PILOT STUDY REPORT

Implementation of adaptive forest management as a tool for reducing the risks of fire and drought in mid-mountain holm oak forests

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Contents

1 What are the reasons behind this pilot study? ... 1

2 What does the pilot study involve? ... 2

3 Where is the pilot study being implemented? ... 3

4 What actions have been implemented? ... 7

4.1 What was the initial condition of the study area? ... 7

4.2 What specific actions were developed? ... 9

4.3 What monitoring measures were established? ... 14

5 What changes have been brought about by the pilot study? Main Results ... 19

5.1 Fuel Moisture ... 19

5.2 Forest Decline (Forest Health status) ... 21

5.3 Crown Fire Hazard ... 22

6 Conclusions ... 25

7 References ... 26

1 What are the reasons behind this pilot study?

MONTCLIMA is a project that is co-funded by the Interreg SUDOE programme. It builds on and makes use of the best strategies and tools detected for **risk diagnosis, prevention and management, integrating the climate change component**. The objective of the project is to draw up and implement a **transnational strategy for strengthening the resilience of the SUDOE territories**, based on using and capitalising on successful experiences and replicating them in the SUDOE mountain areas.

To this end, MONTCLIMA compiles the best practices in natural risk management and prevention, selects the most successful and replicates them in representative mountain areas or areas of special interest in the SUDOE territories through pilot studies. These studies aim to translate the local strategic priorities of each site into concrete actions. Similarly, the pilot studies provide results on the best practices implemented, allowing their effectiveness to be evaluated and possible improvements to be introduced.

The MONTCLIMA project comprises five pilot studies on the prevention and management of natural risks:

1. Assessment of the erosion in sloping vineyards, comparing the use of vegetation cover with the traditional farming techniques (Basque Country).
2. Evaluation of the impact of forest fires on erosion and torrential flood risks (France, eastern Pyrenees).
3. Diagnosis and multi-risk planning at a municipal level (France, western Pyrenees).
4. Forest fire risk prevention and improvement of the protective function of the forest against erosion and falling blocks and rocks (Andorra).
5. **Application of adaptive forest management as a tool for reducing the risks of fire and drought in mid-mountain holm oak forests (Catalonia).**

This document focuses on assessing the fifth pilot study implemented, which is based on the application of adaptive forest management to reduce the risks of fire and drought. Therefore, it describes the characteristics of the pilot site, its implementation and the results obtained.

2 What does the pilot study involve?

The pilot study focuses on the implementation of **forest management adapted to climate change and applied in Mediterranean holm oak forests that have a high fire risk**, with the objective of reducing this risk. Similarly, it promotes the maintenance of forest treatments through silvopastoralism, thus improving the sustainability of forest management in the medium to long term. This translates into the execution of the following specific actions:

1. Development of **silvicultural treatments** to reduce the vulnerability of the forest stands to fires. The silvicultural treatments to be developed include:
    - Selective thinning: of tree species ensuring a selection of trees of all ages and fostering those that are better formed, more robust and healthier.
    - Coppice management: selection of young sprouts of tree species such as holm oak and oak.
    - Selective clearing: of shrub species, using the coppice-with-standards system for any tree-like species. The species most vulnerable to fire are removed and those of interest in terms of biodiversity (proportion of fruit or shelter) are maintained/encouraged.

2. Creation of a **control area** with no intervention to compare the different monitoring parameters of the silvicultural treatments.

3. Improvement of **forage resources** to encourage grazing and thus maintain the effect of the silvicultural treatments over time, taking advantage of the presence of a mixed flock of sheep and goats that regularly graze the estate. This improvement is achieved through the following two actions:
    - Creation of a dehesa (grazing area) on the sites of two old forests of maritime pine (*Pinus pinaster*) and Aleppo pine (*Pinus halepensis*) that have been clearcut for disease control purposes (presence of *Matsococcus feytaudii* in the maritime pine forest and trees affected by gales in the Aleppo pine forest). The holm oaks were not cleared from the sites to create, in the long term, a grazing area for livestock. This also leaves an open area, which is of interest for fire prevention and must be maintained. To improve forage resources in the area, the removal of logging residues was carried out through controlled burns where there was no tree vegetation.
    - Fostering of silvopastoralism where silvicultural treatments have been implemented. These treatments improve accessibility and make forage resources available to livestock. Furthermore, with the animals passing through these areas the structure created by the treatments is maintained over time.

These actions are carried out in an area that is strategic for reducing the spread of fire and are essential for fire prevention in the massif where the area is located.

Similarly, all the actions are included in the estate's forest management plan, the Technical Plan for Forest Management and Improvement (PTGMF in its Catalan acronym).

3 Where is the pilot study being implemented?

The pilot study is being carried out in the Montnegre-Corredor massif, which is part of the Catalan Coastal Range, and covers a surface area of 45 323 ha, of which 33 176 ha is forest and 14 711 ha is under the special protection of the Montnegre-Corredor Natural Park. The massif affects 22 municipalities where approximately 300 000 people live. Similarly, it is delimited by two main roads that lie parallel to each other and connect Barcelona and Girona (AP7, C32), the Tordera river and the C60 motorway (Figure 1).

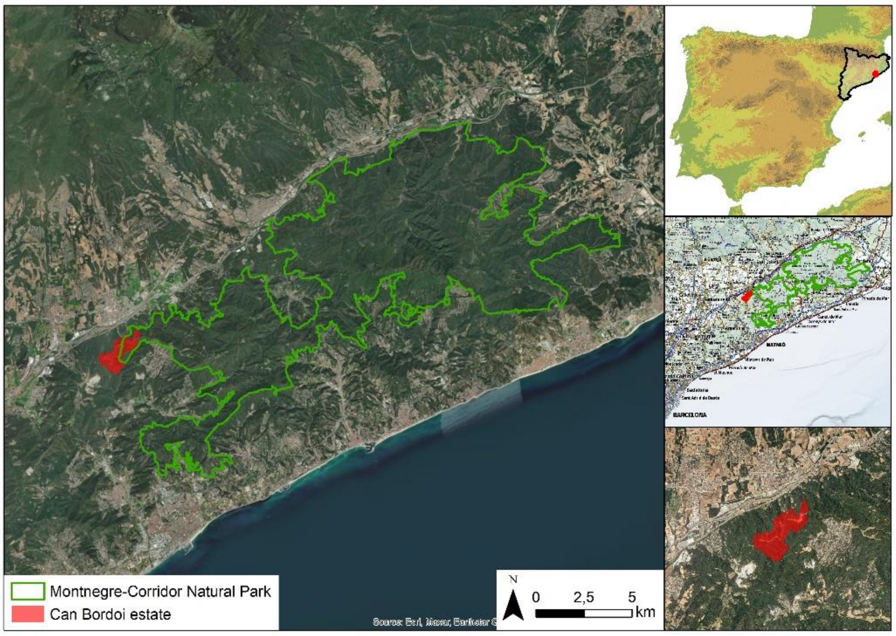


Figure 1. Location of the study area. In green, the boundary of the Montnegre-Corredor Natural Park. In red, the estate where the pilot study is being carried out.

The Montnegre-Corredor is a Mediterranean massif, with sub-humid features in its highest parts, a siliceous substrate (granites and leucogranites), characterised by steep gradients (30-60 %) and two slopes with very different features: inland (with a greater forestry tradition, medium-sized estates, dominated by holm oak and cork oak); and coastal (small estates, formerly agricultural and currently highly urbanised, with little forestry tradition, dominated by stone pine).

The Montnegre-Corredor area as a whole and specifically the pilot study area has been significantly **affected by pests**. On the one hand, the pine forests are in a state of general decline due to the interaction of various factors, such as the orography, forest management of the area, repeated episodes of drought, etc. This decline triggered a serious infestation of the *Tomicus destruens* bark beetle in stone pines (*Pinus pinea*) from 2015 to 2018, leading to the death of many of them. Maritime pine has also been affected by the sucking insect *Matsococcus feytaudii*, which weakens it and increases its vulnerability to bark beetles. To control both plagues, sanitation felling and thinning have been carried out over the last few years. On the other hand, during the 2018-2020 period, the forest suffered significant defoliation caused by

Lymantria dispar, which particularly affected holm oak and cork oak. The pilot study area has also suffered from these pests, especially the episode of defoliation caused by *Lymantria* in 2020 after the pilot treatments were carried out.

In terms of **fire prevention**, the massif is part of the priority firebreak area, B3 Serra del Montnegre i el Corredor. Although there is currently no associated planning with a breakdown of the Strategic and Complementary Areas of the massif, the zoning of Priority Management Areas (AGP in its Catalan acronym) developed by Barcelona Provincial Council has been established (Figure 2).

