Ecological Engineering 228 (2026) 108001

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Assessing early-stage natural regeneration and reforestation after wildfires using *Cistus ladanifer* (rockrose) as an indicator species

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A R T I C L E I N F O

Keywords:
Post-fire reforestation
Assisted natural regeneration
Early-stage response
Rockrose
Allometric models
Eco-physiological responses
indicator plant

A B S T R A C T

Wildfires pose an increasing threat to many ecosystems worldwide. While part of Mediterranean ecosystems, fire frequency and severity have been drastically increasing, necessitating assisted reforestation and regeneration. Success of these efforts is difficult to quantify, as many facets of ecosystem regeneration must be measured, such as survival of planted species and native vegetation cover. We propose gum rockrose (*Cistus ladanifer*) as an early stage bioindicator of post-fire ecosystem recovery by relating some of its ecophysiological and allometric traits to reforestation success with native tree species and patterns of natural regeneration. Specifically, we (i) quantify traits of rockrose in different treatments; (ii) relate them to survival rates of planted species and indicators of natural regeneration and (iii) develop allometric biomass models to assess fuel load and competitive pressure. After 12 months, rockrose height was 20.5 cm in the vegetation removal treatment, increasing to 28.5 where swales were applied and nearly doubling if swales were filled with woodchip or compost (38.3 and 35.3 cm, respectively). Survival rates of planted species increased in a similar way (13.6% in the swales and 46.9% in the compost treatment) while natural regeneration decreased (463.1 g/m^2 for vegetation removal and 175.1 g/m^2 in the compost treatment). Our results demonstrate that rockrose is a promising candidate to serve as an indicator species and especially some of its ecophysiological parameters such as leaf area, plant height and abundance deserve further attention as simple variables to estimate overall ecosystem response.

1. Introduction

Wildfires have increased in extension, frequency, intensity and severity in Portugal over the past decade (Mateus and Fernandes, 2014; Turco et al., 2019; Anjos et al., 2022). The country is part of the Mediterranean ecosystem, where fire is a significant ecological disturbance and regenerative process (Pausas et al., 2008). However, in recent decades, wildfires have increased in intensity and magnitude and have lost their ecological role, becoming a highly relevant environmental problem in the area (Larchevêque et al., 2005; Anjos et al., 2022).

Such fire events are posing significant challenges to the functioning of the ecosystems, and besides the loss of vegetation, they may trigger soil erosion and associated losses of soil organic matter and soil microbiota perturbation, finally leading to desertification, thus creating a necessity for post-fire rehabilitation strategies (Guerrero et al., 2001; De Luís et al., 2001; Gomez-Aparicio et al., 2004; González-Pelayo et al., 2024; Prats et al., 2014). Reforestation and natural regeneration are both crucial components of such strategies, aiming to restore biodiversity, ecosystem functionality, and mitigate soil erosion (Vizinho et al., 2023). However, in order to select the most cost-effective strategies,

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https://doi.org/10.1016/j.ecoleng.2026.108001
Received 21 April 2025; Received in revised form 26 January 2026; Accepted 30 March 2026
Available online 17 April 2026

indicators must be developed to quickly and reliably measure the successfulness of the restoration plan. Post-fire rehabilitation strategies consist mainly of the sum of various operations involving the use of heavy machinery, such as post-fire salvage logging, soil preparation through subsoiling or soil ripping creating swales along contour lines, as well as the planting of seedlings with the addition of diverse soil ameliorants such as mulches, wood chips, compost, etc. (Bohlman et al., 2016; Carmona-Yáñez et al., 2023; Lucas-Borja et al., 2021). These operations typically impact the soil and plant development itself (Prats et al., 2021; Prats et al., 2022), but without the use of a robust ecologic indicator, it is unknown whether the methods are cost-effective or not (Gomez-Aparicio et al., 2004; Moreira et al., 2009).

Cistus ladanifer L., commonly known as gum rockrose, is a dominant obligate seeder shrub endemic to the Mediterranean region (Frazão et al., 2018). It generally shows a high abundance after fire and other disturbance events and it was previously used as an indicator species of Portuguese landscapes (Muñoz and Alcántara, 2013), which makes it an excellent candidate to explore as a potential bioindicator species of ecosystem recovery. Moreover, the impact of *C. ladanifer* on other species could be negative or positive, as it has been described as both a competitive and a nurse plant, respectively. Various authors claim that its presence can trigger competition for water and nutrients and inhibit the growth of several other plants by releasing allelochemicals (Bohlman et al., 2016; Frazão et al., 2018). Other authors claim that this species plays an important role in water-limited systems by controlling erosion, maintaining biodiversity, supporting the development of plant growth-promoting rhizobacteria and ectomycorrhiza, as well as facilitating tree regeneration (Castro et al., 2002; Ramos Solano et al., 2007; Ruiz-Peinado et al., 2013; Vizinho et al., 2023; Ulm et al., 2017). The presence of *C. ladanifer* is also of high biological interest because it quickly establishes in poor or burned soils and contributes to carbon sequestration (Silva Dias et al., 2019).

The main aim of this study was to evaluate the performance of *C. ladanifer* as an early-stage bioindicator of ecosystem recovery following wildfire in a Mediterranean ecosystem. Specifically, the objectives were to: (i) quantify the ecophysiological (e.g. growth rate, leaf area) and allometric traits (e.g. plant height, dry and fresh biomass) of *C. ladanifer* over one year under four treatments: bulldozer plant removal, swale creation, swale creation with woodchip application, and swale creation with compost application; (ii) relate *C. ladanifer* ecophysiological and allometric responses to restoration success, assessed through survival rates of planted species (*Quercus suber*, *Arbutus unedo*, and *Rosmarinus officinalis*) and indicators of natural regeneration (e.g. dry and fresh biomass and vegetation cover); and (iii) develop allometric models to estimate *C. ladanifer* biomass in order to assess potential fuel load and competitive pressure, and to identify key predictors of reforestation success and natural regeneration dynamics.

