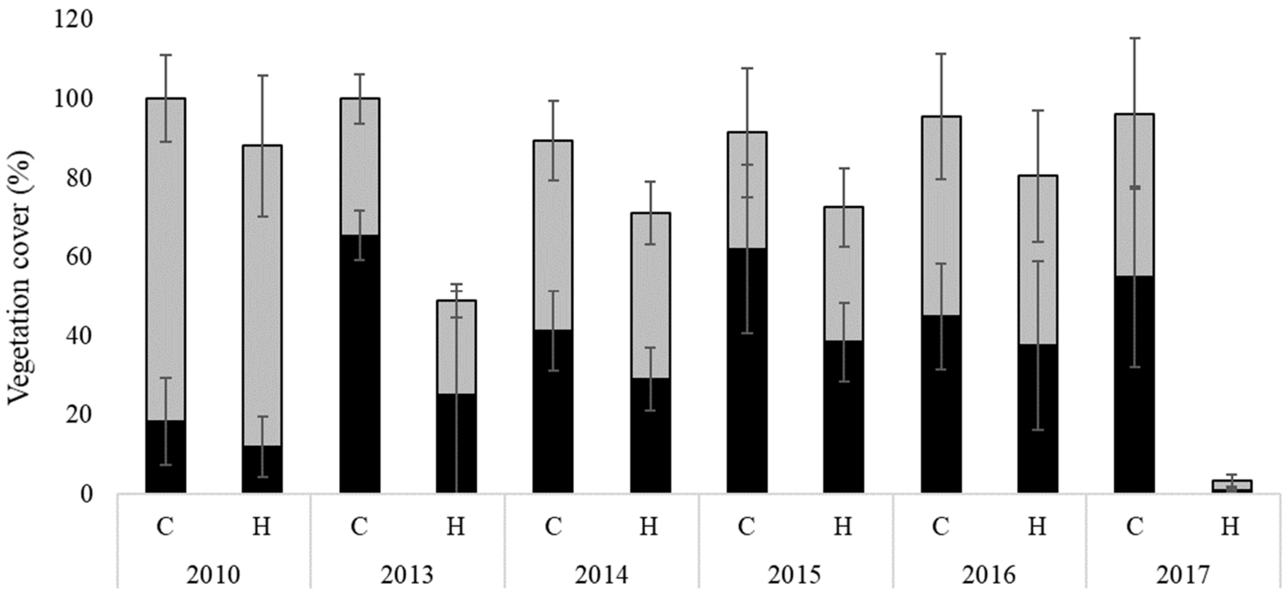

Figure 3. Mean weed cover in Torres Vedras study area, evaluated as percentage of woody species cover (black bars) and herbaceous species cover (grey bars), observed at control (C) and herbicide (H) plots in the sampling years of 2010 (1.0 year after the last herbicide application), 2013 (0.1 years after the last herbicide application), 2014 (1.0 year after the last herbicide application), 2015 (2.0 years after the last herbicide application), 2016 (3.1 years after the last herbicide application), and 2017 (1.0 years after the last herbicide application).