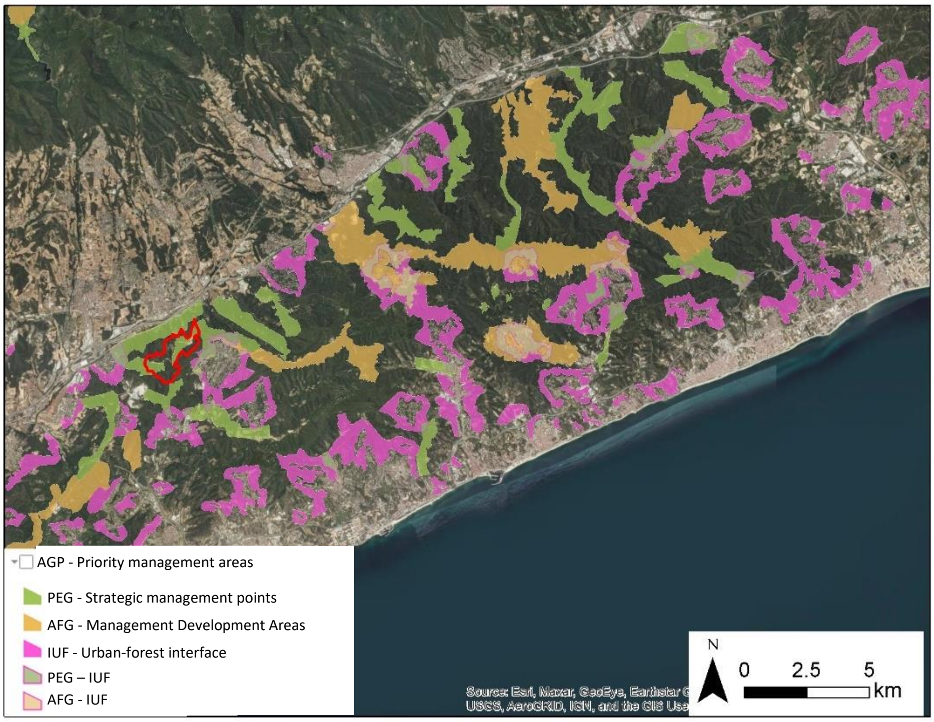


Figure 2. Priority Management Areas of the Montnegre-Corredor massif, defined by Barcelona Provincial Council: Strategic Management Points (green), Management Development Areas (orange) and Urban-Forest Interface areas (purple). In red, is the line marking the estate where the pilot study is being carried out.

The pilot study area is on the Can Bordoi estate, which has a surface area of 214 ha and is located in the municipality of Llinars del Vallès (Figure 3). This is a key fire prevention zone as it is within a Priority Management Area (AGP), more specifically in a Strategic Management Point (PEG in its Catalan acronym), meaning, in a zone where fuel modification and/or infrastructure preparation allows the fire service to carry out safe attack manoeuvres that reduce the spread of large forest fires.

Furthermore, the PEG where the pilot study is being carried out is located in the west of the massif so that, in the event of a large forest fire coming from the west, which would be the most likely scenario, the area could help reduce the intensity of the fire, facilitating fire-fighting tasks and having a protective effect on the Montnegre-Corredor massif as a whole.

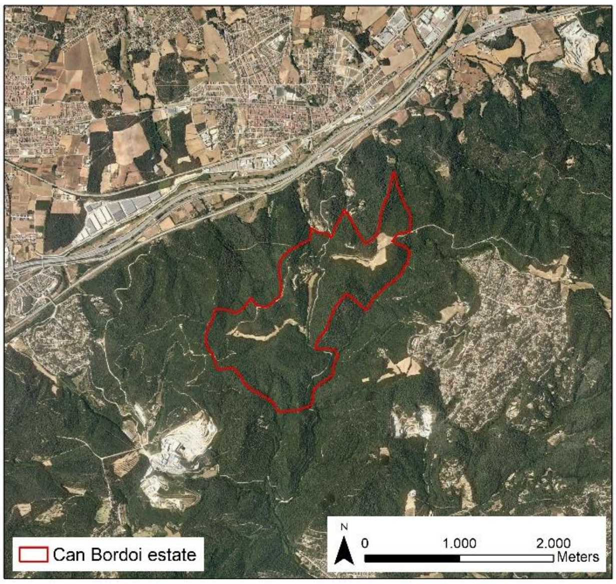


Figure 3. Location of the Can Bordoi estate, in the Llinars del Vallès municipality, to the north of Barcelona.

In addition to its strategic location for fire prevention, where forest treatment is necessary, the estate was chosen for the following reasons:

- Willingness of the owners to implement forest treatment actions.
- Willingness of the livestock farmer who grazes the land to use the pilot study area in the short and medium term.
- Location of part of the estate in a PEG for fire prevention, where forest improvement actions are required.
- Existence of a plan to create two open spaces for silvopastoral use in the area through clear-cutting for disease control. These, together with the existing fields on the estate, form an agro-forest mosaic within the PEG, which helps reduce the risk of fire.
- Ease of access and proximity to Barcelona, facilitating guided tours for the dissemination and replicability of results.

Within the 214 ha of the estate, the pilot study has been implemented in the far southwest area, within the PEG zone, in three different areas according to the type of forest management to be implemented (Figure 4):

- An area of 5.4 ha where adaptive **silvicultural treatments** have been implemented (thinning, coppice management and selective clearing) to reduce the vulnerability of the massif to fire.
- A **control area** of 1.87 ha, which has been left untouched and is used to compare the different monitoring parameters.
- An area of 4.7 ha for **forage resource improvement**, so that open spaces that hinder the spread of fire are maintained. This is where the Association of Forest Owners of the Montnegre-Corredor has carried out sanitation felling, removing the pines affected by pests and gales, to favour the recovery of the holm oak grove and create a *dehesa* (grazing

area). In addition, as part of the pilot study, the logging residues have been removed from the area to encourage the spontaneous appearance of herbaceous species.

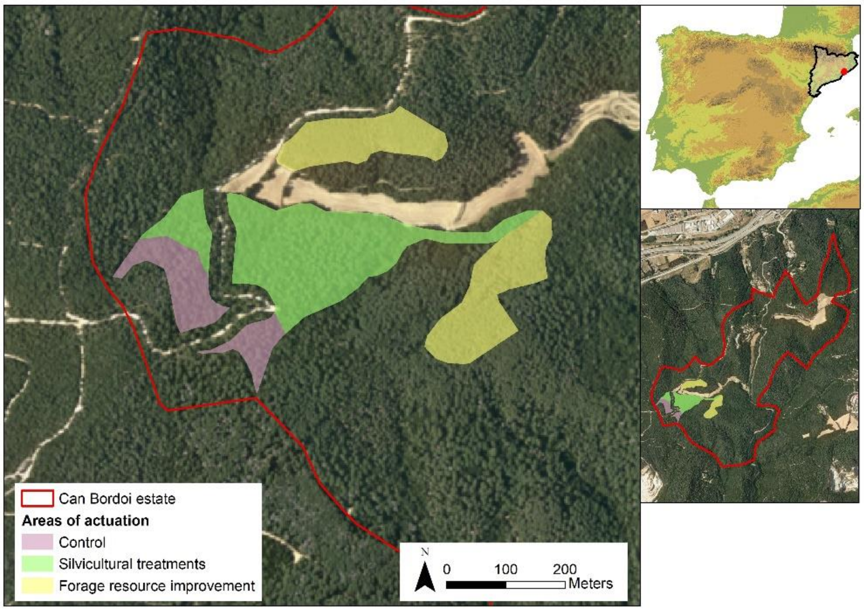


Figure 4. Boundary of the pilot study area on the Can Bordoi estate. Silvicultural treatment area in green, control area in purple and forage resource improvement area in yellow.

4 What actions have been implemented?

4.1 What was the initial condition of the study area?

4.1.1. Area where silvicultural treatments have been implemented

The area of the pilot study where the silvicultural treatments have been developed has remained untouched for the past 20 years. Although the estate has a forest management plan (PTGMF no. 125), none of the actions that affect the study area have been carried out. Additionally, the area is used extensively for leisure activities, particularly by cyclists who have opened small paths in neighbouring areas.

The forest is made up of a holm oak grove scattered with cork oak and small patches of stone pine and an undergrowth of tree heather and strawberry trees. The presence of holm oak varies and is distributed in patches, with some that are denser and others that have more tree heather and strawberry trees (Figure 5).

Figure 5. Holm oak grove in the pilot study area before the forest management.