2. Materials and methods

2.1. Setup and experimental design

The experimental site was located in the south of mainland Portugal, Algarve (37°0.1420 N, −8°0.8119 E) and is characterized by a Mediterranean climate, with cold winters and hot summers (Csa, Köppen climate classification) and an annual rainfall average of 550 mm for the period 1979–2020 at the nearest Meteorological station of Bensafrim (6 km east; SNIRH, 2022). It is located on an east-facing slope with an inclination of 10–15°, an elevation varying from 150 m a.s.l. to 180 m a.s.l. A forest fire on 19 June 2020 burned a total of 2200 ha of mainly cork oak (*Quercus suber*), pine (*Pinus pinea*), eucalypt plantations (*Eucalyptus globulus*) and *C. ladanifer* shrubland. Before this fire, the experimental site was occupied by mosaics of shrublands dominated by *Cistus ladanifer* and *Ulex argenteus* subsp. *argenteus*, interspersed with grasslands composed of greater quaking-grass (*Briza maxima*), cock's-foot (*Dactylis glomerata*), and purple false brome (*Brachypodium phoenicoides*). Scattered cork oaks and strawberry trees (*Arbutus unedo*) were also present, reflecting anthropogenic degradation, currently driven by recurrent fires, but formerly by livestock grazing, of the cork oak woodlands that would potentially occur in this area under natural conditions (Vila-Viçosa and Arsénio, 2021). The site was divided into 19 adjacent square plots of 100 m^2 on which four treatments were applied: “Machine”, “Swales”, “Woodchip” and “Compost” (Fig. 1). These treatments were created using the following methodology: A 20-tons bulldozer (KOMAT'SU D65EX-18, California, US) was driven across the site, using the shovel blade to remove pre-existing burned vegetation in October 2020 (“Machine” plots; $n = 5$). After that, the same machine reworked the plots to create the other three swale treatments (Swale, Woodchips, Compost) with a ripper to excavate 30 cm ditches on contour every 2 m. Subsequently, the swales were either left uncovered (“Swales” plots; n = 5), filled with wood chips (“Woodchip” plots; $n = 4$; 117 tons per hectare), or filled with compost (“Compost” treatment plots; n = 5; 134 tons per hectare). The application of compost and woodchips was carried out using a tractor equipped with a linear dispersion system (Polycrok 1750, Kuhn, Saverne, France) and took place in January 2021. To estimate fire severity, the Twig Diameter Index (mean diameter of the smallest twigs after the fire) was used. For each treatment, the diameter of the tip of five randomly selected twigs from the soil surface per plot was measured with a calliper, and the mean value was used as the TDI. The average diameter was calculated for each treatment and then re-scaled by dividing by the maximum diameter measured in this study, resulting in an index that ranged from 0 to 1. As the TDI values did not differ among treatments (Machine =0.30; Swale = 0.38; Woodchip =0.40; Compost = 0.32), fire severity was considered of moderate severity, and comparable across all plots (Keeley, 2009; Maia et al., 2012).

In spring 2021, after the plots were established, three different species were planted: cork oak (*Quercus suber* L.), rosemary (*Rosmarinus officinalis* L.) and strawberry tree (*Arbutus unedo* L.).

2.2. Soil sample collection

In each plot, a random composite topsoil (ca. 10 cm depth) sample, gathered from five locations inside each plot, was collected in spring 2021, resulting in a total of 19 samples. Following collection, samples were weighed to determine fresh weight and subsequently placed in a drying oven (Memmert, Schwabach, Germany) at 65 °C until constant weight. The dried samples were then re-weighed to establish dry weight and calculate soil moisture. Subsequently, samples were sieved at 2 mm and the fine portion was ground using a ball mill (Mixer mill MM 400, Retsch, Haan, Germany) to ensure homogeneity. The powdered samples were then used to quantify soil organic matter (SOM), using a modified loss on ignition method as described by Heiri et al. (2001). For this technique, precise amounts (1 ± 0.02 g) were weighed on a fine scale (AS 220.R2, Radwag, Radom, Poland) into crucibles and subjected to controlled burning in a muffle oven (L3, Nabertherm, Lilienthal, Germany) at 550 °C for a duration of 4 h. After cooling to room temperature, the resulting ashes were re-weighed to determine SOM percentage.

2.3. Green vegetation cover and biomass collection

Both green vegetation cover of naturally regenerated (NR) plants (GVC_{NR} [%]) as well as vegetation biomass wet weight (WW_{NR} [g]) were assessed in April 2022. We focused on the first year after planting due to the consistently low seedling survival rates, particularly among oaks, observed in restoration efforts across the Mediterranean region (Acácio et al., 2024). Both green vegetation cover of naturally regenerated (NR) plants (GVC_{NR} [%]) as well as vegetation biomass wet weight (WW_{NR} [g]) were assessed in this first year (April 2022). Across the four treatments, NR vegetation was dominated by herbaceous species, which accounted for most of the total cover in all plots and eight shrub species. While *Arbutus unedo*, *Asparagus aphyllus* and *Quercus suber* are resprouter