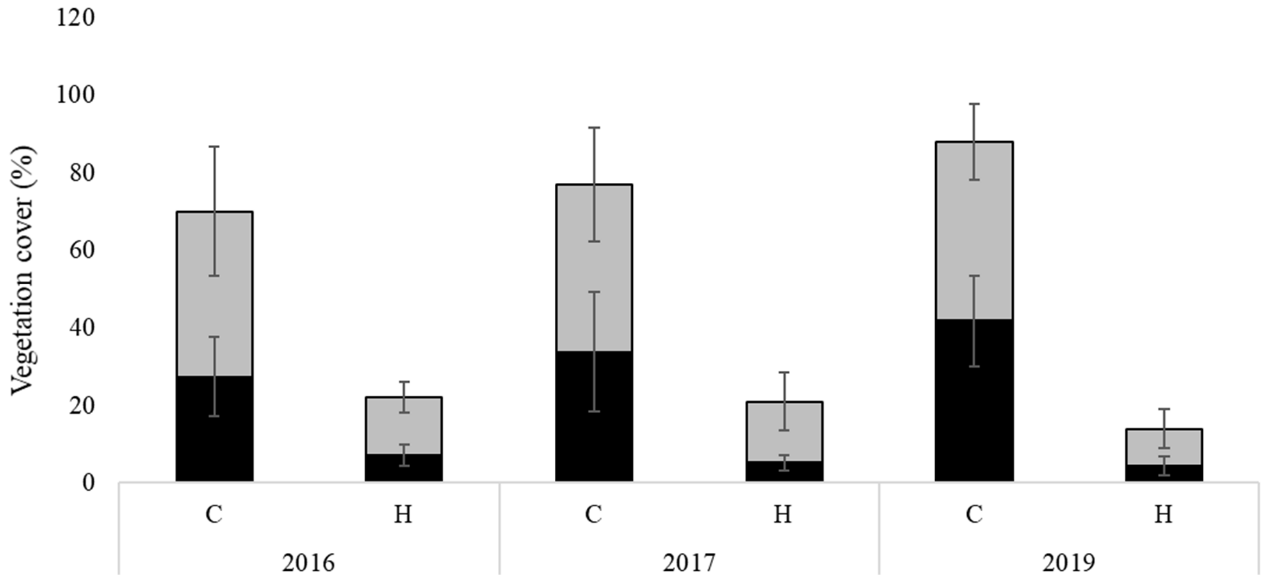

Figure 4. Mean weed cover in Soure study area, evaluated as percentage of woody species cover (black bars) and herbaceous species cover (grey bars), observed at control (C) and herbicide-treated (H) plots in the sampling years of 2016 (0.2 years after the last herbicide application), 2017 (1.1 years after the last herbicide application), and 2019 (1.9 years after the last herbicide application).

Time after herbicide application (years after treatment, Table 2) had a direct relation with overall plant cover in both study areas; however, according to the GLM, the differential effect of the herbicide for the two functional types does not seem to be consistent for all the sampling years. The best model estimated for explaining the variability in the plant cover data, to a significant extent, included all of the above-mentioned factors: treatment (control or herbicide), plant functional type (herbaceous or woody), and years after treatment, in addition to the effect of the year of the plant cover assessment and the interaction therein between treatment and cover assessment year. The study area was not a significant factor in explaining the variability in plant cover, so it was removed from the first version of the model estimation (Table 2).

Table 2. Factors affecting vegetation cover at Torres Vedras and Soure study areas, obtained by applying a generalized linear model (GLM) to the observed data.

	Estimate	Std. Error	t Value	p (>∣t∣)
Intercept	5550.91	1861.4488	2.982	0.00337
A—Treatment (herbicide)	6742.60	2235.4671	3.016	0.00303
B—Functional type (herbaceous)	8.50	2.9490	2.881	0.00457
C—Years after treatment	6.75	1.7255	3.912	0.00014
D—Cover assessment year	−1.67	0.8075	−2.066	0.04059
Interaction between A and D	−3.36	1.1092	−3.026	0.00293

3.2. E. globulus Productivity

At the Torres Vedras study site, the mean height of *E. globulus* in the control plots ranged from 4.1 m at 1.5 years to 17.5 m at 8.8 years, while the DBH varied from a mean value of 3.5 cm to 14.9 cm (Table 3). In terms of mean VOL per tree, values went from 2.3 dm^3 (at 1.5 years) to 148.8 dm^3 by the final evaluation of the trial (at 8.8 years). In the Soure study site, the *E. globulus* H in the control plots was 6.0 m at 1.6 years, reaching 15.2 m at an age of 5.2 years, when the experiment was terminated due to a windstorm (Table 4). The DBH of the same *E. globulus* trees ranged from the mean value of 9.0 cm (3.2 years) to 12.5 cm. Regarding the VOL of *E. globulus* trees in the same time frame (from 3.2 to 5.2 years), the variation found was from 38 dm^3 to 91.4 dm^3.

Table 3. *E. globulus* height (H), diameter at breast height (DBH), and individual tree volume (VOL) of the trees in control plots by age from the start of the experiment in 2009 (1.5 years) to its conclusion in 2017 (8.8 years) in the Torres Vedras study area.