Following are the results of the pre-treatment forest inventory (see methodology in section 4.3) and although tree heather and strawberry trees are actually bush species, they have been included. The data shows a **high fraction of canopy cover (FCC of 84 %), high density (1122 trees/ha) and basal area (25.3 m^2/ha) and a moderate to high crown fire hazard** (Table 1). Forest inventories were carried out before the silvicultural treatments, between January and February 2020 (Figure 6).

Inventory Plot	Fraction of Canopy Cover (%)	Density (number of trees/ha)	Basal Area (m^2/ha)	Normal Diameter (cm)	Average Height (m)	Fuel Continuity Model	Crown Fire Hazard
Control 1	75	955	27.2	15.4	6.7	B9	Moderate
Control 2	80	1464	36.4	16.5	7.9	A3	High
Control 3	80	1178	23.4	14.0	8.0	B3	Moderate
Treatment 1	80	859	22.1	15.2	7.2	B3	Moderate
Treatment 2	90	1496	30.3	15.8	9.5	B9	Moderate
Treatment 3	90	665	22.2	14.2	6.3	B3	Moderate
Treatment 4	80	1114	27.9	16.0	7.9	B10	Moderate
Treatment 5	100	1241	13.2	10.0	6.6	B3	Moderate

Table 1. Summary of inventory variables carried out between February and March 2020.

Figure 6. Pre-treatment forest inventory plots.

4.1.2. Area for forage resource improvement

This covered two sites, one with maritime pine (1.87 ha) affected by *Matsococcus feytaudii* and the other with Aleppo pine (2.39 ha) affected by gales; both with a lower storey of young holm oaks in patches. In June 2020, the Association of Forest Owners of the Montnegre-Corredor (APMC) carried out sanitation felling during which they removed all the pine trees from both sites due to their poor condition. The holm oaks in the lower storey were left untouched in order to create a *dehesa* (grazing area). Finally, selective clearing was carried out on the tree heather and strawberry tree shrub stratum, with a coppice treatment being implemented for the more tree-like shrubs (Figure 7).

Figure 7. *Dehesa* (grazing area) before and after the APMC's forest actions.

For disease prevention reasons, trees with complete crowns were removed and stacked for subsequent on-site shredding for biomass, so that most of the logging residues from the pine forest felling were concentrated around these piles. The shredding of these piles of logging residues wasn't carried out until December 2020 due to accessibility problems.

4.2 What specific actions were developed?

4.2.1. Silvicultural treatments

The **objective** of the silvicultural treatments developed for the pilot study was to **reduce the forest stand's vulnerability to fire** based on improving its resistance and resilience to disturbances, increasing the complexity of its structure and composition. To this end, the aim was for the treatments to have an impact on the following fire prevention aspects:

- Obtain a structure with a lower crown fire hazard, reducing fuel continuity.
- Modify the amount and distribution of available fuel.
- Increase the complexity of the forest to foster its resilience after a fire: encourage mixed forests and a variety of structures.
- Reduce water competition and stress.
- Maintain a semi-shade environment, preventing direct insolation, which can cause water stress and significant sprouting, with high FCC.
- Reduce the possibility of fires becoming large forest fires.

To meet the objective, the plan was to apply the forest management model to the holm oak groves developed by the APMC (Guitart y Rosell, 2014), which is based on the modification of holm oak grove models defined in the Sustainable Forest Management Guidelines of Catalonia (ORGEST) (Vericat et al., 2011) and adapted to the characteristics of the massif. In addition, criteria for the management of mixed sub-Mediterranean forests adapted to climate change were also included (Coello et al., 2022).

Finally, an **irregular forest management model, involving gentle but frequent thinning** was applied. This model considers that the application of a treatment is necessary when a basal area of at least 25 m^2/ha is reached, which typically occurs in the massif every 10 years (rotation period) and was the situation of the stand being studied.

Therefore, the silvicultural treatments implemented consisted of the following actions:

1. **Thinning:** gentle felling in patches of holm oak and the densest patches of stone pine, according to the following criteria:
   - Selection of the healthiest and most robust trees of all ages: stable, healthy and balanced crown, smooth bark, etc.
   - Promotion of secondary or accompanying species, favouring biodiversity. Specific encouragement of large trees for seed production.
   - Fostering of the vertical discontinuity between strata through the extraction of trees.
   - Favouring of a homogeneous distribution and seed-bearing trees.
   - Ensuring the presence of regenerated areas and abundant stands of younger types of trees across the entire area.
   - Basal area: maintain a remaining basal area equal to or greater than 20 m^2/ha and a maximum reduction of 25 %.
   - Maintain a high residual FCC: 70-80%

   Table 2 shows the ideal curve for the thinning measures implemented.

Diameter Class	Density (trees/ha)	Basal Area (m^2/ha)	Volume (m^3/ha)	Spacing (m)
10	450	3.5	9.1	5.1
15	250	4.4	13.0	6.8
20	190	6.0	18.8	7.8
25	80	3.9	13.1	12.0
30	25	1.8	7.3	21.5
35	10	1.0	4.4	34.0
TOTAL	1005	20.6	65.7	3.4

Table 2. Ideal curve of the thinning treatments implemented.

2. **Coppice management:** this is carried out on the younger oak trees to reduce competition among resources, concentrating growth in the trees that are best developed and positioned. Between 1 and 3 sprouts are selected per stump.

3. **Selective clearing**: this aims to reduce shrub-level competition with tree regeneration, favour certain shrub species that have value for the biodiversity and modify the vertical and horizontal structure of the fuel layers to reduce vulnerability to fires. This involves a partial elimination of the shrub layer, considering the following criteria:
   - Scrub FCC: < 30 %
   - Height: < 1.3 m
   - Coppice method applied to tree-like shrubs, such as tree heather and strawberry trees, maintaining the best developed and best positioned (1-3 sprouts/stump).

- Removal of flammable species and promotion of species that provide protection and/or food for fauna.

Implementation of the silvicultural treatments was subcontracted to APMC and carried out between February and June 2020. Some of the actions were carried out before the COVID-19 pandemic but had to be stopped before completion and postponed until June 2020, when work was resumed and finished. Figure 8 shows the state of the area after the silvicultural treatment.

Figure 8. State of the Can Bordoi holm oak grove after implementation of the silvicultural treatments.

Once the treatments were completed, at the end of June 2020, the forest inventories were repeated for all the plots to characterise the treatments and establish the starting point for the monitoring campaigns (see methodology in section 4.3). The inventories were planned between March and May 2020 but due to the COVID-19 pandemic, the delay in implementing the silvicultural treatments and the restrictions that prevented field visits, inventorying was delayed. In addition, at the beginning of June, the holm oak forest suffered a severe attack of *Lymantria dispar*, covering the trees in caterpillars and causing defoliation, making transiting and field data collection impossible.

Once the post-treatment inventories had been carried out, the field data were analysed, making it possible to characterise the silvicultural treatments implemented (Table 3). In terms of forest structure, the **treatments have led to a reduction in the fraction of canopy cover by 14 %, density by 19 % and basal area by 8 %**. The main treatment was applied to accompanying vegetation and scrubland, where **scrub cover was reduced by 77 % and fuel biovolume by 97 %**. This has led to the initially moderate to high crown fire hazard (A3-B3-B9) being reduced to moderate after the treatment (B14-15). It is hoped, however, that as the logging residues integrate with the soil and degrade, this will be reduced even further to a much lower hazard level.

Inventory Plot	Fraction of Canopy Cover (%)	Density (number of trees/ha)	Basal Area (m^2/ha)	Normal Diameter (cm)	Average Height (m)	Fuel Continuity Model	Crown Fire Hazard
Treatment 1	60	605	20.5	13.2	7.2	B15	Moderate
Treatment 2	90	1241	28.6	16.1	9.5	B14	Moderate
Treatment 3	80	509	20.1	14.1	6.3	B14	Moderate
Treatment 4	75	1114	27.9	16.0	7.9	B14	Moderate
Treatment 5	75	891	9.7	10.0	6.6	B14	Moderate

Table 3. Summary of inventory variables after implementation of the silvicultural treatments in June 2020.

In terms of expenses and income derived from the silvicultural treatments applied (Table 4), the expenses were more than double the income, specifically because of the clearing activities, which were very costly given the initial density of the scrubland. Therefore, the silvicultural treatment resulted in a **negative balance of €5722.68**. However, by maintaining a semi-shade environment, which prevents significant regrowth, and fostering silvopastoralism in the area, the effects on the shrub layer are expected to be maintained in the long term, which will reduce the cost of future treatments.