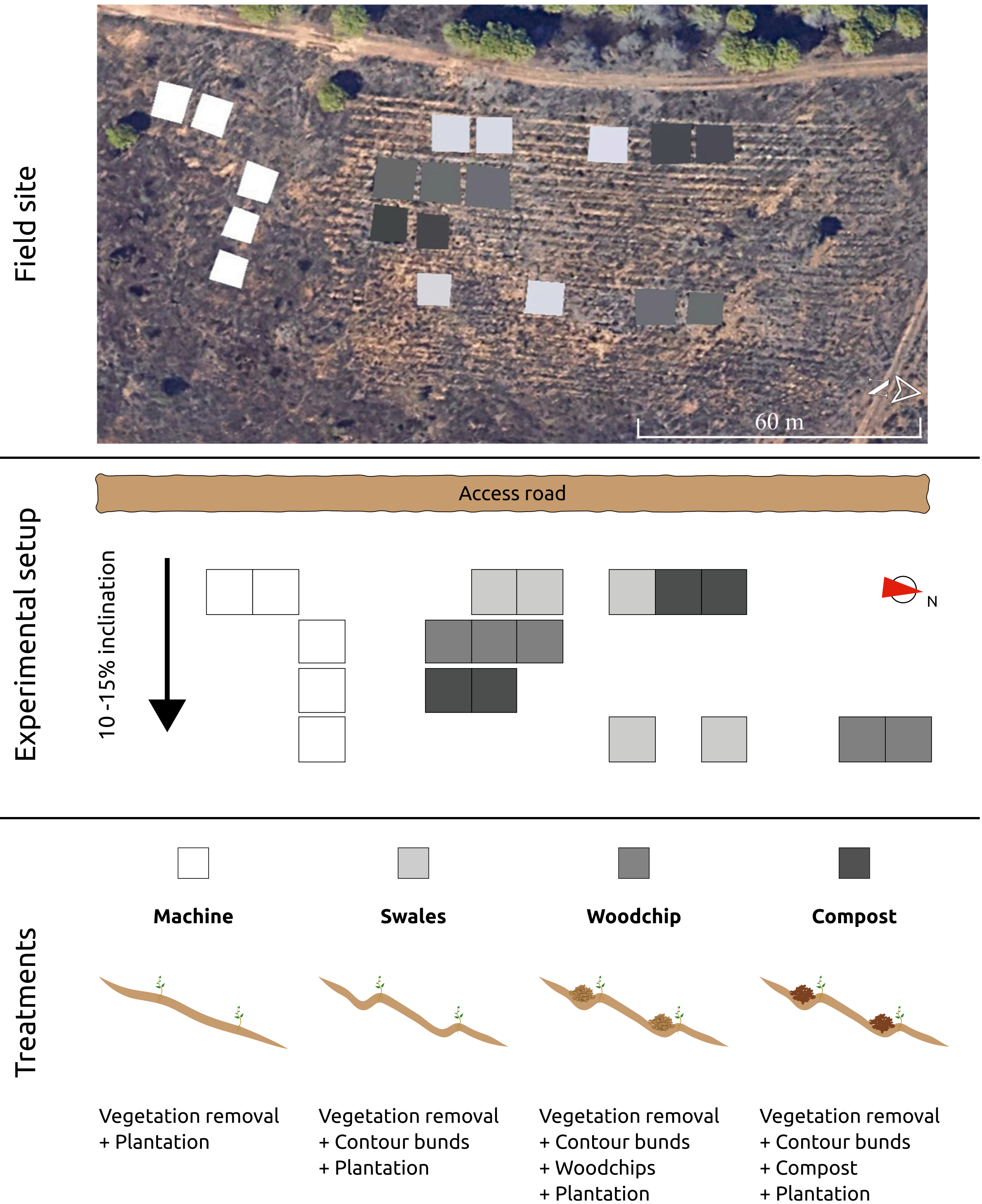

Fig. 1. Experimental site (above), plot setup on site (mid) as well as treatment setup (below).

shrub species (they resprout from surviving parental tissues), *Cistus ladanifer*, *C. salviifolius*, *Genista hirsuta*, *Lavandula stoechas* and *Ulex argenteus* are seeders (individuals die but release seeds able to germinate) (Chozas et al., 2017; Chozas et al., 2025). The GVC_{NR} was randomly measured in each plot, using a 0.34 m^2 (58 cm × 58 cm) quadratic frame. Six pictures per plot were taken vertically at a height of 1.20 m above the frame, three in between the swales and three on the swales. The images were then processed using Photoshop software (Photoshop, Adobe, San José, USA) and cropped by perspective. The calculation of the GVC_{NR} was carried out using the Canopeo web application (2022 Canopeo App, Oklahoma State University Department of Plant and Soil Sciences, Oklahoma City, USA), which generates a percentage of GVC_{NR} for each image by classifying the image according to ratios of RGB (Chung et al., 2017; Patrignani & Ochsner, 2015). Naturally, GVC_{NR} includes all naturally regenerated herbaceous and shrubs, while planted specimen were avoided.

Vegetation biomass wet weight (WW_{NR}) was determined by harvesting all aboveground vegetation >1 cm in height from a 20 × 20 cm quadrat (400 cm^2) in the upper left corner of the GVC_{NR} frame. Vegetation biomass was then collected from three sampling points (the in-between contour bund samples) and joined to form one composite sample. Samples were stored in a cool place in hermetic bags until they were weighed to determine WW_{NR} (PGW3502e, AdamLab, Oxford, UK). The samples were then dried in an oven at 65 °C (Memmert, Schwabach, Germany) until constant weight to determine the naturally regenerated vegetation dry weight (DW_{NR}) and vegetation humidity (Hu_{NR}).

2.4. Cistus ladanifer collection

In April 2022, three *C. ladanifer* individuals taller than 15 cm were randomly selected and harvested in each plot. Rockrose plants were first measured from the highest point to the ground for total height (H_{Cistus}; cm) and then cut at ground level. The three plants were placed in a hermetic bag and stored in a cool place before the total sample was weighed (PGW3502e, AdamLab, Oxford, UK) to determine WW_{Cistus}. The three plants were then treated individually for further analysis. The new growth height of the plant was determined by measuring the green, non-lignified part of the stem, while old growth height was calculated by removing the new growth height from the total height. Growth rate (GR_{Cistus}) was then determined by dividing total plant height (H_{Cistus}) by new growth height. Stem diameter (D_{Cistus}; cm) was measured with a calliper (DIN 862, Wurth, Künzelsau, Germany) at soil level. On each plant, the number of branches was counted in addition to the main stem (NrB_{Cistus}; branches/plant]). To calculate the leaf area (LA_{Cistus}; mm^2) of each plant, four leaves were randomly selected from each plant and placed on an A4 sheet. After covering the sheet with a Plexiglas plate to flatten the leaves, a picture of the leaf was taken, processed using Photoshop (Adobe, San José, USA) and leaf area then calculated using ImageJ software (Image J, National Center of Health, Bethesda, USA). To calculate specific leaf area (SLA_{Cistus}; mm^2/mg), individual leaves were placed at 65 °C in a drying oven (Memmert, Schwabach, Germany) until constant weight and weighed (AS 220.R2, Radwag, Radom, Poland). Total dry and wet weights and plant humidity (DW_{Cistus}, WW_{Cistus} and Hu_{Cistus}), were determined from the whole composite samples of each plot, after weighing and a drying oven at 65 °C (Memmert, Schwabach, Germany) until constant weight (AS 220.R2, Radwag, Radom, Poland). Plant abundance (unit/plot) was assessed from the pictures used in the GVC_{NR} determination.

2.5. Survival rate of planted trees and shrubs

Several native shrubs and trees were planted in January 2021. Originally, ten seedlings each of cork oak (*Q. suber*), rosemary (*R. officinalis*) and strawberry tree (*A. unedo*) were planted per plot (0.3 plants/m^2), summing up to a total of 570 plants in the 19 plots. The survival of seedlings planted was visually certified in December 2021 along with measuring all plants using a meterstick and survival rate was then expressed in % for each species (SR_{Qsub}, SR_{Roff} and SR_{Aune}, respectively) as well as all species together (SR_{Tot} [%]).

2.6. Statistical analysis

Allometric variables were used as indicators of plant size and growth, reflecting biomass allocation and structural development. The whole data set was separated into five groups, of which two were related with *C. ladanifer* variables and three groups related with response variables. *C. ladanifer* groups are: Allometric variables (Dry weight [DW_{Cistus}]; Number of branches [NrB_{Cistus}]; Height [H_{Cistus}]; Stem diameter [D_{Cistus}]) and Ecophysiological (EPP) parameters (Leaf area [LA_{Cistus}] Specific leaf area [SLA_{Cistus}]; Plant humidity [Hu_{Cistus}]; Growth rates [GR_{Cistus}]). Response variables were: Regeneration parameters (Green vegetation cover [GVC_{NR}]; Vegetation dry and wet weight [DW_{NR}, WW_{NR}]; Vegetation humidity [Hu_{NR}]), Planted species survival rates (Total survival rates [SR_{Tot}]; *Arbutus unedo* survival rates [SR_{Aune}]; *Quercus suber* survival rates [SR_{Qsub}]; *Rosmarinus officinalis* survival rates [SR_{Roff}]) and Soil related parameters (soil organic matter [SOM] and soil water content). To compare treatment effects, pairwise Welch's *t*-tests were conducted, with treatment as grouping factor and, when the normality assumption was not met (using Shapiro wilk test for normality), pairwise Wilcoxon's t-tests were employed.