Plantation Age (Years)	H (m)	DBH (cm)	VOL (dm^3)
1.5	4.1 ± 0.7	3.5 ± 0.8	2.3 ± 1.3
2.3	5.4 ± 1.0	5.7 ± 1.1	7.6 ± 3.8
3.6	8.9 ± 1.4	8.5 ± 1.8	26.5 ± 13.3
4.6	10.6 ± 1.3	10.3 ± 1.9	44.5 ± 19.4
5.6	12.4 ± 1.5	11.5 ± 2.1	64.9 ± 28.4
6.1	13.1 ± 1.5	12.1 ± 2.2	75.6 ± 31.9
7.2	16.0 ± 1.7	13.7 ± 2.4	116.7 ± 46.2
8.0	16.4 ± 1.7	14.3 ± 2.6	129.6 ± 51.8
8.8	17.5 ± 1.9	14.9 ± 2.7	148.8 ± 58.6

Table 4. *E. globulus* height (H), diameter at breast height (DBH), and individual tree volume (VOL) of the trees in control plots by year since the establishment of the experiment in 2015 (1.6 years) until its end in 2019 (5.2 years) in Soure study area (na means no available data).

Plantation Age (Years)	H (m)	DBH (cm)	VOL (dm^3)
1.6	5.9 ± 1.1	na	na
2.5	9.8 ± 1.3	na	na
3.2	11.5 ± 1.3	9.0 ± 1.4	38.0 ± 14.0
3.8	13.0 ± 1.3	9.8 ± 1.5	50.4 ± 17.2
5.2	15.2 ± 1.4	12.5 ± 1.9	91.4 ± 30.8

Growth (increment) in H, DBH, and VOL was calculated for the periods between herbicide applications. The results suggest that the H growth increment (Figure 5) was significantly higher ($p < 0.05$) in the herbicide-treated plots in the time period between the first (T0) and second (T1) applications and between the third application (T2) and the end of the trial (T3). No significant differences in H increase were observed between the second and the third applications among treatments.

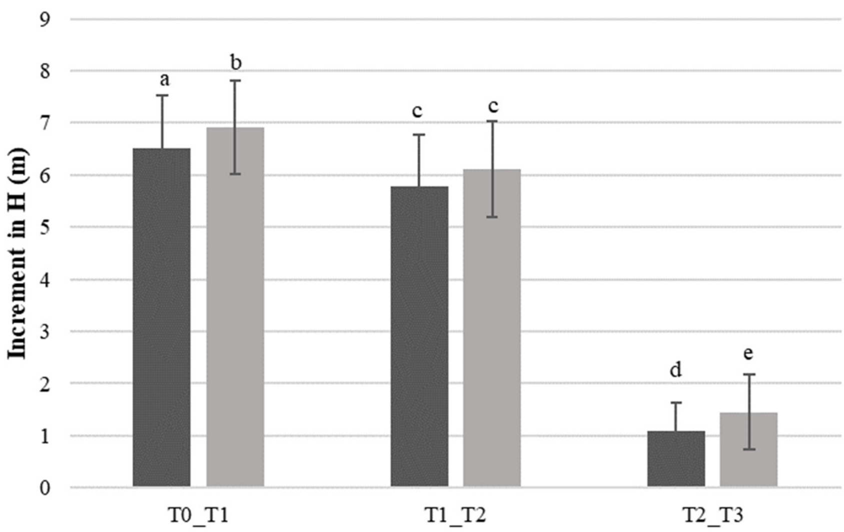

Figure 5. Mean increment in H (m) of *E. globulus* trees at Torres Vedras study area in the control treatment (dark grey) and in the weed control treatment (light grey) between herbicide applications: from 1.5 years to 5.2 years (T0_T1), from 5.5 years to 8.2 years (T1_T2), and from 8.2 years to 8.8 years (T2_T3). Different letters indicate significant differences ($p < 0.05$) in height increment as detected by the two-way ANOVA test.

