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Advancing Integrated Fire Management and Closer-to-Nature Forest Management: A Holistic Approach to Wildfire Risk Reduction and Ecosystem Resilience in Quinta da França, Portugal

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Abstract: Forests, due to climate change, already face the impacts of drier conditions and prolonged fire seasons caused by rising global temperatures, that exceed 1.1°C above pre-industrial levels and reach the 1.5 threshold set by the Paris Agreement. In addition to human-induced climate change, other drivers that increase the risk of extreme wildfires include land abandonment, urban-wildland interface (WUI) expansion, and poor or inadequate forest and landscape management. Traditional firefighting methods, extensive fire suppression and exhaustive fire exclusion, are proving inadequate in the face of increasingly intense wildfires, necessitating a move towards Integrated Fire Management (IFM). IFM is a holistic and comprehensive proactive approach that encompasses a variety of tactics to manage wildfires effectively (proactive prevention measures, controlled response operations and proactive restoration efforts), while also promoting ecosystem resilience, social equity and viable economy. The EU Forest Strategy for 2030 recognizes the urgent need towards prevention, emphasizing Closer-to-Nature Forest Management (CTNFM) as a Nature-Based Solution (NbS) to reduce wildfire risk, to improve the quantity and quality of EU forests and fortify adaptive capacity in the context of climate change. In Quinta da França (Covilhã), Portugal, the implementation of IFM and CTNFM approaches has been implemented within a Sustainable Forestry 4.0 approach, in an observation – modelling – intervention – evaluation cycle, with the massive use of sensing and data modelling combined with activities including grazing, prescribed burning, controlled clear cuttings, pruning, thinning and mastication. These operations are tailored to enhance the sustainability and resilience of the landscape mosaics taking into account the local socioeconomic and environmental context as well. This approach fits within the implementation of IFM through the SILVANUS platform, by addressing the challenges outlined in the three phases of disaster risk management (A – Prevention and Preparedness, B – Early Detection and Response and D – Restoration). The evaluation of the approach shows namely its capacity to reduce fuel load and horizontal and vertical vegetation continuity, enhancing biomass carbon sequestration and soil protection, hence showing how the integration of these tools and methods allows the establishment of sustainable and resilient landscapes and communities.

Keywords: integrated fire management; closer-to-nature forest management; ecosystem resilience; forest functioning; ecosystem services; wildfire risk reduction; nature-based solutions

1. Introduction

From 2011 to 2020, the world experienced a concerning increase in global temperatures by approximately 1.1°C compared to pre-industrial levels (1850-1900). This alarming trajectory suggests that we are highly likely to surpass the critical 1.5°C warming threshold sometime between 2021 and 2040, even under optimistic low-emission scenarios [1]. The implications of this warming are already manifesting, particularly in forest ecosystems, which are increasingly vulnerable to the interplay of warmer temperatures that create drier conditions and extended growing seasons. Climate conditions that have been observed in recent decades have undergone a series of changes, thereby creating an environment favorable to the increase of extreme wildfire events [2–10]. This phenomenon is not solely attributable to climate change; it is also exacerbated by factors such as land abandonment and increased human activity in or near vulnerable areas, which are often referred to as Wildland Urban Interface (WUI) areas [11–22]. Poor forest management practices, in conjunction with the buildup of flammable biomass, resulting from past extensive fire suppression efforts in fire-adapted ecosystems and fire exclusion, have been shown to increase wildfire risk [23–26], with the potential for devastating ecological and economic consequences.

In light of the mounting challenges, reliance on conventional firefighting methodologies has been shown to be inadequate for effectively combating extreme wildfires, which can result in significant financial expenditures [27]. This underscores the necessity for enhanced strategies and methods to combat these pressing issues, considering both the present and the anticipated future challenges [28]. As these fires advance faster than conventional suppression strategies can address, Integrated Fire Management (IFM) emerges as a crucial solution for modern fire management. IFM is a comprehensive approach that integrates ecological, socio-economic, and technical considerations in the management of fire [29–37]. It redefines human relations with fire, transitioning from merely combating it to strategically leveraging it for prevention, suppression, and even ecological restoration. By employing this holistic method, communities can minimize the adverse impacts of wildfires while also taking advantage of the natural benefits of fire, a natural process in Mediterranean forests, fostering a proactive rather than reactive stance towards wildfire management and aligning practices with natural processes [38].