Allometric biomass models were created for plant height (H_{Cistus}), number of branches (NrB_{Cistus}) as well as stem diameter (D_{Cistus}) and combinations thereof, to predict total plant dry weight DW_{Cistus} via linear regression models. By describing these models using both r^2 and the Akaike Information Criterion (AIC), best fit and most parsimonious models could be selected. The final model chosen (Fig. 2) had a non-heteroscedastic error structure ($p = 0.153$, studentized Breusch-Pagan test).

Concerning multivariate analysis, procedures for community ecology data were applied (Oksanen et al., 2022). This involved variance partitioning as explained by different sets of predictors, performing a constrained ordination via redundancy analysis, and refining this model through stepwise variable selection that combined both forward and backward methods (Blanchet et al., 2008). The statistical significance of the redundancy analysis model was tested using the *anova.cca()* function, which employs a permutation test on either the total model or on selected axes of the model output. To clarify the data's variance structure, an initial, non-canonical, exploratory analysis was conducted using principal component analysis (PCA), with ellipses calculated depicting standard error of the factor centroids. This was followed by a canonical, constrained ordination using redundancy analysis (RDA) to identify the key environmental variables related to *C. ladanifer* that best explain variance in natural regeneration and planting success. Variable partitioning on the blocks of explanatory variables described above was performed for survival rates and natural regeneration.

Statistical analyses were performed with the package "*stats*" using R version 4.2.1 (R Core Team, 2022) and executed on RStudio (Version 2023.06.0). Further packages used were "*lmtest*" (Zeileis and Hothorn, 2002) as well as "*dplyr*" (Wickham et al., 2022) and "*magrittr*" (Bache and Wickham, 2022) for data manipulation.

3. Results

3.1. Plant allometric and ecophysiological parameters

Cistus ladanifer allometric and ecophysiological parameters varied significantly with the soil treatments (Table 1). The most vigorous rockrose individuals were found in the Woodchip treatment, which yielded the tallest plants (38.3 cm), greatest new growth (28.8 cm), largest stem diameter (0.5 cm), highest growth rate (5.6), and largest leaf area (9.2 cm^2). The Compost treatment promoted the most developed plant structure, producing the highest number of branches (3.7 per plant) and the greatest dry weight (9.1 g). Plant humidity was highest in Woodchip and Compost treatments (68.7% and 66.0%, respectively), significantly exceeding the Machine treatment (61.0%). The Machine treatment resulted in the highest *C. ladanifer* abundance (40.8 plants m^{-2}) but supported the smallest individuals, with the lowest new growth height (14.6 cm), stem diameter (0.3 cm), and number of branches (0.4 per plant).

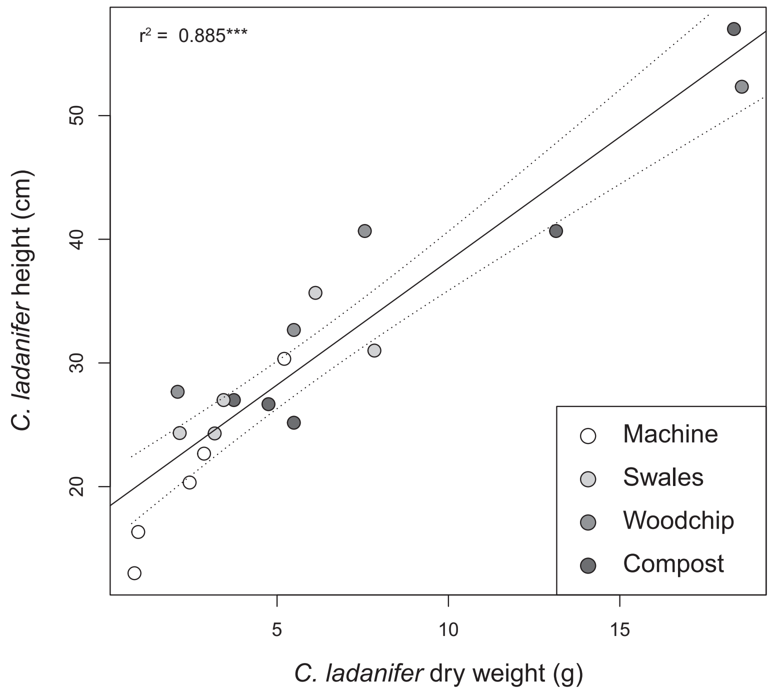

Fig. 2. Allometric biomass model for *Cistus ladanifer* dry weight versus plant height ($n = 19$), r^2 = coefficient of determination; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.

Table 1

C. ladanifer allometric and ecophysiological parameters, as well as planted species survival rates in each treatment. The numbers are given as means, letters represent the significant differences by treatment for each variable, calculated by Pairwise-*t*-test or Pairwise-Wilcox-test (*) in case the variables did not respect normal distribution and homoscedasticity of variances.

	Machine	Swales	Woodchip	Compost
Cistus ladanifer Allometric parameters				
Plant height (H_{Cistus}, cm)	20.5	28.5	38.3	35.3
Plant new growth height (cm)	14.6 (a)	19.8 (ab)	28.8 (b)	23.3 (ab)
Plant old growth height (cm)	5.9	8.7	9.6	12
Stem diameter (D_{Cistus}, cm)	0.3 (a)	0.4 (ab)	0.5 (b)	0.5 (ab)
Number of branches (NrB_{Cistus}, per plant)	0.4 (a)	1.3 (ab)	1.8 (ab)	3.7 (b)
Plant wet weight (WW_{Cistus}, g)	6.6	13.7	26.8	26.1
Plant dry weight (DW_{Cistus}, g)	2.5	4.5	8.4	9.1
Cistus ladanifer Ecophysiological parameters (EPP)				
Growth rate (GR_{Cistus})	3.7	3.4	5.6	3.3
Plant humidity (Hu_{Cistus}, %)	61 (a)	66.4 (ab)	68.7 (b)	66 (ab)
Leaf area (LA_{Cistus}, cm^2)	5.1 (a)	7.7 (ab)	9.2 (b)	8.2 (ab)
Specific leaf area (SLA_{Cistus}, mm^2/mg)	0.5 (a)	0.6 (ab)	0.6 (b)	0.5 (ab)
Plant abundance ($number/m^2$)	40.8 (a)	7.1 (b)	5.5 (b)	7.9 (b)
Planted species survival rates				
General survival rate (SR_{tot}, %)	13.6 (a)	21.7 (ab)	40.1 (bc)	46.9 (c)
A. unedo survival rate (SR_{Aune}, %)	25.3 (a)	33.1 (ab)	42 (ab)	72 (b)
Q. suber survival rate (SR_{Qsub}, %)	20.3 (a)	41.1 (ab)	68.4 (b)	72 (b)
R. officinalis survival rate (SR_{Roff}, %)	17.5	15.3	45	48
Natural regeneration variables (NR)				
Dry Biomass (DW_{NR}, g/m^2)	463.1 (a)	384.5 (ab)	283.3 (ab)	175.1 (b)
Wet Biomass (WW_{NR}, g/m^2)	1564.9	1689.8	1365.1	949.8
Green vegetation cover (GWC_{NR}, %)	34.2	30.3	28.1	26.3
Biomass humidity (Hu_{NR}, %)	70.7 (a)	77.4 (ab)	81 (b)	81.8 (b)
Soil variables				
Soil organic matter (SOM, %)	8.2	8	9.6	9.8
Soil water content (%)	7.2 (a)	9.1 (a)	20.5 (b)	20 (b)