Concept	Amount Removed (t/ha)	Total (t, ha, hours, etc.)	Units	Unit Amount (€/unit)	Income	Expenses
Holm Oak Firewood	10.54	56.94	t	68	3871.92	
Oak Firewood	0.93	5.00	t	51	255.00	
Transport	12.21	65.94	t	-16		-1055.04
Clearing		5.40	ha	-1100		-5940.00
Thinning	12.21	65.94	t	-24		-1582.56
Improving Access		5.00	hours	-60		-300.00
Technical Monitoring		5.40	ha	-180		-972.00
Total					**4126.92**	**-9849.60**
Balance						**-5722.68**

Table 4. Summary of income and expenses derived from the application of the silvicultural treatment.

4.2.2. Improvement of forage resources

The pilot study proposed improving forage resources in the open areas created after the sanitation felling measures to facilitate their maintenance through grazing. By creating and maintaining these open areas, the diversity of structures and composition of the landscape are enhanced, affecting the following points at a fire prevention level:

- Change in fire behaviour
- Detain the spreading of the fire

To this end, **logging residues were removed**, through controlled burns in areas with no tree vegetation (Figure 9a). These were concentrated in places where whole trees were piled for subsequent on-site shredding and affected a total of eight specific areas. In these areas, leaf and branch residues had been gathered, as well as other non-shreddable felling residues. These were moved to the areas of ground that had been most compacted by the shredding machine during the shredding process so that the burn would improve the soil in these areas. Once the logging residues had been removed, we waited for the natural regeneration of **spontaneous herbaceous vegetation** during the spring of 2021, observing a significant amount of edible forage species with a good proportion of grasses and leguminous plants, which revealed the viability of this area for grazing (Figure 9b).

Treatments on the grazing land were also implemented by the Association of Forest Owners of Montnegre and Corredor. The logging residues were piled in heaps with the intention of burning them before spring 2021. However, the spring of 2021 was so wet that the burn could not take place. This, together with the large size of the piles, their location and the availability of the foresters, meant that the burn wasn't carried out until winter 2022. The burn was carried out by three specialist operators and took two days to extinguish (the mixture of logging residues and soil made it difficult to extinguish the fire) (Figure 9a).

a) b)

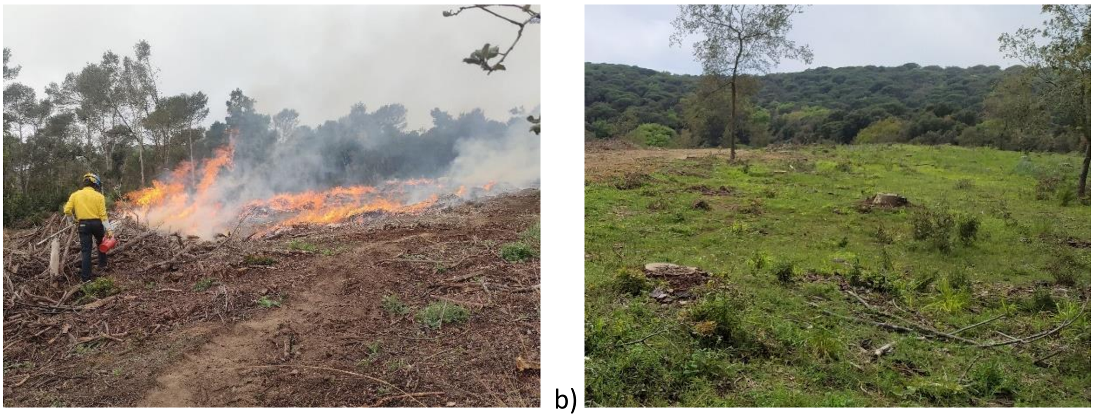


Figure 9. a) Burning of logging residues. b) *Dehesa* (grazing area) in spring 2021.

Table 5 shows the costs derived from the elimination of residues. Burn expenses are usually lower. The increase is due to the presence of soil that made extinguishing the fire more complicated.

Concept	Total (t, ha, hours, etc.)	Units	Unit Amount (€/unit)	Expenses (€)
Removal of Residues	4.27	ha	-566	-2416.82
Slope Improvement	5.00	hours	-60	-300.00
Technical Monitoring	4.27	ha	-100	-427.00
Total				**-3143.82**

Table 5. Summary of expenses derived from improving forage resources in the open areas.

4.3 What monitoring measures were established?

To assess the pilot study actions, a monitoring network was designed that allows quantification of the treatments over time and comparison with the initial condition. The objective of monitoring is to **assess the effectiveness of the pilot study actions in improving the adaptive capacity of the holm oak forest to deal with the threats of climate change**, mainly the **risks of fire, drought and the impact of disease**.

The monitoring campaign was planned to start in May 2020, covering three summers (2020-2021-2022) thanks to the extension granted for the project. However, due to delays caused by the COVID-19 pandemic, the campaign began in July 2020. Despite the delay, all the necessary data for the 2020 campaign could be obtained and results are also available for the second and third campaigns in 2021 and 2022.

Monitoring focuses on the area of the holm oak forest where the silvicultural treatments were applied to establish parameters for changes that occur and to evaluate the forest's adaptation to climate change. The monitoring consists of:

- A network of eight **forest inventory plots** where the pre- and post-treatment inventories were carried out: 5 in the treatment area and 3 in the control area.
- A network of **moisture sensors**.
- A network of **air temperature and relative humidity sensors**.

Figure 10 shows the monitoring network installed and Table 6 lists the monitoring variables.

Figure 10. Installed monitoring network: left, forest inventory plot; centre, dataloggers and soil moisture sensors; right, air temperature and relative humidity sensors.

Type of Information / Methodology	Variables Measured	Frequency of Measurements
Forest Structure / Forest Inventory	Tree density Distribution of diameter class Average height Biovolume of understorey Regeneration	Pre-treatment, post-treatment and annual (monitoring)
Fuel Continuity / Crown Fire Hazard	Aerial fuel cover(%) Ladder fuel cover (%) Surface fuel cover (%) Height of surface fuel cover (m) Distance between surface fuel and ladder or aerial fuel (m) Distance between ladder fuel and aerial fuel (m)	Pre-treatment, post-treatment and annual (monitoring)
Fuel Moisture / Fuel Samples	Relative water content (RWC)	Nine annual measurements during summer
Forest Health Status / Forest Decline	Mortality (%) Defoliation (%) Discolouration (%)	Pre-treatment, post-treatment and annual (monitoring)
Soil Moisture / Sensors	Soil water content (SWC)	Continuous
Temperature and Relative Humidity / Sensors	Temperature and relative humidity	Continuous

Table 6. Type of information, methodology, variables measured and frequency of pre-treatment, post-treatment and monitoring inventories.

4.3.1. Forest inventory plots

There are eight permanent forest inventory plots, five in the treatment zone and three in the control zone. The plots are round and have a 10 m radius, except for one of the treatment plots which, due to the low number of trees on the plot, was extended and has a 20 m radius. Figure 11 shows the location of the forest inventory plots.

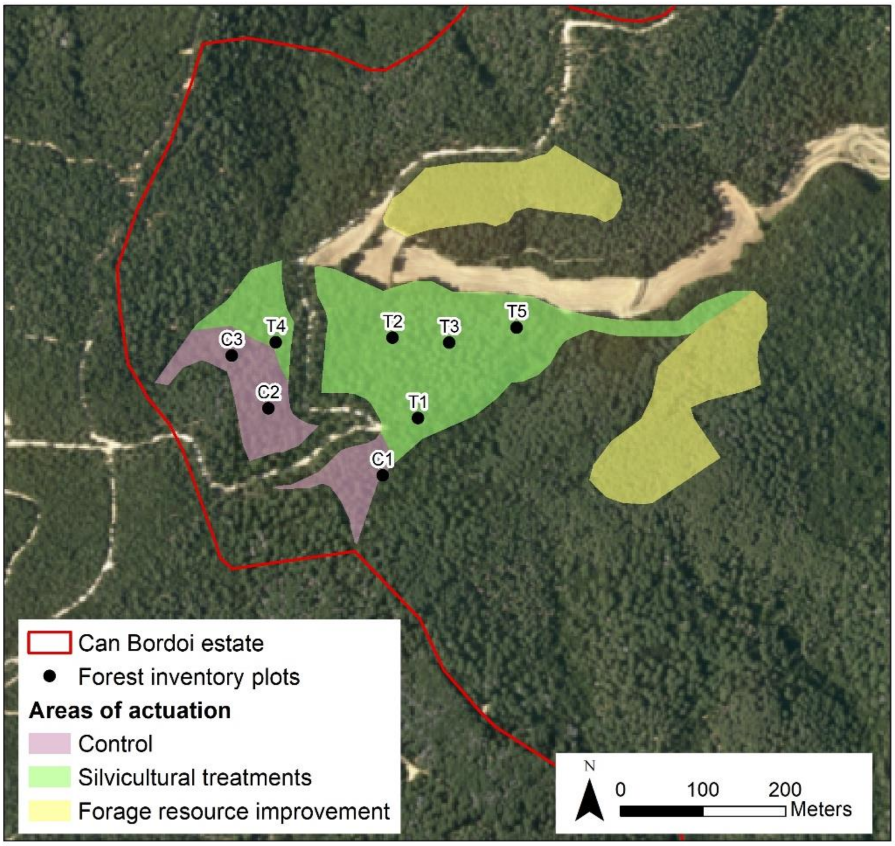


Figure 11. Location of the forest inventory plots within the area of the pilot study.

