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ORIGINAL PAPER

# Effectiveness of slash and burn treatments in controlling *Acacia dealbata* Link invasion

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**Abstract** Slash and burn treatments are often recommended and employed for controlling the invasive tree *Acacia dealbata* Link. In this study, we aimed to evaluate the effectiveness of this approach. We established eight experimental blocks with burn, slash and slash-and-burn treatments distributed across central Portugal. The density and height of new seedlings and resprouts of the invasive alien plant were monitored for three years. Our results showed that slash treatments stimulated resprouting, while burn treatments promoted seed germination. Resprouts and seedlings were significantly taller in the slash treatments compared to the burn treatments. When combined treatments were applied, different combinations of slash-and-burn reduced the number of resprouts and seedlings; however, the minimum stem density remained at 6.5 stems $m^{-2}$, compared to 0 in the control plots. These results demonstrate that, under the conditions of this study, slash-and-burn treatments without follow-up interventions are not effective for controlling *A. dealbata* populations, despite their role in reducing the soil seed bank.

**Keywords** Non-native tree species · Control methods · Fire · *Acacia dealbata* · Disturbance

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## Introduction

Invasive alien plants are considered one of the most serious threats to global biodiversity, causing significant ecological and economic impacts (IPBES 2024). They outcompete native vegetation, alter soil chemistry and nutrient cycling, and can rapidly establish and dominate the invaded areas (Vilà et al. 2011; Castro-Díez et al. 2019; Wohlgemuth et al. 2022). Particularly in Mediterranean ecosystems, invasive tree species have been shown to increase fire hazards and alter fire regimes, posing additional challenges to

ecosystem management (Brooks et al. 2004; Underwood et al. 2019; Aslan and Dickson 2020). Fire disturbances often facilitate the expansion invasive plant species, either by stimulating germination (Cruz et al. 2017; Riveiro et al. 2019, 2020) or by other factors that favour its expansion, such as creating open areas and degrading native ecosystems (Keeley 2006; García-Duro et al. 2019). In some alien species, fire plays a crucial role in promoting their expansion, as seen in *Acacia* species (Souza-Alonso et al. 2017; Nunes et al. 2021). Acacias form persistent soil seed banks that germinate after fire (Arán et al. 2017), leading to the replacement of native vegetation and significant changes in nutrient cycles, particularly nitrogen (Gaertner et al. 2014).

*Acacia dealbata* Link, commonly known as silver wattle or mimosa, is a tree species native to South Australia. It has become naturalized in several regions, including southern Europe, South America, South Africa and New Zealand, due to its high adaptability to a wide range of environmental conditions, rapid growth, and prolific seed production. In these regions, it forms dense stands that displace native vegetation, reduce plant diversity (Lorenzo et al. 2012), alter nutrient cycling, and disrupt ecosystem processes (Lazzaro et al. 2014; Pereira and Ferreira 2021; Wohlgemuth et al. 2022). The most severe impacts of *A. dealbata* invasion have been documented in Chile, Portugal and South Africa (Orchard and Wilson 2001; Lorenzo et al. 2010; Souza-Alonso et al. 2017). This species invades areas with intermediate rainfall (750–1250 mm per year) and it is well adapted to various soil types, including schist, granite, and sandstone (Boland et al. 2006). The invasion of *A. dealbata* leads to profound changes in soil nitrogen levels and the release of allelopathic compounds, creating a positive feedback loop that favors its own growth, as described by the Biochemical Recognition Hypothesis (Lorenzo and Rodríguez-Echeverría 2012; Yannelli et al. 2020). Each pod contains an average of nine seeds, which are released from May to July in the Northen Hemisphere, contributing to the formation of extensive and long-lived soil seed banks (Passos et al. 2017). The species' ability to establish novel mutualistic relationships further enhances its high seed production (Montesinos et al. 2016). Like other acacias, fire acts as a germination cue by breaking the seed coat (Cruz et al. 2021). Additionally, *A. dealbata* can produce vigorous resprouts after cutting or fire (Lorenzo et al. 2012; Nunes et al. 2021). Unlike some related acacias, *A. dealbata* has a long lifespan, exceeding 20 years (Boland 1986). Due to its resilience and significant ecological impacts, *A. dealbata* has been ranked among the four plant invaders with the highest environmental and socioeconomic impacts in Europe (Nentwig et al. 2018).