To further bolster forest resilience and sustainable management practices, the EU Forest Strategy for 2030 [39] provides a robust framework that emphasizes a shift from traditional fire suppression methods to an Integrated Fire Management policy. This strategy not only aligns with the broader goals of the EU Green Deal [40] but also strongly prioritizes enhancing forest resilience against climate change impacts. Concrete actions outlined in the strategy include increasing the size and health of EU forests, fortifying their protection and restoration efforts, and adapting them to meet emerging climate-related challenges such as extreme weather events and increased variability. The overarching vision of the strategy is to enhance the socio-economic benefits of forests while maintaining their ecological integrity, ultimately fostering a sustainable coexistence between human activity and forest ecosystems.

A critical aspect of wildfire risk reduction lies in implementing sustainable forest management practices. The recent wildfire related peer review program in the EU – Wildfire PRAF 2023 [41] underscores the value of Nature-Based Solutions NBS), such as traditional sustainable planed grazing methods and diverse forestry techniques, in mitigating wildfire risks. Concurrently, the recent Landscape Fire Governance Framework (LFG) [42] highlights the integral role of IFM in sustainable landscape stewardship. This framework advocates for collaborative governance approaches that incorporate a variety of stakeholders, merging scientific insights with cultural knowledge and political perspectives to effectively manage fire risk. The report proposes international guiding principles that can enhance the effectiveness of wildfire management efforts worldwide.

In response to these challenges, the European Commission has introduced also the Closer-to-Nature Forest Management (CTNFM) framework [43]. CTNFM provides a framework for forest management that promotes biodiversity, adapts to climate change, and aligns with the EU Green Deal goals. The core objective of CTNFM is to bolster the ability of forests to provide diverse

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ecosystem services, including timber production, biodiversity conservation, wetland preservation, water quality maintenance, recreation, and carbon sequestration and storage [44]. The key seven principles of this sustainable forest management strategy are: a) retention of habitat trees, special habitats, and dead wood, b) promoting native tree species as well as site adapted non-native species, c) promoting natural tree regeneration, d) partial harvests and promotion of stand structural heterogeneity, e) promoting tree species mixtures and genetic diversity, f) avoidance of intensive management operations and g) supporting landscape heterogeneity and functioning [43,44].

Sustainably managed forests not only enhance resilience to disturbances like wildfires but also serve to create landscapes that are less susceptible to severe damage [38,45–56]. Conversely, effective wildfire risk reduction practices contribute to the overall resilience of forest ecosystems, safeguarding both the forests themselves and the communities that depend on them. Enhancing the resilience, resistance, and adaptive capacity of existing and future forest stands amid natural disturbances requires a strategic focus on promoting compositional, functional, structural, and genetic diversity [57–66]. A shift in forest management practices is imperative to mitigate the risk of widespread destruction caused by wildfires. Transitioning from even-aged monocultures of conifers to diverse, uneven-aged mixed forest structures with enrichment has been identified as a potential solution. This approach involves increasing the proportion of broadleaves in the forest ecosystem [67–76].

Achieving this goal necessitates the adoption of various silvicultural tools to emulate the natural disturbances along with appropriate harvest techniques during the forest successional sequence. Practices such as prescribed burning, controlled clear-cutting, pruning and thinning of overcrowded forests, as well as managing woody material through mastication and reducing herbaceous and shrubby fuels via cattle grazing, trampling behavior of animals, consumption of biomass or use of mechanical means, can promote a healthier and resilient forest structure. By fostering a diverse array of site adapted tree species that respond differently to fire dynamics, the risk of wildfires can be effectively mitigated, while simultaneously lowering the vulnerability of individual trees and the broader ecosystem. This multifaceted strategy not only enhances the health and resilience of forests but also strengthens their capacity to withstand the pressures imposed by climate change and human activity.