The following variables are monitored in the forest inventory plots:

- **Forest structure:** by carrying out a forest inventory, forest mensuration variables are obtained, allowing the characteristics of the forest stand to be defined before and after the treatments. These variables include density, diametric distribution, average height, wood volume and regeneration.

- **Fuel continuity:** Forest fuel continuity refers to the spatial and height distribution of the different fuel strata (aerial, ladder or surface), which has a direct effect on the forest's vulnerability to fire. Forest fuel continuity is monitored using the following methodologies:
  - Fuel biovolume: Two transects are defined per plot, measuring 10 m in length and 0.5 m in width, in the direction of maximum slope. These two 10 x 0.5 m polygons are then divided into 0.5 x 0.5 m squares. In each square, the percentage occupied by each type of cover (scrub, herbaceous, leaf litter, stones) is recorded. For the scrub, the species, percentage occupied by each and average height are recorded. The data from these transects are used to estimate scrub cover and fuel biovolume.
  - Crown fire hazard: Following the methodology in the Crown Fire Hazard Manual (Piqué et al. 2011), the following measurements are taken: surface fuel cover (%); ladder fuel cover (%); height of surface fuel (m); distance between surface and ladder fuel (if ladder fuel cover > 25 %) (m); distance between surface and aerial fuel (if ladder fuel cover < 25 %) (m); distance between ladder and aerial fuel (if ladder fuel cover > 25 %)

(m); and fraction of canopy cover of the aerial stratum (%). From these data, the fuel continuity model of the forest stand (Figure 12) and the crown fire hazard are obtained.

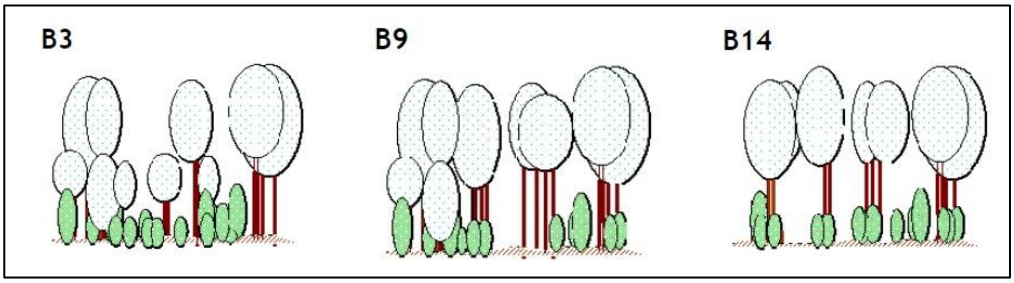


Figure 12. Graph of what the fuel continuity models look like according to the methodology in the Crown Fire Hazard Manual (Piqué et al. 2011).

- **Fuel moisture:** Fuel moisture refers to the water content present in the vegetation during the dry season (summer). Fuel moisture is linked to the flammability and combustibility of the vegetation and, as a result, to fire risk. The higher water content of vegetation in periods of high fire risk results in lower flammability and combustibility of the vegetation. Fuel moisture is measured using the following methodology: using a pole, branch samples are collected from ten random trees and ten random shrubs in the treatment plots and the control plots. The branches are cut from the uppermost, north-facing part of the canopy. Samples are taken 9 times a year, approximately on the following dates: 1 May, 1 and 15 June, 1 and 15 July, 1 and 15 August, 1 September and 1 October. The samples are kept in a cool box until they are processed in the laboratory. First, they are weighed to obtain the fresh weight (W). They are then oven-dried at 80 °C for 24 hours and again weighed to determine the dry weight (DW). This allows the relative water content to be determined: RWC (%) = [(W-DW) / W] x 100.
- **Annual sampling of forest decline (defoliation, discolouration and mortality):** Forest decline refers to the state of deterioration of the forest due to the effects of climate change (mainly droughts) and other related threats (pests, disease, etc.). Forest decline is defined by the degree of defoliation, discolouration and mortality of forest species. Using a field manual, the state of decline is assessed by visually estimating the percentage of tree mortality (dry crowns), the percentage of defoliation (leaves not present compared to leaves present on a healthy tree) and the percentage of foliage discolouration (leaves not green compared to green leaves on a healthy tree). Forest decline is assessed for 10 trees per forest inventory plot. The trees are marked and identified with a number tag so that their evolution can be followed throughout the study. Forest decline is assessed before the treatments, after the treatments and every year in September. This field identification method is based on the DEBOSCAT project (Banqué et al, 2013) and the Spanish Forest Monitoring Network (Level II). Information available in Spanish at: https://www.miteco.gob.es/es/biodiversidad/temas/inventarios-nacionales/redes-europeas-seguimiento-bosques/red_nivel_ll_danos.aspx.

4.3.2. Moisture sensors

There is a network of moisture sensors distributed across the forest inventory plots to monitor the evolution of water in the first centimetres of the soil, as an indicator of water availability for vegetation and recovery of soil function. The network of sensors includes the following instruments:

- **HOBO U30-NRC USB weather station data logger**: This data logger (DL) allows data to be recorded over an extended period and has been programmed to take data every hour. A total of six DLs have been installed, four in the treatment plots and two in the control plots.
- **S-SMC-M005 soil moisture smart sensor**: These sensors, which are connected to the data logger where the information is recorded, measure the soil's moisture. They are buried 5 cm deep and inserted into a corrugated tube for protection, mainly to prevent them from being chewed by livestock and wildlife. A total of twelve sensors have been installed in the treatment plots and eight in the control plots.

4.3.3. Air temperature and relative humidity sensors

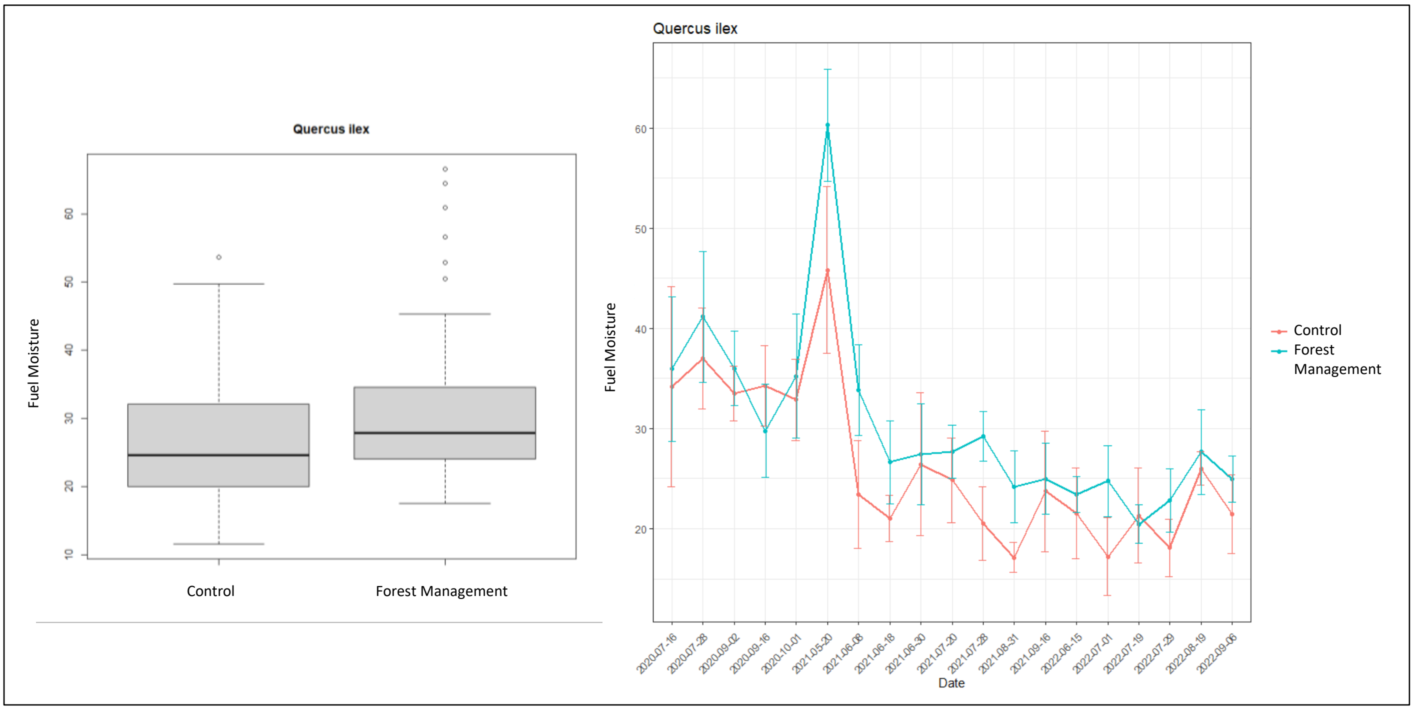
A network of air temperature and relative humidity sensors has been installed to continuously record the meteorological conditions, which are essential for understanding the evolution of the previously mentioned variables for the duration of the project. To this end, a total of six air temperature and relative humidity sensors have been installed, four in the treatment plots and two in the control plots. They are HOBO Pro v2 sensors (U23-001) by Onset Computer Corporation, which have been installed 130 cm above the ground and take measurements at a recording interval of 60 min.