3.2. Planted species, natural regeneration and restoration success

Treatment success diverged sharply between planted species survival and natural regeneration (Table 1). The Compost treatment achieved the highest general survival rate for planted species (46.9%), with exceptional results for *Quercus suber* (72%) and *Arbutus unedo* (72%). This was followed by the Woodchip treatment (40.1% general survival). In contrast, the Machine treatment had the lowest survival rate (13.6%). Across the four treatments, NR vegetation was dominated by herbaceous species, which accounted for most of the total cover in all plots and eight shrub species. These shrubs present two different strategies to persist after fire: *Arbutus unedo*, *Asparagus aphyllus* and *Quercus suber* are resprouters, while *Cistus ladanifer*, *C. salviifolius*, *Genista hirsuta*, *Lavandula stoechas* and *Ulex argenteus* are obligate seeders. Some of the *Rockrose* allometric and ecophysiological parameters (EPP) were significantly influenced by the treatments (Table 1). Rockrose was negatively correlated with planted species survival rates (SR_{Tot}) and the correlation was significant (Pearson correlation, $r = -0.54$, $p < 0.05$). Conversely, Rockrose plants in the machine treatment demonstrated lower new growth height, stem diameter, humidity and smaller leaf area compared to woodchips. Similarly, the number of branches for machine treatment was nine times lower compared to compost treatment. Regarding natural regeneration, while dry biomass was higher in the machine treatment compared to compost, the biomass humidity was lower than that observed in the other treatments. Soil water content presented higher values when woodchips and compost were added compared to machine and swales.

3.3. Modelling rockrose biomass

The allometric biomass models are presented in Table 2. The best models included all variables and a model using only plant height and number of branches, followed by a model including plant height and stem diameter, and a model only containing plant height. Considering AIC, the best performing model was the one containing plant height and number of branches, followed by the model including all variables and the model containing stem diameter and height. The most parsimonious

Table 2
Allometric biomass models for *Cistus ladanifer*, described with goodness of fit (r^2) and Akaike Information Criterion (AIC). Abbreviations used: Dry weight [DW_{Cistus}]; Number of branches [NrB_{Cistus}]; Height [H_{Cistus}]; Stem diameter [D_{Cistus}].

Model	r^2	AIC
$DW_{Cistus} \sim H_{Cistus}$	0.89	80.7
$DW_{Cistus} \sim D_{Cistus}$	0.82	89.5
$DW_{Cistus} \sim NrB_{Cistus}$	0.56	106.3
$DW_{Cistus} \sim D_{Cistus} + NrB_{Cistus}$	0.84	88.9
$DW_{Cistus} \sim D_{Cistus} + H_{Cistus}$	0.9	80
$DW_{Cistus} \sim H_{Cistus} + NrB_{Cistus}$	0.91	78.6
$DW_{Cistus} \sim H_{Cistus} + NrB_{Cistus} + D_{Cistus}$	0.91	79.2

model, however, was the model only containing plant height (Fig. 2) and had error rates that were similar to the more complex models, as evidenced by the root mean square errors (Fig. 3). Models spanned plants from 13 to 57 cm, with weights from 0.8 to 19 g, thus containing mainly younger specimens (Fig. 2).

Variables concerning allometric data and survival rates were highly autocorrelated, as can be seen by their clustering in the PCA biplot (Fig. 4). Variables related to survival rates were also clustering with leaf area and negatively related with green vegetation cover. PC1, explaining 48% of the total variance, was mainly related with survival rates and allometric variables (29% each) as well as EPPs (ecophysiological parameters, 19%), natural regeneration (18%) and soil (5%) to a lesser extent. This axis also discriminates significantly between the different treatments as revealed by a pairwise Welch's *t*-test (Machine: a; Swales: ab; Woodchip: bc; Compost: c). Thus, treatment effects were mainly related to survival rates and allometric variables. PC2, explaining 15% of the total variance, was mainly related with EPPs (41%), allometric variables (32%) as well as natural regeneration and soil (9% each) and survival rates (10%). This axis does not discriminate significantly between the different treatments.

Variable partitioning on the blocks of explanatory variables described above was performed for survival rates and natural regeneration. For survival rates, variables for EPPs and natural regeneration were the main groups sharing overall variation ($r^2 = 0.29$ and 0.26, respectively), with allometric variables only exhibiting a small adjusted r^2 ($r^2 = 0.08$) while for natural regeneration, variance was mostly shared between allometric variables and EPPs ($r^2 = 0.44$ and 0.23, respectively).

Using permutation tests for redundancy analysis, for each block the most important variables were selected (Table 3). From the allometric data set, H_{Cistus} was always the selected variable, whereas from the EPPs dataset it was always LA_{Cistus}. When using natural regeneration as an explanatory data set for plantation survival rates, both DW_{NR} and GWC_{NR} were selected (Figs. 5 and 6).