Controlling invasive tree species is a major challenge for land managers due to their resilience. Invasive acacias are particularly difficult to manage because of their ability to resprout after cutting (Fuentes-Ramírez et al. 2011; Le Maitre et al. 2011) and their capacity to produce large, long-lived soil seed banks (Richardson and Kluge 2008; Leino and Edqvist 2010). Therefore, there is a need to improve existing control methods and/or develop new strategies to effectively reduce the invaded areas. Current control methods for acacias include mechanical treatments (cutting or debarking), prescribed burns, chemical treatments, and biological control (March 2000; Tu et al. 2001; Souza-Alonso et al. 2013; Murillo Vilanova et al. 2018; Duarte et al. 2023). While mechanical and fire-based methods have shown success in controlling some invasive species, their impact on *A. dealbata* regeneration remains understood. Although wildfires can promote the expansion of fire-adapted plants (Brooks et al. 2004), using fire under controlled conditions has been proposed as a potential management tool (DiTomaso and Johnson 2006). Fire can stimulate sprouting from stumps and roots, as well as seed germination in acacias, but it can also destroy seeds and seedlings, potentially depleting the soil seed bank (Pieterse and Cairns 1986; Richardson and Kluge 2008; Silva and Marchante 2012; Wilson et al. 2011). Similarly, cutting plants stimulates resprouting (Pieterse and Boucher 1997), but repeated slashing may deplete stump resources, leading plant death (Bellingham and Sparrow 2000). However, there is a knowledge gap in the demonstration of the effectiveness of these methods. Moreover, there is a lack of experimental evidence demonstrating the effectiveness of these methos, particularly when combined.

For these reasons this study was performed to evaluate the effect of different combinations of slash and burn treatments on the regeneration of *A. dealbata*. With this purpose, we monitored the effect of these treatments on the density and growth of seedlings and resprouts of the invasive alien plant over three years,

using a network of experimental blocks installed in Central Portugal.

## Materials and methods

### Experimental design

We conducted an experiment consisting of different combinations of slash and burn treatments on *A. dealbata*. The study was carried out in the Coimbra district of central Portugal (Fig. 1) between October 2018 and December 2021. The region has warm-summer Mediterranean climate, with an average precipitation of 880 mm per year and an average temperature of 16 °C (IPMA 2024). Soils in the area are derived from marls, schists, limestone conglomerates, and clays, reflecting the local parent rocks composition (Comissão Nacional do Ambiente de Portugal 1982). The altitude of the study sites ranges from 65 to 546 m above sea level.

The experiment was established in eight *A. dealbata* stands (study sites): Arganil, Buçaco, Carregal, Góis1, Góis2, Lousã1, Lousã2, Montemor (Table 1).

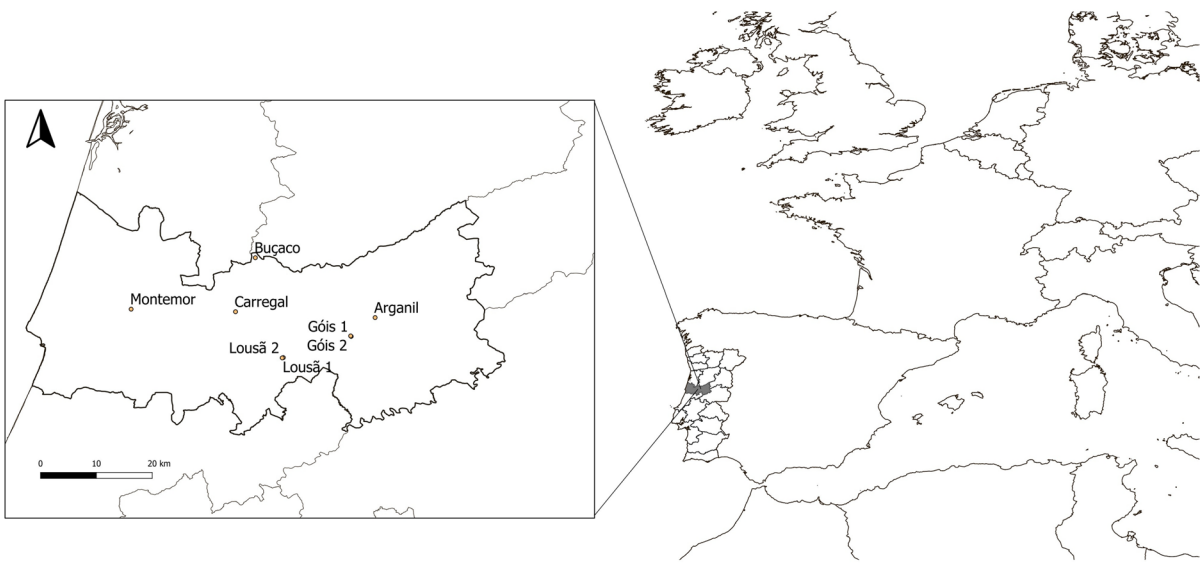



**Fig. 1** Location of the eight *Acacia dealbata* stands in the Coimbra district (Portugal) where the experiment was conducted. Note that Góis1–Góis2 and Lousã1–Lousã2 are located close to each other and may overlap in the map visualization