5 What changes have been brought about by the pilot study? Main Results

The results obtained in the different monitoring campaigns, carried out in the summer/autumn of 2020, 2021 and 2022, are shown below.

5.1 Fuel Moisture

First, the moisture content of the main tree species (*Quercus ilex subsp ilex*, holm oak) and the main shrub species (*Erica arborea*, tree heather) is shown (Figure 13 and Figure 14). A **significantly higher moisture content can be observed in the areas where silvicultural treatments have been applied and this difference is more evident in periods of high fire risk (summer).** This higher moisture content translates into lower flammability and combustibility of the vegetation.



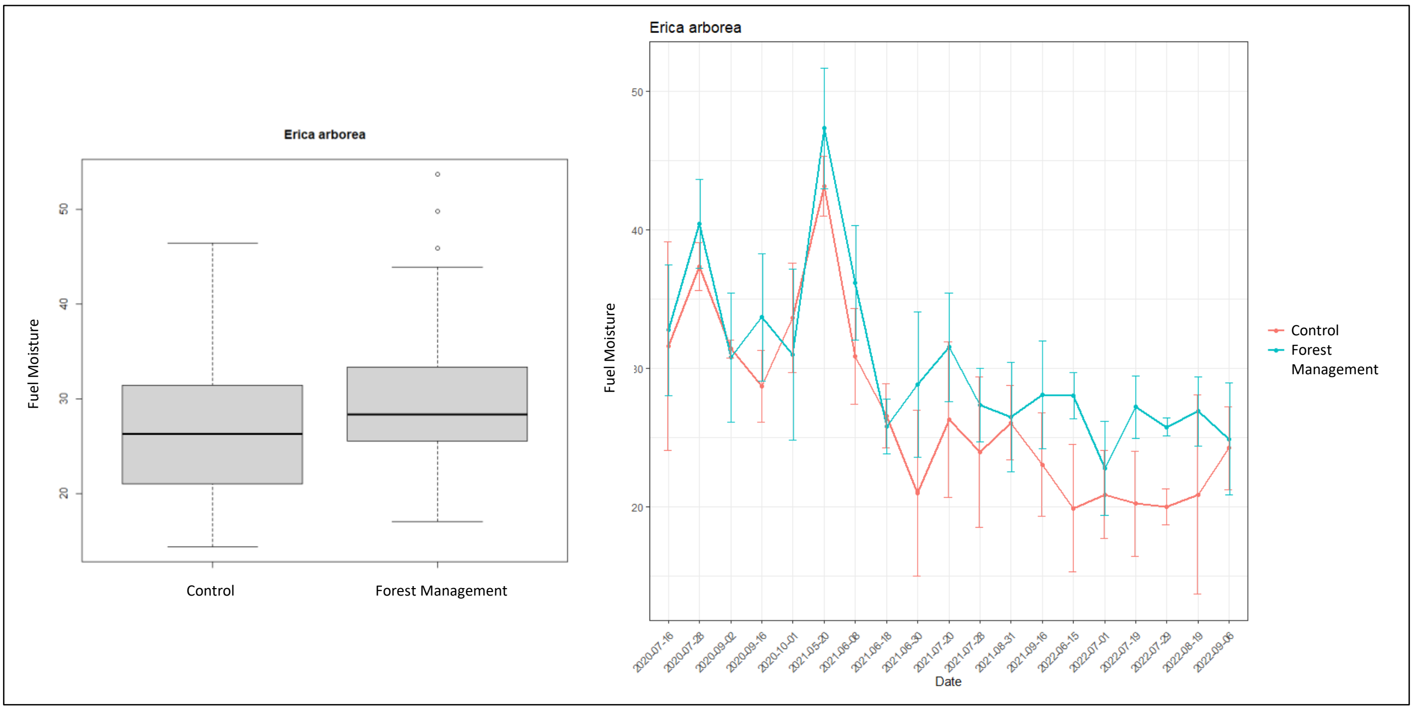


Figure 13. Fuel moisture content of holm oak (top) and tree heather (bottom), grouped by treatment or control plot (left) and broken down through the summers of 2020, 2021 and 2022 (right).

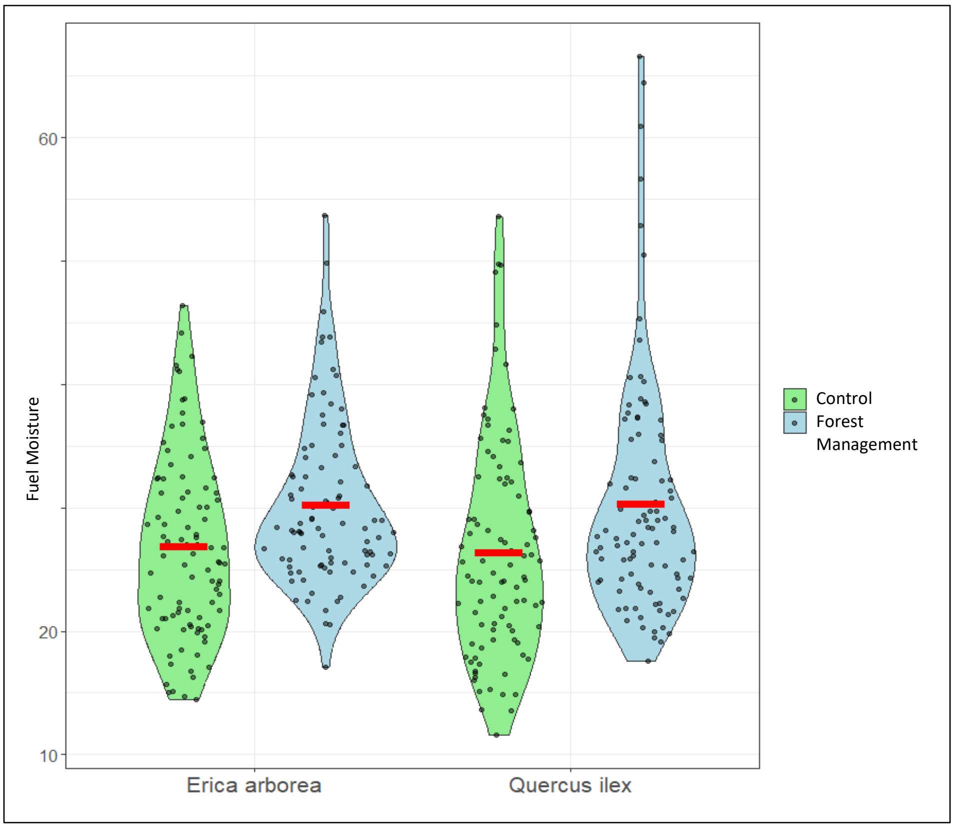


Figure 14. Violin plot of fuel moisture content for holm oak and tree heather, comparing data by treatment and control plot over the monitoring period.