Similar results were obtained relating to the average tree DHB. Differences in the increment of the DBH (Figure 6) were significantly higher in the herbicide-treated plots during the first (T0) and second (T1) applications and between the last application (T2) and the end of the trial (T3). No significant differences were observed between the second and the third applications in both variables.

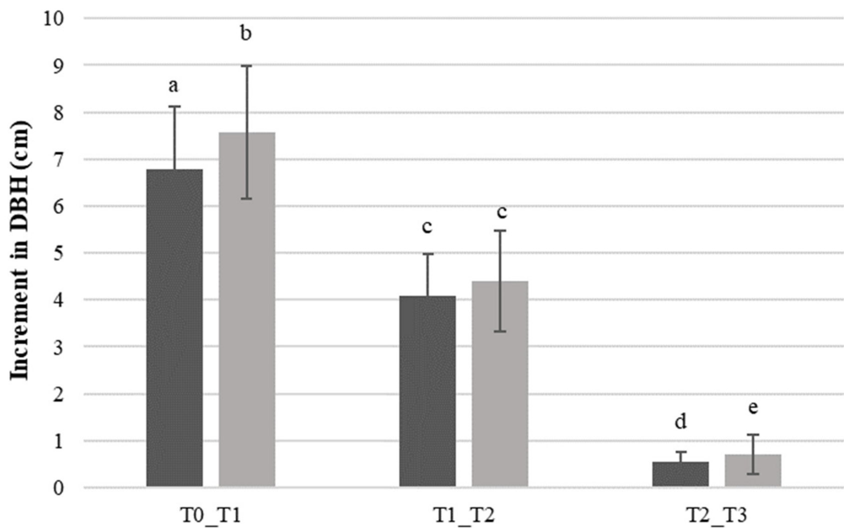

Figure 6. Mean increment in DBH (cm) of *E. globulus* trees at Torres Vedras study area in the control treatment (dark grey) and in the weed control treatment (light grey) between herbicide applications: from 1.5 years to 5.5 years (T0_T1), from 5.5 years to 8.2 years (T1_T2), and from 8.2 years to 8.8 years (T2_T3). Different letters indicate significant differences ($p < 0.05$) in DBH increment as detected by the two-way ANOVA test.

By analyzing the increment in VOL during the same periods of time (Figure 7), differences between treatments were more evident. Trees from the herbicide-treated plots presented a significantly ($p < 0.05$) higher increment between all application intervals. Between T0 and T1, the VOL increased by 51.9 dm^3 and 42.2 dm^3 in the herbicide-treated plots and in the control plots, respectively. The same tendency was observed between T1 and T2, with trees from the herbicide plots increasing by an average of 102.7 dm^3 in VOL, while trees from the control plots grew 85.1 dm^3. From the last herbicide treatment (T2) to the final evaluation (T3), trees increased by 27.1 dm^3 and 19.2 dm^3 in the herbicide and control plots, respectively.