**Table 1** Characterization of *Acacia dealbata* stands before treatments.

| | DBH (cm) | Basal area ($m^2$ $ha^{-1}$) | Modal height (m) | Cover (%) | Coordinates | Aspect | Average density (plants $m^{-2}$) |
|---|---|---|---|---|---|---|---|
| Arganil | 4.04 ± 2.81 | 110.95 | 5.30 | 96 | 40°12'43.32"N; 8° 3'23.36"W | W | 8.63 ± 8.58 |
| Buçaco | 1.53 ± 0.90 | 15.17 | 3.43 | 100 | 40° 6'47.12"; 8°17'5.44"W | F | 8.20 ± 6.56 |
| Carregal | 5.65 ± 4.68 | 34.45 | 8.29 | 98 | 40°12'43.32"N; 8° 3'23.36"W | E | 1.38 ± 1.57 |
| Góis1 | 2.96 ± 1.62 | 20.75 | 5.43 | 86 | 40° 9'56.79"N; 8° 6'55.28"W | E | 3.01 ± 2.69 |
| Góis2 | 1.30 ± 0.55 | 11.42 | 2.20 | 98 | 40°10'0.98"N; 8° 7'0.05"W | NE | 8.59 ± 4.80 |
| Lousã1 | 2.42 ± 2.53 | 20.22 | 4.06 | 100 | 40° 6'49.55"N; 8°16'55.95"W | F | 4.38 ± 3.93 |
| Lousã2 | 1.92 ± 2.00 | 27.63 | 4.07 | 98 | 40°13'57.68"N; 8°39'22.45"W | F | 9.55 ± 8.68 |
| Montemor | 7.16 ± 7.45 | 34.56 | 7.31 | 100 | 40°21'29.73"N; 8°21'3.29"W | F | 0.86 ± 0.32 |

DBH: average diameter at breast height (mean ± SE), measured in nine trees per block; Basal area; Modal height; Average density (mean ± SE), Percentage of *Acacia dealbata* cover (%); Coordinates (WGS84 system); Aspect, where "F" indicates flat terrain

These sites were separated by distances ranging from a minimum of 175 m to a maximum of 51 km. The study sites were predominantly occupied by *A. dealbata* with sporadic occurrences of *Eucalyptus globulus* Labill., *Quercus suber* L., *Q. robur* L., *Q. lusitanica* Lam., *Acacia longifolia* (Andrews) Willd., and *Hakea decurrens* R. Br. (listed from most to least abundant). The understory was largely absent in most study sites, although some shrub species were present in certain areas, including: *Rubus ulmifolius* Schott, *Calluna vulgaris* (L.) Hull, *Ulex europaeus* L., and *Erica* spp. One block of treatment plots was established at each study site. Each block included a control plot (control), a burned plot (burn), a clear-cut plot (slash) and one or more plots subjected to combined slash and burn treatments (slash and burn). Treatments were repeated to assess the effects of consecutive interventions on seedlings and resprouts. The number of replications for each treatment was variable (Table 2) due to unexpected challenges during the experiment. These included the accidental cutting of some plots (including control plots) by forest workers, the felling caused by a hurricane, and constraints related to experimental burns. As a result, some study sites, specifically Arganil and Montemor, lacked control plots due to accidental cutting, rendering them unsuitable for use as controls.

Treatments were categorized into three groups: (1) single treatments (control, burn, slash), (2) repeated treatments (slash once and twice), and (3) slash and burn treatments (different combinations of repeated slash and burn treatments). In control plots, vegetation was left undisturbed, and no intervention was performed in these plots. Burn plots were subjected to experimental burns conducted between February and June under moderate weather conditions. Fire was typically ignited upslope and against the wind, except when burning conditions were too challenging. Flame length residence time (the duration of flame contact with a reference point) were measured using a video camera and a range pole. Average flame length across plots ranged from 0.20 to 2.00 m, with an overall mean of $1.17 \pm 0.11$ m ($n = 14$). Average residence time (measured at three points per plot) ranged from 45 to 900 s, with an overall mean value of $226.91 \pm 11.26$ s ($n = 14$). In slash plots, trees were cut using chainsaws, and left on the ground aiming to create a shadow effect over seeds and resprouts. Twigs and branches with diameters greater than 7.5 cm (classified as 1000 h fuels, following Fosberg (1970)) were removed to facilitate fire propagation. The minimum interval between repeated slash treatments was three months. In combined treatments, slashing was performed first. Slashed fuels were cut during a period ranging between 29 and 165 days before the experimental burn. In some plots, either the slash or the burn treatment was repeated. Overall, the eight study sites encompassed a minimum of four and a maximum of seven treatments (Table 2).