5.2 Forest Decline (Forest Health status)

The forest decline sampling results show a similar impact of the effects of the lepidoptera *Lymantria dispar* on all the forest inventory plots in 2020 (Figure 15, left). **The pest attack in 2020 was so extensive that it caused extreme defoliation of all the holm oaks and cork oaks present** and even affected tree heather, which is very unusual. In 2021 and 2022, forest decline sampling showed an even greater impact on all the inventory plots (Figure 14), indicating that the **forest stand had not managed to recover from the previous attack and that this has been considerably hindered by the drought of 2021-2022**. We will have to wait several years to see which of the plots, treatment or control, recover better.

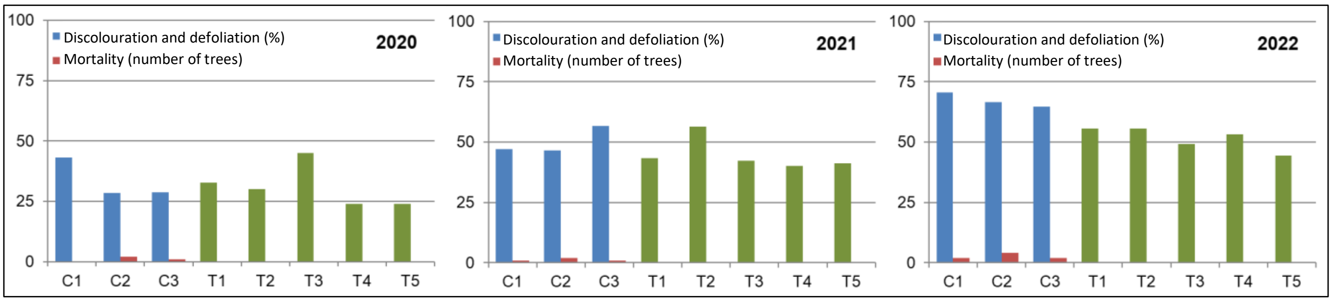


Figure 15. Percentage of discolouration and defoliation in all plots in 2020, 2021 and 2022.

Figure 16 shows that the **decline is significantly higher in the control plots** in all three samplings (2020, 2021 and 2022), although **the slope of the two curves (treatment and control) is similar**. Whether this trend is amplified over time remains to be seen, it is still too early for this to be confirmed or refuted.

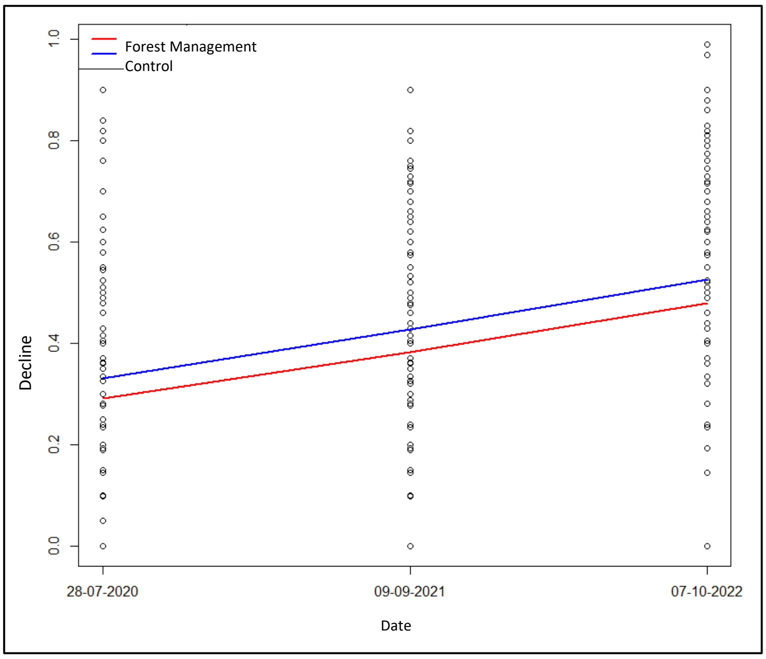


Figure 16. Average discolouration and defoliation (expressed as a fraction of one) in control plots and treatment plots in 2020, 2021 and 2022. Regression using a quasi-binomial model.

5.3 Crown Fire Hazard

The results of the crown fire hazard assessment show a **change in forest structure and a decrease to low vulnerability in some of the treatment plots one year after the actions were implemented** (Table 7). As explained previously, the forest treatments led to a change from a moderate-to-high crown fire hazard before the action, with fuel continuity models A3, B3 and B9, to a moderate hazard after the treatment, but with less-continuous models, B14 and B15. In the 2021 monitoring campaign, the hazard was observed to have decreased to low in two of the treatment plots (C13 and C17), remaining moderate in the rest and maintaining the same fuel continuity models. In the 2022 campaign, the crown fire hazard remains moderate in all the treatment plots due to slight vegetation growth but with discontinuous models.

Inventory Plot	Before adaptive forest management February 2020		After adaptive forest management June 2020		Second monitoring campaign September 2021		Third monitoring campaign September 2022	
	Fuel Continuity Model	Crown Fire Hazard	Fuel Continuity Model	Crown Fire Hazard	Fuel Continuity Model	Crown Fire Hazard	Fuel Continuity Model	Crown Fire Hazard
Control 1	B9	Moderate	B9	Moderate	B9	Moderate	B9	Moderate
Control 2	A3	High	A3	High	B9	Moderate	B9	Moderate
Control 3	B3	Moderate	B3	Moderate	B9	Moderate	B9	Moderate
Treatment 1	B3	Moderate	B15	Moderate	B14	Moderate	B14	Moderate
Treatment 2	B9	Moderate	B14	Moderate	C13	Low	B14	Moderate
Treatment 3	B3	Moderate	B14	Moderate	C17	Low	B14	Moderate
Treatment 4	B10	Moderate	B14	Moderate	B14	Moderate	B14	Moderate
Treatment 5	B3	Moderate	B14	Moderate	B15	Moderate	B15	Moderate

Table 7. Model of fuel continuity and crown fire vulnerability at four different points in time: initial, post-treatment, second and third monitoring campaigns.

5.3.1. Soil moisture

Figure 17 shows the mean of the hourly soil moisture data recorded by the soil moisture sensors installed in the control plots and in the plots where forest treatments were applied. The data shows similar trends for the two types of plots but with **significantly higher moisture levels recorded in the last year for the treatment areas**.

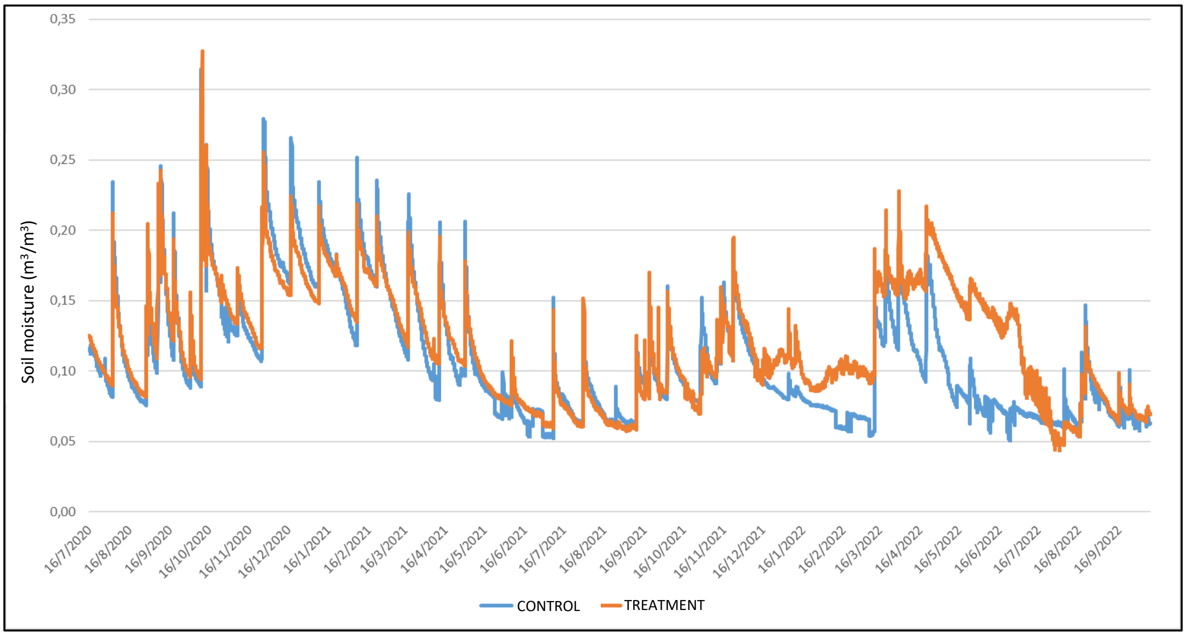


Figure 17. Average amount of water in the soil throughout the project, measured by the sensors installed on the plots.