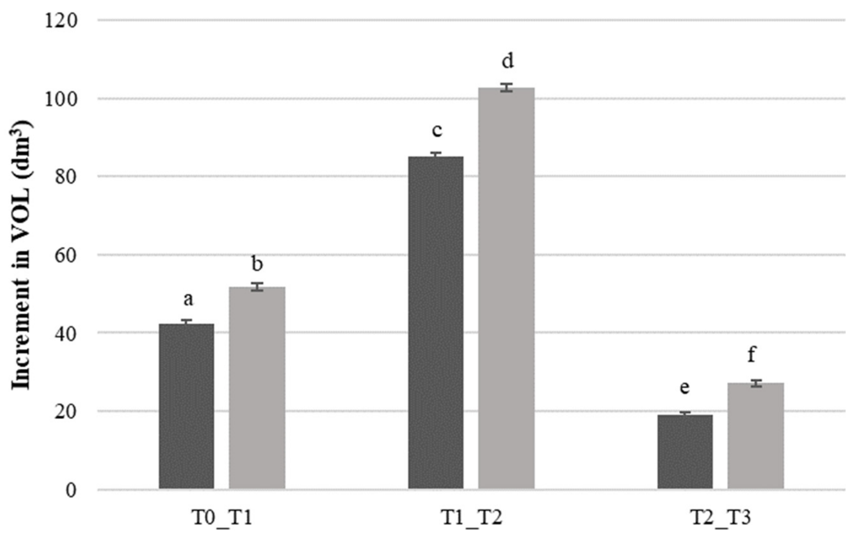

Figure 7. Mean increment in individual volume (dm^3) of *E. globulus* trees at Torres Vedras study area in the control treatment (dark grey) and in the weed control treatments (light grey) between herbicide applications: from 1.5 years to 5.2 years (T0-T1), from 5.5 years to 8.2 years (T1-T2), and from 8.2 years to 8.8 years (T2-T3). Different letters indicate significant differences ($p < 0.05$) in volume increment as detected by the two-way ANOVA test.

The mean annual increment in tree volume (MAI) was significantly higher ($p < 0.05$) in trees from the herbicide plots than in trees from the control plots for the timing T2-T3 (Table 5), showing a rising trend throughout the three periods of study with MAI values of 16.7 dm^3 $year^{-1}$ (T0-T1), 30.2 dm^3 $year^{-1}$ (T1-T2), and 33.9 dm^3 $year^{-1}$ (T2-T3).

Table 5. Mean annual increment in individual volume (MAI) of *E. globulus* trees at Torres Vedras in the control plots (dark grey) and in weeding plots treated with herbicide (light grey), determined between herbicide applications: from 1.5 years to 5.2 years (T0-T1), from 5.5 years to 8.2 years (T1-T2), and from 8.2 years to 8.8 years (T2-T3). Different letters indicate significant differences ($p < 0.05$) in volume increment as detected by the two-way ANOVA test.

Time Period	MAI (dm^3 $Year^{-1}$)	
	Control	**Herbicide**
T0-T1 (1.5 to 5.2 years)	13.6 ± 6.0^{a}	16.7 ± 6.7^{a}
T1-T2 (5.5 to 8.2 years)	25.0 ± 10.1^{cd}	30.2 ± 10.2^{bc}
T2-T3 (8.2 to 8.8 years)	24.0 ± 12.7^{d}	33.9 ± 10.2^{b}

The increment in height was significantly different ($p < 0.05$) between treatments after the first time period (T0-T1), with trees from the weed control plots presenting a growth of 4.4 m, higher than the increase of 3.9 m determined in the height of trees from the control plots (Figure 8). In the second period (T1-T2), the trees had a mean height increment of 1.7 m, and in the third period (T2-T3) of 3.7 m, irrespective of the treatment.

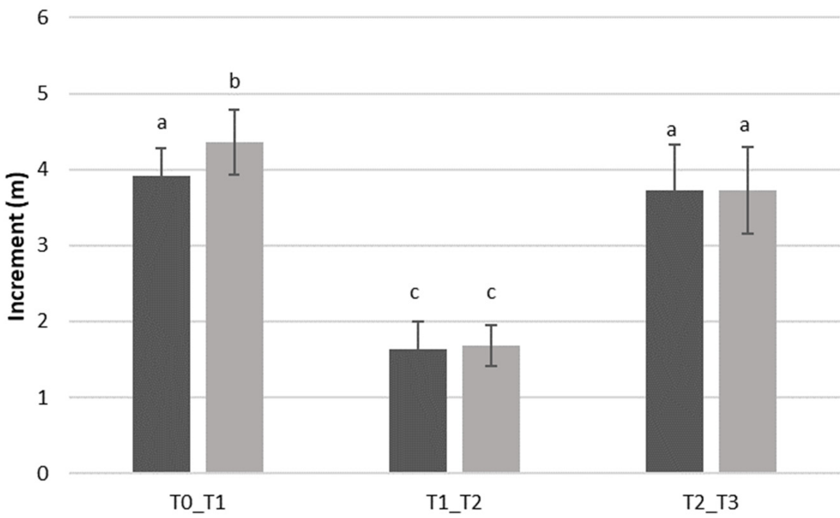

Figure 8. Mean increment in height (m) of *E. globulus* trees at Soure study area in the control (dark grey) and in the herbicide plots (light grey) between herbicide applications: from 1.6 years to 1.9 years (T0-T1), from 1.9 years to 3.1 years (T1-T2), and from 3.1 years to 5.2 years (T2-T3). Different letters indicate significant differences ($p < 0.05$) in height increment as detected by the two-way ANOVA test.