## Data collection

Plot size was $5 \times 5$ m. Within each plot, we randomly established one $1 \times 1$ m subplot to monitor germination and resprouting. Monitoring was performed every two months over approximately three years. During each visit, we registered the number of resprouts, the number of seedlings, the modal height of resprouts, and the modal height of seedlings. Resprouts were distinguished from seedlings based on emergence location and their vigor. Resprouts were defined as stems emerging from a main *Acacia* stump or very close to it, while seedlings were stems emerging directly from the ground. Additionally, resprouts were differentiated from seedlings by examining the base of the stem: seedling typically have a

**Table 2** Dates of treatments performed for controlling *Acacia dealbata* at each study site.

"X" indicates the presence of a control plot. Note that the same treatment was performed in more than one plot at some study sites

| Treatment | Arganil | Buçaco | Carregal | Góis1 | Góis2 | Lousã1 | Lousã2 | Montemor |
|---|---|---|---|---|---|---|---|---|
| Control | | X | X | X | X | X | X | |
| Burn | 05/2019 | 03/2019 | 02/2019 | 06/2019 | 06/2020 | 05/2019 | 05/2019 | 03/2019 |
| Slash | 12/2018 | 02/2019 | 11/2018 | 12/2018 | 03/2020 | 01/2019 | 01/2019 | 11/2018 |
| 2 Slash | 12/2018 | | | 10/2021 | 11/2020 | 11/2020 | 11/2020 | |
| 1Slash 1Burn | 05/2019 | 03/2019 | 02/2019 | 06/2019 | 06/2020 | 05/2019 | 05/2019 | 03/2019 |
| 2Slash 1Burn | 11/2020 | 06/2019 | 11/2020 | 10/2021 | 10/2021 | 10/2021 | 11/2020 | |
| 1Slash 2Burn | 05/2021 | | 03/2021 | | 05/2021 | 05/2021 | 05/2021 | |

straight base, whereas resprouts usually resprouts exhibit a curved base.

The total monitoring duration varied depending on the treatment. Treatments requiring fewer management operations, such as single burn or slash, were monitored over a longer period. In contrast, treatments involving multiple interventions, (*e.g.,* 2 slash 1 burn) were monitored for a shorter period due to the time required to perform the initial management operations. Specifically, single treatments were monitored for 1080 days (~3 years), repeated slash were monitored for 720 days (~2 years), and combined treatments were monitored for 720 days except for the 1 slash−2 burn treatment, which was monitored for 360 days (~1 year). As the plots were monitored up to 3 years, some seedlings had developed into saplings by the end of the study. However, to maintain consistency and readability, we used the term "seedling" throughout the entire monitoring period.

## Data analysis

We used Generalized Linear Mixed Models (GLMM) to analyze the effect of different treatments and time, on the *density of resprouts,* the *density of seedlings,* and the *total density* (resprouts + seedlings). The total density was included because it is more meaningful from a management perspective, as managers are primarily concerned with the total number of new stems, regardless of their origin. To standardize the time variable, we used the time since the last treatment (hereafter, *TSLT*), in which we grouped all monitoring events into six-months intervals, resulting in two monitoring assessments per year. In order to better understand the isolated effect of each single treatment and their combinations, we developed four models for each dependent variable: (1) a model with single treatments (control, slash, burn); (2) a model with the number of slash treatments for plots with repeated slash, and (3, 4) two models with the number of slash treatments and burn treatments, specifically for slash and burn plots. One model included data for 720 days and the other for 360 days. *TSLT* was included as an explanatory variable in all models.

For single treatments, a Zero-inflated Negative Binomial model (ZINB, a specific case of GLMM) was used to address overdispersion caused by the high number of zeros in resprout and seedling counts (Zuur et al. 2009). For repeated and combined treatments, GLMMs were built with a negative binomial error distribution. The study *site* and the *plot* were initially included as nested random effects. However, following recommendations by Matuschek et al (2017) and Bates et al (2015), the model should always be simplified a priori, and because the variance–covariance of variable *plot* was close to zero, only the study site was included as a random factor. The fixed factors were *number of slashes*, *number of burns* and *TSLT*. Interactions between variables were tested in all models. Additional explanatory variables, such as *basal area*, *basal diameter*, *modal height*, *flame length* and *residence time*, were also tested. To avoid multicollinearity between explanatory variables, we used the variance inflation factor (VIF) from the R package car (Fox and Weisberg 2019) to select the final predictor variables. Variables with VIF > 4 were discarded, as this threshold is an indicator of highly correlated variables (Zuur et al. 2009). Basal diameter was removed from the model due to its high correlation with basal area. The variables basal area, modal height, flame length, and residence time were not retained in any of the final models due to their lack of significance. The GLMMs were built using the R package lme4 (Bates et al. 2015), and the ZINB models were built using the glmmTMB package (Brooks, et al. 2017). The significance of variables in the models was tested using ANOVA from the *car* package. The variance explained by the GLMMs was calculated using the MuMIn package (Bartoń 2009), which provides a marginal $R^2$ and a conditional $R^2$, that represent the variance explained by the fixed effects and the whole model respectively (Nakagawa and Schielzeth 2013). Model performance was evaluated using the performance package (Lüdecke et al. 2021). To address heteroscedasticity, the model residuals were verified using the DHARMa package (Hartig 2022). To assess the differences between treatments in each model, post-hoc Tuckey tests were performed.

For height analysis, a similar modelling approach was initially attempted, but the models performed poorly. Therefore, a Kruskal–Wallis test was used, followed by a post-hoc Dunn test (FSA package, Ogle et al. 2022) to evaluate significant differences in *height of resprouts*, *height of seedlings* and *total height* (resprouts + seedlings). These differences were assessed using the same criteria applied to build the density (single treatments, repeated slash treatments and combined slash and burn treatments). All

analyses were performed using *R* software (R Core Team 2023).