4. Discussion

Overall, our results highlight a clear negative correlation between rockrose abundance and the general survival rate (SR_{Tot}) of planted trees and shrubs (Table 1, Subsection 3.1). This observation is consistent with existing literature that suggests a negative impact of rockrose on surrounding species (Bohlman et al., 2016; Frazão et al., 2018; Acácio et al., 2024). A comprehensive exploration of this association in the literature reveals documented instances of allelopathic activity exhibited by the species, potentially influencing the growth of other shrubs (Gallego et al., 2020) or trees (Rivest et al., 2011), which is in accordance with the negative correlation between rockrose height (H_{Cistus}) and the biomass of naturally regenerated vegetation (DW_{NR}) (Fig. 5), emphasizing the potential competitive nature of rockrose in post-fire landscapes and reducing the likelihood of observing merely spurious relationships. Ultimately, *C. ladanifer*-dominated shrublands may constitute disclimax communities, which are defined as stable ecosystems that replace the expected climax community due to recurrent and intense disturbances (Woodward, 2009). In this case, only active management practices, such as shrub control through extensive grazing and repeated cutting, are likely to promote the transition of the community to later successional stages (Mendes et al., 2015). Indeed, periodic harvesting cycles have been proposed to not only break *C. ladanifer*-

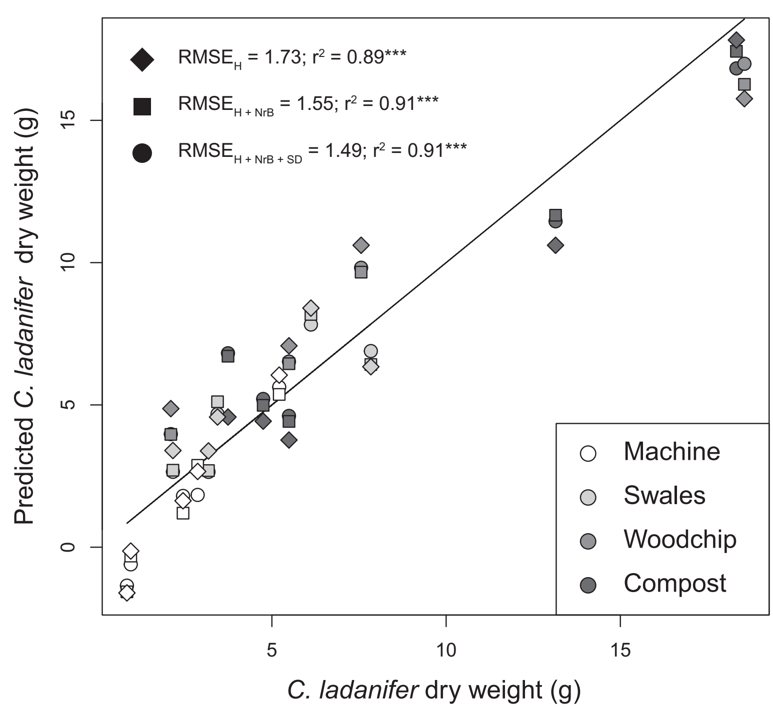

Fig. 3. Allometric biomass models for *Cistus ladanifer* dry weight (n = 19). Predicted dry weight vs. measured dry weight for three models of increasing complexity, the line indicates a perfect fit. Right: Dry weight versus plant height (most parsimonious model). H = plant height; NrB = number of branches; SD = stem diameter; RMSE = root mean square error; r^2 = coefficient of determination;* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.

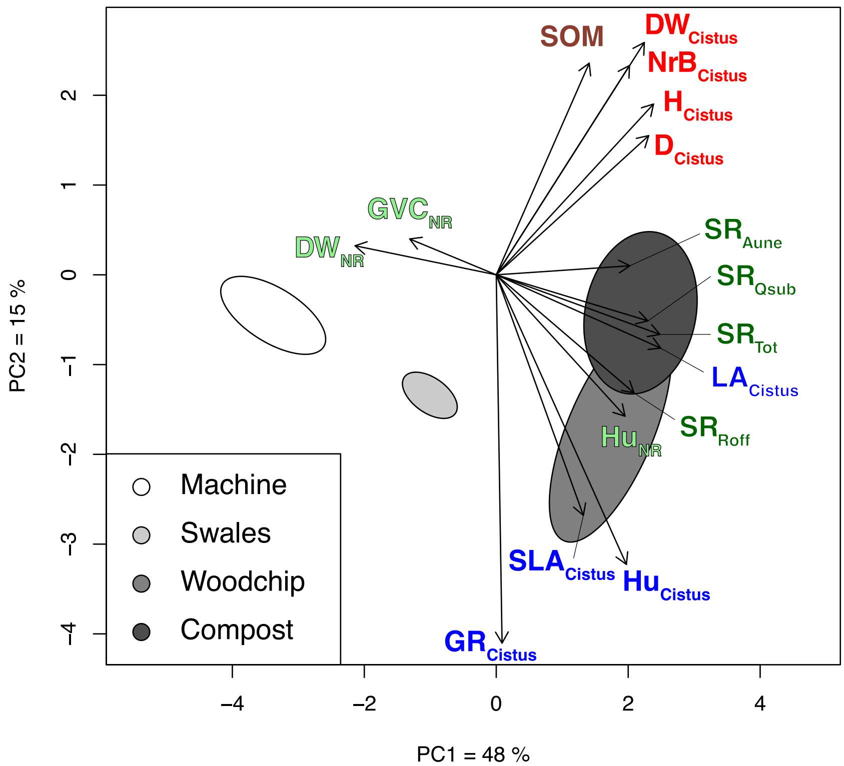

Fig. 4. Principal component analysis (PCA) of the whole data set. The scores of the first two principle components were plotted against each other, and are here represented as standard error of the factor (treatments) centroids Loadings are depicted as arrows and grouped as following: Allometric (red) = Dry weight [DW_{Cistus}]; Number of branches [NrB_{Cistus}]; Height [H_{Cistus}]; Stem diameter [D_{Cistus}]), Ecophysiological parameters (EPPs) (blue) = Leaf area [LA_{Cistus}]; Specific leaf area [SLA_{Cistus}]; Plant humidity [Hu_{Cistus}]; Growth rates [GR_{Cistus}])]. Survival rates (darkgreen) = Total survival rates [SR_{Tot}]; *Arbutus unedo* survival rates [SR_{Aune}]; *Quercus suber* survival rates [SR_{Qsub}]; *Rosmarinus officinalis* survival rates [SR_{Roff}]. Natural regeneration (lightgreen) = Green vegetation cover [GVC_{NR}]; Vegetation dry weight [DW_{NR}]; Vegetation humidity [Hu_{NR}].

Table 3
Selection of most significant variables from each explanatory variable set. Variable sets were: Allometric = Dry weight [DW_{Cistus}]; Number of branches [NrB_{Cistus}]; Height [H_{Cistus}]; Stem diameter [D_{Cistus}]), Ecophysiological parameters (EPPs) = Leaf area [LA_{Cistus}]; Specific leaf area [SLA_{Cistus}]; Plant humidity [Hu_{Cistus}]; Growth rates [GR_{Cistus}])]. Survival rates = Total survival rates [SR_{Tot}]; *Arbutus unedo* survival rates [SR_{Aune}]; *Quercus suber* survival rates [SR_{Qsub}]; *Rosmarinus officinalis* survival rates [SR_{Roff}]. Natural regeneration = Green vegetation cover [GVC_{NR}]; Vegetation dry weight [DW_{NR}]; Vegetation humidity [Hu_{NR}].