The DBH increment was only determined in the third time period after the last herbicide application (T2-T3). During this period, the diameter of trees from the herbicide plots differed significantly from the DBH of trees from the control plots, with increments of 3.8 and 3.5, respectively (Table 6).

Table 6. Mean increment in diameter at breast height (DBH), increment in individual volume (VOL), and mean annual increment in individual volume (MAI) of *E. globulus* trees in the control and in the herbicide plots between herbicide applications from 3.1 years to 5.2 years (T2-T3). Different letters indicate significant differences ($p < 0.05$) in the measured variable increments as detected by the two-way ANOVA test.

Time Period	DBH Increment (cm)		VOL Increment (dm^3)		MAI (dm^3 Year^{-1})	
	Control	Herbicide	Control	Herbicide	Control	Herbicide
T2-T3 (3.1 to 5.2 years)	3.5 ± 0.8^{a}	3.8 ± 0.7^{b}	53.4 ± 18.7^{a}	63.8 ± 14.4^{b}	26.7 ± 9.3^{a}	31.9 ± 7.2^{b}

Similar to the DBH results, the increment in volume in the Soure trial was only determined in the time frame between the final herbicide application and the last biometric evaluation of trees (T2-T3). The results showed that the volume increment in trees from the herbicide plots was significantly higher ($p < 0.05$) than the mean increment in volume of trees from the control plots: 63.8 dm^3 and 53.4 dm^3 in the herbicide and control plots, respectively. The MAI calculated between the ages of 3.1 years and 5.2 years (T2-T3) was also significantly higher ($p < 0.05$) in trees from the herbicide plots compared with those of the control plots, with values of 31.9 dm^3 year^{-1} and 26.7 dm^3 year^{-1}, respectively.

4. Discussion

Weed competition is a highly relevant issue in forest management [14,18], particularly due to the limited resources available in young tree establishment and development in spite of understory vegetation growth [15,17]. For this reason, the timing of weed control operations is a major concern to forest managers trying to increase productivity and maintain plantation sustainability at a reasonable cost. In the current work, the prescription for herbicide application was dependent on an objective criteria of understory vegetation development: area occupied by the understory vegetation cover (covering 40% to 60% of the plot) and a mean height of at least 50 cm. This resulted in a differential timing for the application of herbicide: in the Torres Vedras plantation, weed control operations were performed at 1.5, 5.5, and 8.2 years; in Soure, weed control treatments were concentrated in the first 3 years after planting, namely at 1.6, 1.9, and 3.1 years.

Both trials evidenced the effectiveness of the weed control treatments approximately one to two months after herbicide application, with vegetation cover reductions to half (2013) and to one-third (2016) at Torres Vedras and Soure, respectively. The effects of weed control on understory vegetation are usually noticeable within the first weeks after treatment [28,29], but often do not last long depending on site conditions and the composition of the plant community [30]. The duration of the herbicide effect was longer in the Soure study area: two years after the last weed control operation, the area occupied by understory vegetation was about six times lower in treated plots than in control plots. In the present study, the different timings of weed control interventions in both trials were a direct consequence of the criteria established for vegetation control, which did not allow to concentrate the three herbicide applications during the first years after planting at Torres Vedras. A more intensive regime of herbicide applications that allows the concentration of all the interventions in a short period of time may have more effect on controlling the growth and modulating the composition of the understory vegetation, as it could highly diminish competition between forest species and weeds, often during the entire rotation [29]. Herbaceous vegetation typically competes heavily for nutrients and water during the early years of stand formation, while woody vegetation normally develops into a powerful competitor even after crown closure [15].