## Results

### Resprout density

Single treatments positively influenced the density of resprouts (Table S1), with slashed plots having significantly higher resprout density than control and burned plots ($p < 0.001$, Fig. 2A). While control and burned plots maintained consistent resprout density along TSLT, slashed plots peaked at one-year TSLT.

In the short term (up to 360 days TSLT), all combined treatments differed from *1 slash 1 burn*; but no differences were observed among other treatments. In the medium term (up to 720 days) *1 slash 1 burn* differed significantly from *2 slash 1 burn* ($p < 0.001$, Fig. 2G). The *1 slash 1 burn* treatment maintained a low resprout density compared to other combined treatments throughout the monitoring period.

### Germination density

The interactions TSLT*burn and TSLT*slash positively influenced germination density in single management treatments (Table S2). Control plots differed significantly from slash ($p = 0.042$) and burn ($p = 0.007$) plots, but no differences were found between the two treatments. Both slash and burn treatments maintained higher germination rates than the control throughout the monitoring period (Fig. 2B). The number of slashes did not affect germination density (Fig. 2E).

For combined treatments up to 360 days, slash and TSLT negatively influenced seedling density, while burn had a positive effect. All treatments differed significantly ($p < 0.001$), with *1 slash 1 burn* showing the highest germination (Fig. 2H). At the end of monitoring period (720 days) both slash and burn

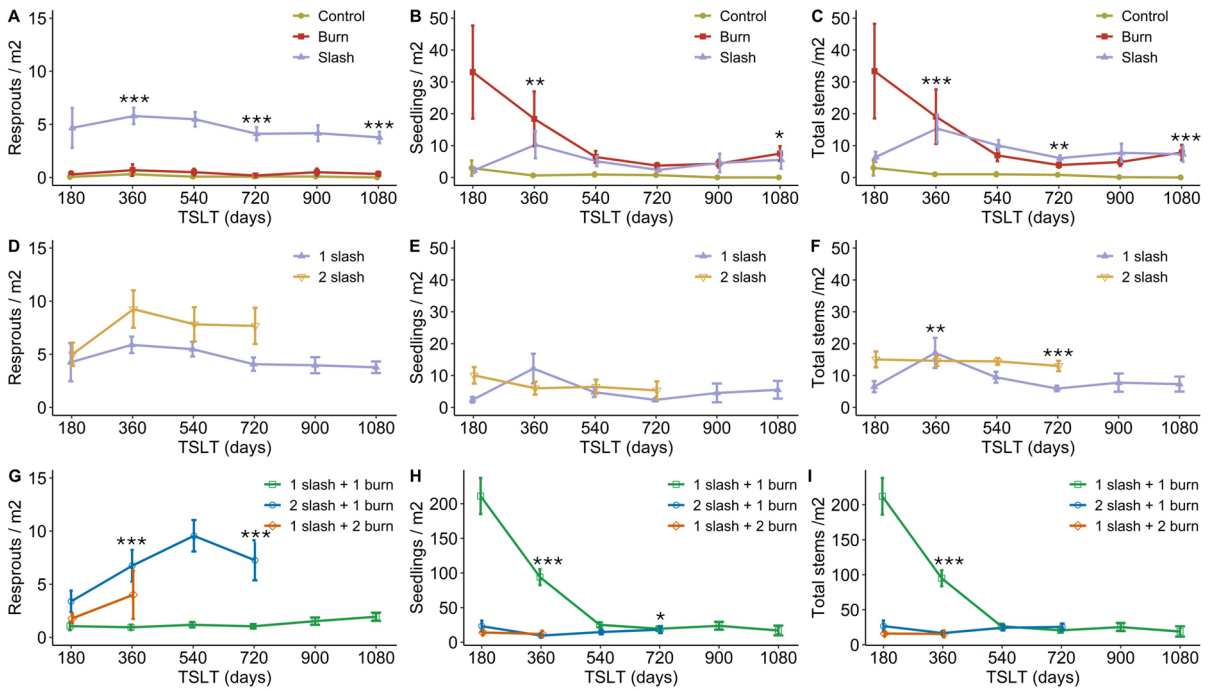



**Fig. 2** Average density (mean ± SE) of resprouts (**A**, **D**, **G**), seedlings (**B**, **E**, **H**), and average total density (**C**, **F**, **I**) of *Acacia dealbata* in plots subjected to different treatments: single treatments (**A**, **B**, **C**), repeated slash treatments (**D**, **E**, **F**), and combined treatments (**G**, **H**, **I**). TSLT indicates the number of days since the last treatment was applied. The graph shows the significance levels of the Tukey tests comparing treatments at each TSLT: ≤ 0.001 = ***; ≤ 0.01 = **; ≤ 0.05 = *; > 0.05 = not shown

negatively influenced seedling density, though their interaction had a positive influence. Significant differences were found between *1 slash 1 burn* plots and *2 slash 1 burn* plots.