5.3.2. Temperature and relative humidity

Figure 18 shows the mean hourly ambient temperature data recorded by the sensors installed in the control plots and in the plots where forest treatments were applied. The data shows the **same pattern for both plot types, with a slight but significant trend towards a higher temperature in the treatment plots**. It is worth noting the different maximum temperature peaks recorded during the summer of 2022 in the pilot study area and how the effect of a particularly hot summer can be appreciated. This trend will have to be assessed in the longer term to see if the effect of forest treatments is reduced over time, as the tree canopy closes and the microclimate conditions of the treatment plots converge with the control plots.

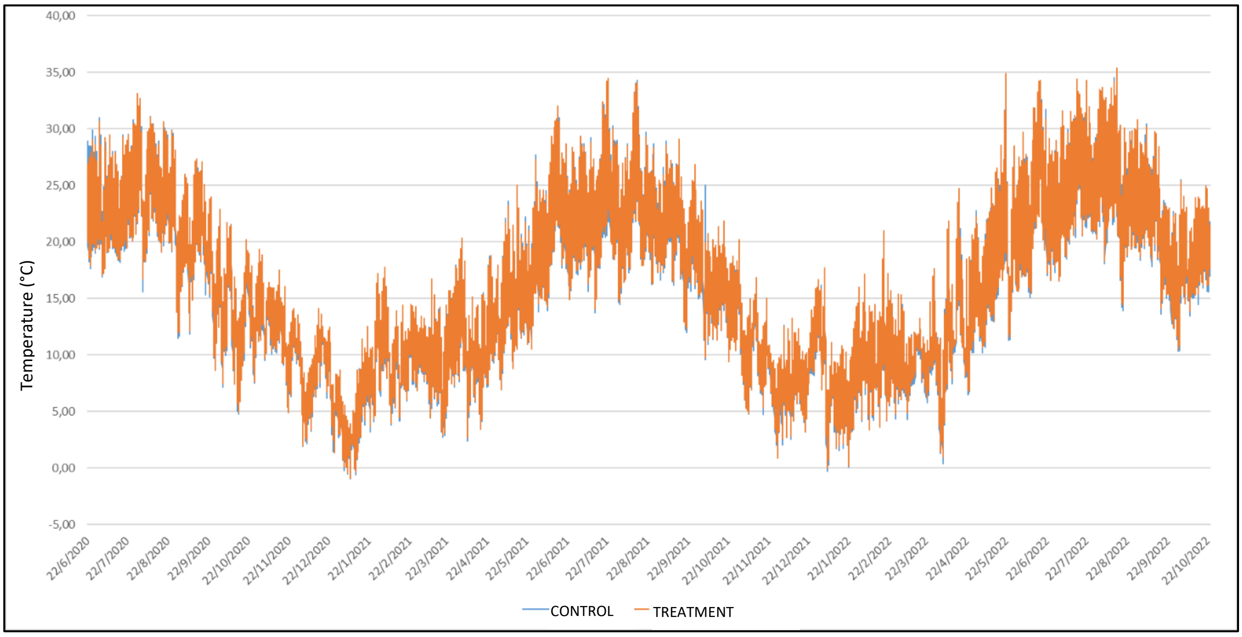


Figure 18. Average ambient temperature (at a height of 130 cm) measured using sensors in the different plots of the pilot study area.

Figure 19 shows the mean hourly relative humidity data recorded by the sensors installed in the control plots and the plots where forest management was applied. The data shows the **same pattern for both plot types, with a slight but significant trend towards higher relative humidity in the control plots**. This trend will have to be assessed in the longer term to see if the effect of forest treatments is reduced over time, as the tree canopy closes and the microclimate conditions of the treatment plots converge with the control plots. Of note is the effect of the heat waves on the low relative humidity recordings during the summer of 2022.

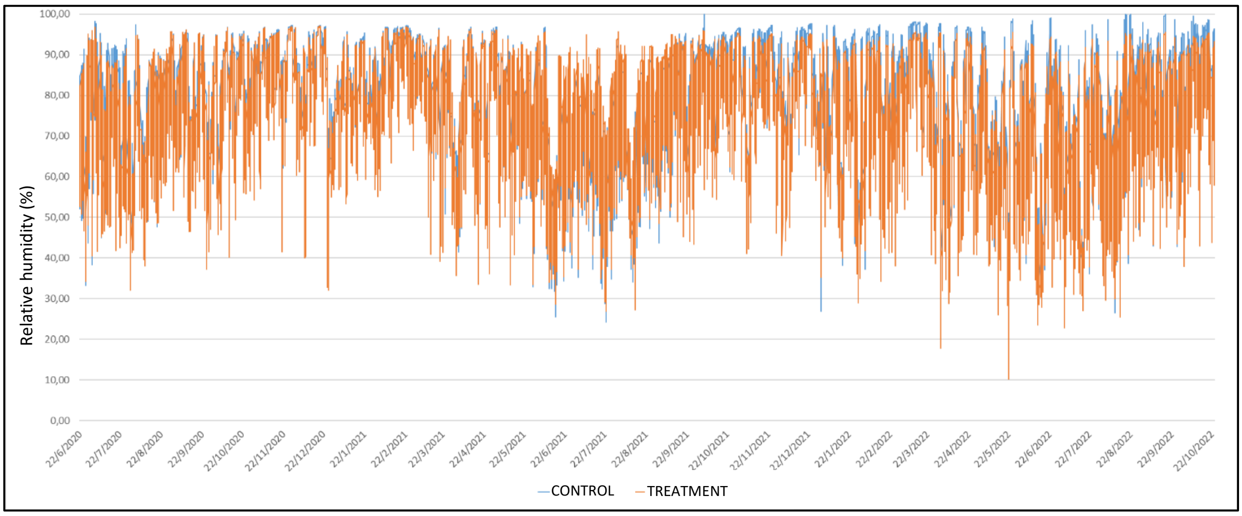


Figure 19. Average relative humidity (at a height of 130 cm) measured using sensors in the different plots of the pilot study area.

6 Conclusions

The **forests of the SUDOE mountains**, both in terms of territorial extension and climate sensitivity, are some of the areas **most vulnerable to risks of drought and fire**. In recent decades, the surface area of forest has increased in many of these mountains, to the detriment of agricultural and scrubland areas. In general, these new forests are dense and poorly managed and are therefore particularly vulnerable to drought and large forest fires. Monitoring of forest decline episodes in Catalonia shows that the recent hot dry summers have led to a greater impact in terms of discolouration, defoliation and mortality.

Climate impacts that are already affecting our forests will be accentuated in the future due to a greater frequency and intensity of periods of drought projected by climate models:

- Increased fire risk.
- Changes in forest function and structure: decrease in productivity and CO_2 storage capacity.
- Increased frequency and intensity of mortality events.
- Increase in the impact of pests and disease in the most fragile forests and introduction of new pathogens (fungi, insects, etc.).

There is evidence that adaptive forest management can help make forests more resilient to these risks. However, the complexity and time frame of many studies make it difficult to develop decision-making tools and adaptive management strategies based on the evaluation of the effectiveness of different silvicultural treatments from multiple perspectives.

For this reason, built on the **principles of adaptive management, this pilot study was designed and implemented** as part of the MONTCLIMA project and **aimed at making a Mediterranean holm oak forest less vulnerable to fire risk**. This study was implemented in a forest that showed evidence of drought and the effects of disease, located in an area defined as strategic in fire prevention management.

The main results obtained two years after the pilot study began are as follows:

- A **slight increase in soil moisture where forest management was implemented**. During spring and summer, higher soil moisture has a **favourable correlation with tree growth and tree health**.
- **Greater water content of the vegetation in periods of high fire risk**, which means that **the vegetation is less flammable and combustible**.
- **Less decline of vegetation** in the tree layer, which consists of holm oak, cork oak, pine and oak, although the rate of this decline has not slowed over time.
- Change in forest structure, which has **clearly reduced the crown fire hazard** by decreasing the vertical continuity of fuel.

The ***Lymantria dispar* infestation** during the monitoring of the pilot study, the impact of the 2021-2022 drought and the **2022 summer heat waves have played a relevant role in the results**

of the study. They occurred almost simultaneously in time and profoundly weakened the vegetation in the study area (as evidenced by the forest decline data collected in the last year). Despite the intensity of the phenomena, which we unfortunately believe will increase in the SUDOE mountains area, the **results of the forest management actions applied are promising in terms of dealing with the risks of fire and drought and reducing their impact**.

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