Both trials presented a positive growth response to the herbicide treatment in terms of H, DHB, and VOL, as reported by other authors [13–15,18,29,31]. A possible explanation may be the increment in the leaf area index and the photosynthetic rate of trees with less competition from understory vegetation, as reported by other authors [18,32]. The results from the experiment demonstrated that at both sites, the understory vegetation development and *E. globulus* growth responded to weed control differently, possibly due to climate conditions, the timing of weed control operations, and understory vegetation composition [13,17,30,31]. Differences between treatments were evident from the start of the trial in Soure, being only perceived in Torres Vedras at a later stage of the experiment. Such a response can be attributed to differences in the competition between weeds and *E. globulus* among the two areas due to the differential herbicide application regime [29].

Weed competition impacted *E. globulus* productivity mainly during the early phase of plantation establishment [5,14,15], but our results demonstrated that later weeding operations also contributed to growth increment at the end of the plantation cycle. Inail et al. [31] found significant differences between the DHB and VOL of *E. globulus pellita* from plots treated with herbicide during the first year and plots treated with herbicide after initial tree establishment, with the last presenting larger mean diameters. Nevertheless, the maintenance of such differences in stand productivity at the end of the rotation was dependent on the site productivity potential [31]. During tree establishment, competition for light, water, and nutrients is limiting for young *E. globulus* trees [14]. In Soure, during the first five years after plantation establishment, the weed control effect on *E. globulus* growth profile was more evident in DBH than in H. The same tendency was observed in Torres Vedras, although no significant differences were detected between treatments at that time. No phytotoxic impacts related to herbicide applications were observed in *E. globulus* trees in either trial. Weed competition substantially reduced the growth of *Eucalyptus pellita*, particularly in low-productivity sites, but this effect was less evident in high to medium-productivity sites [31]. Our results suggested that, although there were differences in site productivity between the two trials, productivity gains during the first five years of *E. globulus* growth, before canopy closure, were apparently more dependent on the timing of weed control operations (defined by weed cover) than on the number of operations per se, as differences in the height increment between treatments at Soure were significantly different between 1.6 and 1.9 years.

After tree establishment, competition for light decreases due to higher average tree height in relation to understory vegetation [17]. While Vargas et al. [15] observed a tendency of decreasing in stand productivity loss with the increase in the intensity of weed control treatments, this effect was reported to be more pronounced before canopy closure, and gradually diminishes with age [31]. However, late weed control, such as what occurred in Torres Vedras, may produce significant effects at the end of the *E. globulus* rotation, even in sites where differences were not evident at younger ages. The continued response to weed control at Torres Vedras may be due to the type of competing weeds, as brambles easily dominated the control and herbicide plots soon after weed control treatments had been applied. The late increment in *E. globulus* productivity may be explained by a late reduction in the competition for water and nutrients [15,31], as a relevant decrease in the understory vegetation cover of the herbicide plots was only observed after the last treatment.

Weed control led to significant increments in *E. globulus* growth and stand productivity in both trials, even though the herbicide application timings were different. Under the scope of sustainable forest management, efforts need to be made to reduce the number of chemical interventions in forestry and to mitigate its ecological impacts [33,34]. Studies such as the present one are extremely important in understanding in which situations the gains obtained in terms of forest productivity justify the use of herbicides.

5. Conclusions

Our results evidenced the effectiveness of weed control on diminishing vegetation cover density to a maximum of 79% and 94% in the Soure and Torres Vedras sites, respectively. Moreover, weed control operations led to significant increments in *E. globulus* growth and, hence, on final stand productivity. Both experiments revealed this effectiveness, even if in different manners. The effects of herbicide application were more noticeable during the first 3 years following planting in the case of the Soure study site, while they only became significant towards the end of the first rotation in the case of the study site of Torres Vedras. This contrast between the two sites could be related to differences in edaphoclimatic conditions and in understory vegetation composition. This study demonstrated that managing the understory vegetation on eucalyptus plantations requires more than one weed control timing. To maximize productivity, however, the timing of the operations must be regulated according to weed cover development throughout the first rotation cycle of E. globulus, rather than being limited to the initial establishment of the trees. Given the present and future challenges to increasing the resilience of forests under imminent climate changes, as well as the need to minimize herbicide application to comply with the norms of forest certification standards, the definition and widespread implementation of simple protocols for monitoring the effectiveness of chemical and other weed control measures would seem highly recommendable.

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