### Total density

The total density of plants, including resprouts and seedlings, varied depending on the treatments applied and TSLT. Single treatments produced changes in total density (Table S3), with significant differences between control and burn plots ($p < 0.001$) and control and slash plots ($p < 0.001$), but no differences were found between the two treatments ($p = 0.806$). By the end of the experiment (3-year TSLT), control plots maintained a lower density compared to slash and burn plots (Fig. 2C).

Repeated slash and TSLT negatively influenced the total plant density. Significant differences were observed between 1 and 2 slash plots ($p < 0.001$). While 1 slash initially had higher stem density (180 days), after 2 years-TSLT, 2 slash presented the highest density (Fig. 2F).

Combined treatments revealed a negative influence of the number of burns, number of slashes and TSLT on total density up to 360 days, with significant differences between all combined treatments. In the medium term, differences were particularly notable between *1 slash 1 burn* plots and *2 slash 1 burn* plots (Fig. 2I).

### Resprout height

Significant differences in resprout height were observed among treatments at 360 days, with slash showing higher resprout height compared to burn (Fig. 3A). By 720 days, no differences were detected.

For repeated slash treatments no differences were observed at 360 days but at 720 days, 1 slash plots had taller resprouts compared to 2 slash plots (Fig. 3D).

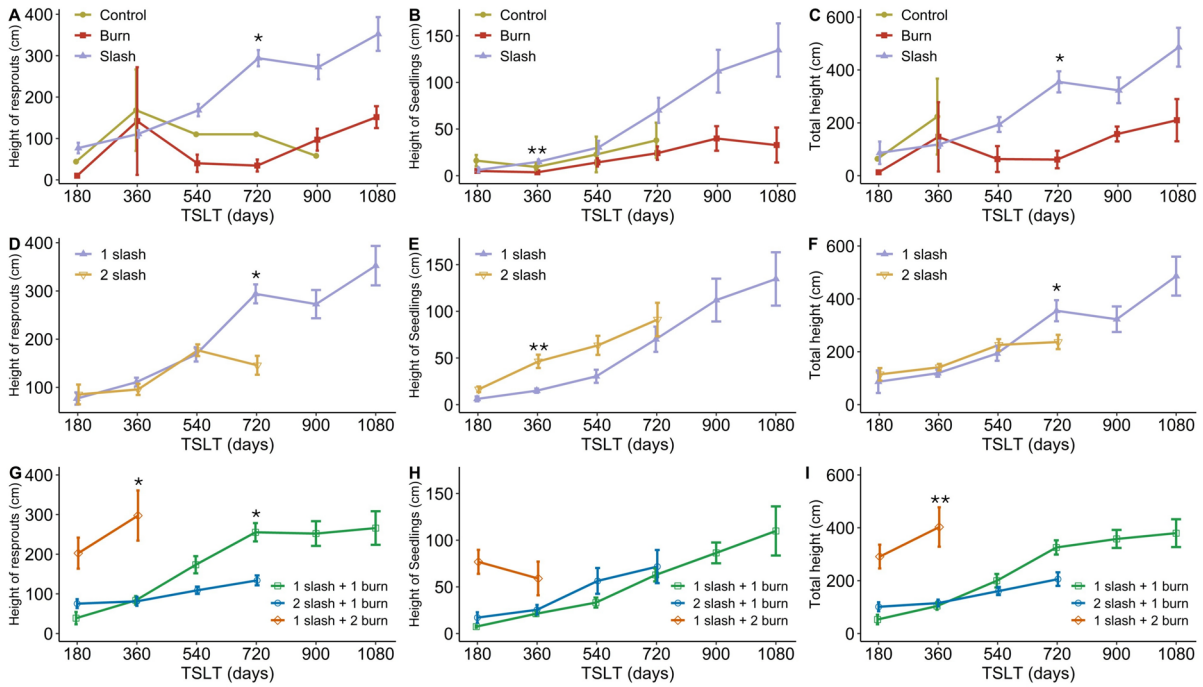



**Fig. 3** Average height (mean ± SE) of resprouts (**A**, **D**, **G**), seedlings (**B**, **E**, **H**), and average total height (**C**, **F**, **I**) of *Acacia dealbata* in plots subjected to different treatments: single treatments (**A**, **B**, **C**), repeated slash treatments (**D**, **E**, **F**), and combined treatments (**G**, **H**, **I**). TSLT indicates the number of days since the last treatment was applied. The graph shows the significance levels of the Kruskal–Wallis tests comparing treatments at each TSLT: ≤ 0.001 = ***; ≤ 0.01 = **; ≤ 0.05 = *; > 0.05 = not shown

In combined management operations, height of resprout differed at both 360 days and 720 days. In the medium term, *1 slash 1 burn* plots had taller resprouts than *2 slash 1 burn* plots (Fig. 3G). In the short term, *1 slash 2 burn* plots showed the highest resprout height among all combined treatments.