Response variable	Explanatory variable set	Exploratory variable selected	p - value
Natural regeneration	Allometric	H_{Cistus}	0.023
Natural regeneration	EPPs	LA_{Cistus}	0.006
Survival rates	Natural regeneration	$DW_{NR} + GWC_{NR}$	0.005
Survival rates	Allometric	H_{Cistus}	0.017
Survival rates	EPPs	LA_{Cistus}	0.002

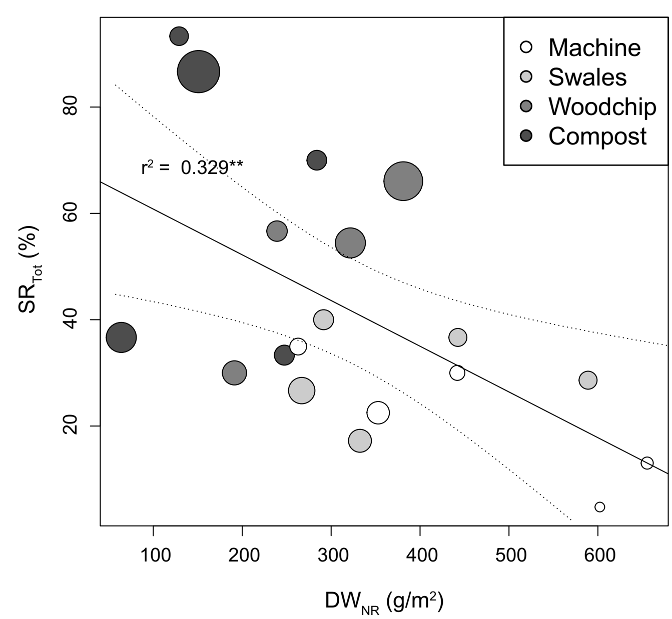

Fig. 5. Dry weight of regenerated natural vegetation (DW_{NR}) plotted against total plant survival rates (SR_{Tot}); Sphere size indicates H_{Cistus} (min = 13 cm, max = 57 cm) which also shows a correlation with DW_{NR} ($r = -0.539$, $p = 0.017$) and SR_{Tot} ($r = 0.544$, $p = 0.016$). r^2 = coefficient of determination. * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.

dominance in affected ecosystems but also yield several byproducts of economic value (Frazão et al., 2023). It has been shown that a shrub clearing strategy is essential to enhance ecosystem services (Lasanta et al., 2024), which is particularly relevant in areas of the Iberian Peninsula, such as the one observed here, characterized by poor soil quality and frequent fire disturbances.

Several authors have demonstrated that the implementation of swales, or contour bunds, and the application of an organic mulch layer can enhance soil infiltration rates and mitigate erosion (de Figueiredo et al., 2012; Prats et al., 2014; Prats et al., 2019). The addition of a compost layer is also documented to promote the growth of trees and shrubs (Guerrero et al., 2001; Larchevêque et al., 2006; Prats et al., 2014). However, vegetation cover in this study was negatively

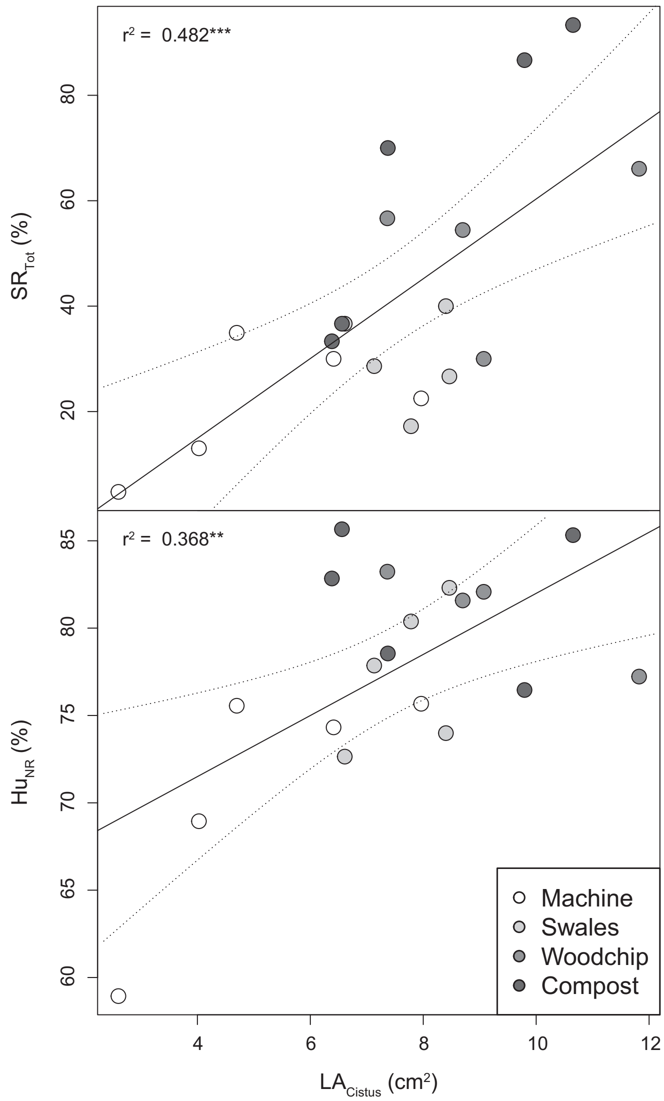

Fig. 6. Top: *Cistus ladanifer* leaf area (LA_{Cistus}) plotted against planted trees survival rates (SR_{Tot}). Bottom: *Cistus ladanifer* leaf area (LA_{Cistus}) plotted against natural regeneration biomass water content (Hu_{NR}). r^2 = coefficient of determination. * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.

correlated with the survival rate of planted seedlings, aligning with the claims of some authors that competition for light, nutrients, or water may occur (Bohlman et al., 2016), ultimately depending on the specific requirements of the seedlings (Benayas et al., 2005). In fact, the experimental setup employed in this study, where a thick layer of organic matter was applied in the field, likely inhibited vegetation growth and was thus responsible for this observed effect. These apparently conflicting results underscore the importance of considering various soil treatments in post-fire restoration efforts. Some authors have documented the baseline of post-fire peak abundances of rockrose, in absence of treatments, at 56 plants/m^2, 6 months after fire. Compared to this, the machine treatment, involving vegetation removal and soil compaction, has reduced rockrose abundance very slightly, only to 40 plants/m^2. The effect of creating the swales, involving vegetation removal and soil ripping may have induced the further decrease until 8–5 plants/m^2, and the lower abundances correspond to the addition of organic mats, which may hinder plant germination (Prats et al., 2014). The observed higher plant abundance in the machine treatment suggests a potential trade-off between efficient vegetation removal and its subsequent impact on plant community composition. In contrast, the other treatments exhibit distinct patterns in rockrose characteristics, emphasizing the role of soil amendments in shaping post-fire vegetation dynamics.