The objective of this paper is to demonstrate the necessity of adapting to instability and uncertainty, as opposed to relying solely on historical models concerning forest and fire management. The integration of IFM and CTNFM is imperative to establish a resilient system that can adapt to market fluctuations, climate variations, community modern needs and natural hazards. Furthermore, in order to optimize the integrated multifunctionality of forests landscapes and their associated ecosystem services, it is imperative to implement effective strategies. Moreover, Quinta da Franca (QF), a study site in the Cova da Beira (Portugal) that are related to cost-efficient fire prevention in local forested and agropastoral sites that are next or close to critical infrastructure facilities. The study site is being explored the last 15 years while has also been the focus of integrated fire management testing of the SILVANUS project (EU Horizon funded) for an integrated wildfire risk platform. The activities focus on the prevention, restoration and adaptation through the continuous monitoring of the area through modern technological means (UAVs, satellites, long range wide area network), the prioritization of areas for potential intervention for fuel treatment, the implementation and test of livestock grazing as a nature-based solution (NbS) and the use of prescribed burning for fuel treatment.

2. Fire and Forest Management at Quinta da França

2.1. Site Description

The case study is located at QF site, an agroforestry farm covering a total area of 500 ha, in the Covilhã municipality in the Cova da Beira region in Portugal. This is a farm with multiple land uses, functions and services including production and conservation forest, habitats, cereal crops, meadows, and pastures for livestock production, soil protection, water cycle regulation, timber and

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forage production and recreation (https://www.terraprima.pt/en/area-de-actividade/4, accessed on 08 May 2025). This experimental site, owned by Terraprima, offers a representative landscape mosaic of the region, encompassing a diversity of land uses and vegetation types. One of the core sites of QF is a 200-ha native Pyrenean oak forest (*Quercus pyrenaica*), where the monitoring, prescribed burning and restoration activities are focused (Figure 1). This area also includes smaller patches of dominant mixed oak forest, primarily composed of planted coniferous species. Besides the forested areas, pasturing activities for livestock production (beef cattle and dairy sheep production), cereal crops and meadows are also conducted.

Cova da Beira region is situated in the east of Portugal and borders with the Natural Park of Serra da Estrela to the north. This park is a significant orographic natural border, with which the Açor and Lousã mountains, set the western end of the Iberian Central Cordillera. Serra da Estrela is the highest point of Portuguese mainland, and an important part of three hydrographic basins (Douro, Tejo and Mondego). The Serra da Estrela region and Natural Park present a unique and diverse landscape with a varied mosaic of habitats, combining representative elements of various biogeographic regions. It is one of the most emblematic areas in Portugal regarding natural values associated to its elevated topography. The area combines a strong industrial base with significant rural influences (agriculture and forestry activities) and a high population density, being widely known for its top-quality agriculture products.