### Seedlings height

The average height of seedlings in control plots increased from 360 to 720 days (Fig. 3B). Significant differences were found at 360 days but not at 720 days, when seedlings in burn plots were significantly shorter than those in slash plots.

For repeated slash treatments, differences were observed at 360 days, with seedlings in 1 slash plots being taller than those in 2 slash plots, but no differences were found at 720 days (Fig. 3E).

In combined management operations, seedling height did not differ among treatments at either 360 days or 720 days (Fig. 3H).

### Total height

The mean total height showed no differences at 360 days but differed at 720 days, with slash plots being taller than burn plots (Fig. 3C). For repeated slash treatments, no differences were observed at 360 days, but at 720, 1 slash plots had lower total height than 2 slash plots (Fig. 3F).

In combined treatments, differences were detected at 360 days but not at 720 days. Specifically, *1 slash 1 burn* plots had lower total height than *1 slash 2 burn* plots (Fig. 3I).

## Discussion

### Effects of management operations on resprouting

Results from the slash and burn experiments produced models with very different $R^2$ values. In this section we only discuss the results of models with $R^2 > 0.10$. Single treatments stand out for a higher density of resprouts in slashed plots, although time had a negative influence, meaning that density of resprouts decreased over the course of the experiment. The decline may be explained by the initial sprouting vigor and post-resprouting competition among stems (Matula et al. 2019). The initial increase of density aligns with findings from other studies (Perrando and Corder 2006; Le Maitre et al. 2011), in which slashing acacias produced similar results. Although burning the plots did not affect the density of resprouts, it reduced their height compared to the control plots. This is likely because the fire killed the existing resprouts at the time of burning, and the resprouts measured in later monitoring were new growth.

Combined slash and burn treatments resulted in lower densities of resprouts in *1 slash 1 burn* plots throughout the experiment. However, plots with combination of a higher number of slashes or burns showed increased densities of resprouts, consistent with findings by Le Maitre et al. (2011), who concluded that acacias rapidly increase their density through resprouting after disturbance. Increasing the number of burns also led to higher densities. It is plausible that plots exposed to more slashes and burns experienced increased resprout density due to the activation of dormant buds and the mobilization of accumulated reserves caused by the disturbance (Pausas et al. 2016). On the other hand, treatments may have a differential effect only in the early stages; one year after the treatments there were no differences among combined treatments. Other factors, such as nutrient depletion of the stump, environmental conditions, soil water or nutrient availability, or the pre-disturbance state of plants could later lead to a homogenization of resprout height, as demonstrated for other *Acacia* species (Moreira et al. 2012; Matsuni et al. 2024). It has been shown for other species that the number of resprouts following disturbances and their heights are neither positively nor negatively correlated (Choeni and Sebata 2014).

### Effects of management operations on germination

Single treatments resulted in an increase in seedling density by the end of the experiment in both slash and burn plots, whereas repeated slash treatments caused a decrease in density over time (TSLT). Repeated disturbances deplete the soil seed bank in two ways: (1) seeds germinate and establish, gradually reducing the number of seeds in the soil seed bank, and (2) repeated slashing reduces the number of adult individuals capable of producing new seeds to replenish the soil seed bank. Additionally, repeated slashing

damages established seedlings, impairing nutrient uptake and affecting plant growth and survival. On the other hand, *A. dealbata* seeds possess intraspecific biochemical recognition (Renne et al. 2014; Yannelli et al. 2020; Riveiro et al. 2024), which facilitates the germination and seedling establishment in already colonized areas. Therefore, a reduction in this biochemical stimulus, caused by the decrease in the number of adult plants, would inhibit the germination of seeds from the soil seed bank.

Combined treatments demonstrated that TSLT has a negative influence on seedling density. This is likely caused by the inherent mortality of seedlings, which is naturally high even without disturbances, combined with the depletion of the soil seed bank. As seeds germinate and new plants have not yet produced seeds, the seed bank is not replenished, further reducing seedling density over time. Other studies have emphasized the necessity of performing repeated management actions to control populations of acacias and other fire-adapted species (Morais et al. 2021; Duarte et al. 2023).

The highest seedling density occurred in plots with *1 slash 2 burn*. Seeds of *A. dealbata* are stimulated by moderate temperatures (Cruz et al. 2021), meaning that controlled burns can trigger a massive event of germination due to the temperature stimulation of seeds. Studies on similar *Acacia* species have shown that burning standing populations is not a feasible approach, as it increases germination post-fire (Pieterse and Boucher 1997).

### Effects on total density and height

Due to the complexity of interpreting separate models for density of resprouts and seedlings, and the practical utility of combined models from a management perspective, we considered it necessary to study total density to have a broader understanding. The best results in terms of reducing total plant density were achieved with combined treatments, as all studied factors contributed to a decrease in density. These treatments showed more significant effects in the short term compared to the medium term. Over time, additional factors likely influenced the forest system, such as predation, climate, or nutrient availability (Gibson et al. 2011; Wandrag et al. 2013; Souza-Alonso et al. 2017).