We also found that both DW_{NR} and SR_{Tot} of planted seedlings exhibit correlations with H_{Cistus}, highlighting its role as a reliable indicator of overall system dynamics. Parameters such as H_{Cistus} and leaf area (LA_{Cistus}) emerge as promising variables to explain and consequently predict biomass of native vegetation or the survival rate of seedlings. The partitioning of variance among different explanatory blocks (Subsection 3.3) provided clarity on the key drivers of survival rates and natural regeneration. The significance of LA_{Cistus} in explaining survival rates underscores its importance in assessing the success of reforestation efforts, at least during the initial stages of plantation establishment. On the other hand, the negative correlation found between DW_{NR} and green vegetation cover (GVC_{NR}) in relation to SR_{Tot} further emphasizes the complex interplay between natural regeneration and the establishment of planted species. Although the literature generally highlights that native vegetation positively influences reforestation success by enhancing shade, water availability, and soil organic matter (Rey et al., 2009), certain plants, particularly r-strategists, also benefit from these conditions, which can ultimately lead to competition with tree seedlings (Croce et al., 2022; Acácio et al., 2024). Moreover, both DW_{NR} and SR_{Tot} show correlations with rockrose height, albeit in opposite directions, making it a reliable indicator for the overall system dynamics. There is generally a facilitation in plant communities and with the presence of shrubs (Brooker et al., 2008; Castro et al., 2002), which is not shown in the results of this study. However, in Mediterranean systems, this has been described as species-specific and, for *C. ladanifer*, been identified as detrimental to the growth and survival of surrounding shrubs and trees (Gallego et al., 2020; Rivest et al., 2011).

The allometric models resulting from our work (Fig. 2, Table 2) demonstrate that simple parameters of rockrose can be used to approximate its overall biomass effectively. This insight is particularly valuable for landowners seeking to estimate the extent of rockrose presence on their property. All models exhibit robust r^2 values, indicating that even using a single simple parameter, plant height, provides a reliable estimation of rockrose biomass. Also, if expanded upon by using crown area or stand area and mean height to model plant/stand volume, these models can be very powerful in predicting stand biomass using remote sensing methods and photogrammetry from drone imagery (Ulm et al., 2022). Furthermore, our findings highlight that *C. ladanifer* possesses parameters suitable for estimating both natural regeneration and reforestation success, being plant height or leaf area the most effective for explaining natural regeneration, as can be seen in the models selected and described in Table 3. For instance, Fig. 6 exemplifies the utility of a straightforward ecophysiological parameter like leaf area, which is simple and reproducible, as a predictive tool for more complex parameters, including the total survival rate of planted plants and the water content of biomass—an indicative measure of water availability within the system.

However, it should be acknowledged that this study was conducted at a single site, which represents a limitation. Nevertheless, our findings are consistent with those reported in previous studies, and both the experimental setup and study design provide strong confidence in the robustness of our results. Moreover, the outcomes of this work, specifically, the beneficial effects of swales and compost on increasing the survival of planted species, offer important insights that can be applied in future plantations, not only in Mediterranean ecosystems but also in other fire-prone regions.

Finally, while not the primary focus of this work, it is worth highlighting that rockrose, a species historically undervalued, has emerged as a valuable economic resource (Raimundo et al., 2018; Frazão et al., 2018). Our results show that roughly 5 ton/ha of rockrose can be produced after our machine treatment. Integrating its management into restoration programs offers substantial potential for generating income, thereby enhancing the sustainability and long-term success of these initiatives. In this context, our simplified biomass model constitutes a valuable tool to perform cost-benefit analyses supporting reforestation and restoration initiatives in Mediterranean ecosystems.

5. Conclusion

This study reveals a negative correlation between the abundance of *C. ladanifer* and the survival rates of planted trees and shrubs and a positive correlation with the biomass of natural regeneration. It was also found that the more intensive soil preparation methods (swales), compared to the less aggressive machine treatment, limited the presence of *C. ladanifer,* thereby reducing competition for resources and improving survival of planted species. Additionally, the application of organic matter amendments into the swales, such as wood chips and, most effectively, compost, greatly enhanced the general survival rates of planted species from 13% in the machine to 46% for the compost treatment, where 72% of the *A. unedo* and *Q. suber* seedlings survived.

These results underscore the importance of coupling soil treatments and organic matter addition, considering species-specific interactions and soil management strategies when developing reforestation plans in Mediterranean ecosystems. Furthermore, a simplified biomass model for *C. ladanifer* is presented, which can be used for fuel estimation and upscaled via remote sensing. Lastly, it could be shown how specific, simple measurements of *C. ladanifer* ecophysiological parameters, such as leaf area and plant height, can serve as proxies to predict more complex, systemic changes, such as survival rates or water content of the surrounding vegetation.

Overall, our work contributes to a better understanding of the complex relationships between vegetation, soil treatments, and reforestation success, with implications for land management and ecological restoration practices.

CRediT authorship contribution statement

Florian Ulm: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Laurent Madeleine Toisoul:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Jean-François Bastin:** Writing – review & editing, Supervision, Methodology. **Joana Guedes Jesus:** Writing – review & editing, Investigation. **Sofia Uyttendaele:** Writing – review & editing, Investigation. **Andreia Anjos:** Writing – review & editing, Investigation. **Cristina Máguas:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition. **Sergio Prats:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Florian Ulm reports financial support was provided by Fundação para a Ciência e a Tecnologia. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

FU was supported by the European Union, in the context of the project "Envisioning sustainable futures in higher education business departments, inspired by Permaculture design principles", with grant number 2023-1-NL01-KA220-HED-000157951. SP was supported by the Portuguese Science Foundation (FCT) through the research contract CEECIND/01473/2020 and the Spanish The Ministry of Science, Innovation and Universities through the research contract RYC2022-035489-I. SC was supported by the project Montados Net-Zero, PRR-C05-i03-I-000236, through a postdoctoral fellowship. This work was made possible through the support from the Portuguese Science Foundation (FCT) in the form of the research project "R3forest" (PCIF/GVB/0202/2017), as well as the CE3C - Centre for Ecology, Evolution and Environmental Changes unit funding (UIDB/00329/2025) and the project "Fight Desert" (POCI-07-62G4-FEDER-181624) funded by the European Union. We also thank the two anonymous reviewers for their valuable and constructive comments, which significantly improved the quality of our manuscript.

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