It would be interesting to explore repeated burns, given their reducing effect on total plant density in combined treatments, as well as a higher number of slashes, due to the promising results observed in repeated slash models. However, other authors have demonstrated that some *Acacia* species are highly resistant to forest fires, even those of high severity (Gordon et al. 2017). Additionally, short intervals between fires did not decrease the number of acacias in already colonized areas, although they altered the characteristics of the acacia individuals present, producing more superficial buds that were more susceptible to fire than deeper buds (Wright and Clarke 2007). Simple slashing and burning, even for other fire-adapted species like *Hakea sericea* (despite their different fire adaptations), have proven to be unsuitable control methods and are associated with high ecological impacts on soil structure and species diversity (Breytenbach 1989; Morais et al. 2021).

### Effectiveness of disturbance methods to control *Acacia dealbata*

Numerous factors could influence the results of slash and burn experiments on *A. dealbata.* Some of these factors were included in the experiment and proved relevant to the study, such as the number of slashes and burns performed and the time since last treatment (TSLT). Other factors, although studied, did not significantly affect the results, including parameters related to the characteristics of the former acacia population (basal area, basal diameter, DHB, and modal height) or fire behavior variables (flame length and residence time). Previous studies have shown that the residence time of fire does not affect the recovery success of other resprouting species (Canadell et al. 1991).

Some factors that, according to previous studies, could help to understand the effect of treatments on stem density were not examined. These include the season of treatment –typically, post-fire resprouts in spring are more vigorous than those in summer (Konstantinidis et al. 2006; Malanson and Trabaud 1988) — as well as the height of cutting in slash treatments, which in our study was performed very close to the ground. Other studies concluded that lower cutting heights yield better results in preventing resprouting (Shackleton 2000). Although the age of the population was not explicitly considered,

we studied the DBH and modal height of the previous *Acacia* population, so it is unlikely that the results would differ significantly from those obtained for these variables.

When interpreting the results produced in this study, it is important to consider the timing of the treatments. Other authors have stated that the best season in which to carry out control measures to avoid resprouting in acacias is summer (Perrando and Corder 2006). However, conducting experiments in summer would not be realistic for practical application, as the use of fire is prohibited during this season in most Mediterranean countries. Instead, we aimed to simulate the effect of prescribed burns, which are typically conducted during the wet, cold season. We observed low efficiency of burns during this period, primarily due to the compacted litter and absence of other vegetation, which made it difficult to ignite and spread the fire. As a result, multiple ignition points were often required in each plot, and in some cases, the fire did not spread evenly across the plot.

The use of fire to control populations of other fire-adapted species has proven ineffective on its own, partly due to the challenges of setting fire to the invader stands. However, combining fire with other control methods (herbicide treatment or bulldozing) improved results (Paynter and Flanagan 2004). Nevertheless, these methods are highly aggressive and have the potential to hinder the natural regeneration of native species (Kato-Noguchi 2023). Other studies have explored the use of slashing after resprouts emerge following a forest fire in other *Acacia* species, and some reported reduced numbers of individuals. However, the decrease in density was not as significant as expected and did not result in an effective control method (Krupek et al. 2016).

The control of *A. dealbata* in Portugal, typically consists of simple slash operations (Passos et al. 2017; Marchante et al. 2023). However, these methods have been shown to be ineffective for completely eliminating the plants (Fernandes 2008), particularly when no follow-up treatments are applied, as observed in *A. longifolia* populations (Duarte et al. 2023). *Acacia dealbata* is classified as an R + P + strategist, meaning it is both a resprouter and a propagule persister, according to Pausas et al. (2004). It resprouts from root suckers, which enhances its success following disturbances (Clarke et al. 2013). These traits explain its strong resilience to slash and burn practices.

Our results suggest that aggressive methods to control species that are highly adapted to disturbances, such as fire and cutting, may not be adequate to achieve long-term population reduction of invasive alien species like *A. dealbata* without consistent follow-up interventions. None of the treatments applied were able to prevent either resprouting or new germination. While some treatments appeared to reduce the seed bank, they did so at the expense of recruiting a massive number of new seedlings. This highlights the necessity of follow-up interventions to target seedlings or saplings before they reach maturity, to achieve effective population reduction. While our study demonstrates that slash-and-burn treatments, applied up to three times, are insufficient to control *A. dealbata* populations, it also suggests that with consistent and well-timed follow-up interventions, effective management of this invasive species is possible. Further work is needed to explore the long-term effectiveness of combined treatments with regular follow-up to optimize control strategies. Slower, but more ecologically-based solutions should also be included in future studies. For example, the potential use of seedling browsing or tree debarking, combined with shading to prevent new germination and reduce seedling growth (Martin et al. 2009), could be explored. However, these methods are probably only applicable in limited situations and require further experimental validation. Further studies should therefore focus on obtaining experimental evidence for these approaches which is lacking in the existing literature on the management of *A. dealbata*.

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**Declarations**

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