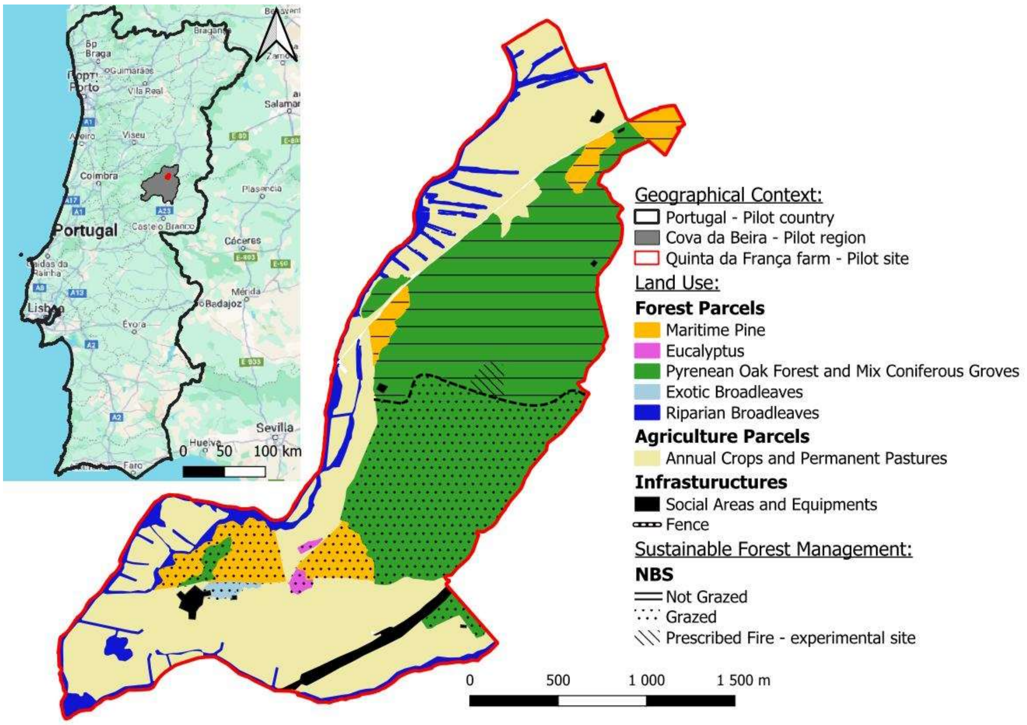

Figure 1. Quinta da Franca.

The Pyrenean oak forest is native to Southwestern Europe and characteristic of sub-Mediterranean mountainous regions, typically occurring at altitudes between 400 and 600 m, in transitional areas between sub-humid temperate and Mediterranean semi-arid climates. Annual average temperature is equal to 12.6 C and precipitation equal to 1012 mm [77]. Three types of forests once dominated this region during the Holocene: Pyrenean oak forests, mesotrophic oak-ash forests, and riparian alder forests. Human activity, especially since the Neolithic, replaced these with agricultural and later forestry uses. In recent decades, land abandonment has allowed native tree and shrub species to recover. Listed under the Habitats Directive (Habitat 9230), this forest plays a key ecological role in soil protection, water regulation, and biodiversity conservation, supporting a pioneer species in post-fire recovery areas. With a strong root system and high regenerative capacity,

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Pyrenean oak (*Quercus pyrenaica)* is resilient to fire and cutting, having a long history of silvo-pastoral use being extensively managed for firewood production and livestock grazing.

The fire regime is generally characterized by a typical Mediterranean fire season, with most wildfires occurring during the hot and dry season (May to September). This is related to the regional climate characteristics of Cova da Beira based on two key factors: the hot and dry summers, and the wet and humid falls and winters seasons. This is also influenced by the typical vegetation phenology that includes a growing peak in the spring, with longer daylights and rising temperatures, followed by a senescence dry biomass period in the summer, and thus, contributing to the wildfire hazard increase.

The occurrence of severe and intense wildfires is characteristic for the area affecting large areas of shrubland and forestland in the region, with some severe wildfires occurred in 2003, 2005 and 2022. Terrain is characterized by deep slopes, which are difficult for fire fighters to access. Along with the summer adverse climate characteristics and large areas of monoculture forest production regime, namely Maritime Pine (*Pinus pinaster*) and Eucalyptus (*Eucalyptus sp.*) a unique blend for intense wildfires is being created. Nevertheless, the agricultural mosaic, combined with the autochthonous Pyrenean oak forests in the pilot region, largely contributes for an enhanced resilience of the territory against forest fires. In contrast, agricultural practices such as burning for pasture areas, burning ended annual crops for the new seeding season as well as the mechanical agriculture operations, are being identified as contributing factors to unintentional and negligent fire ignitions.

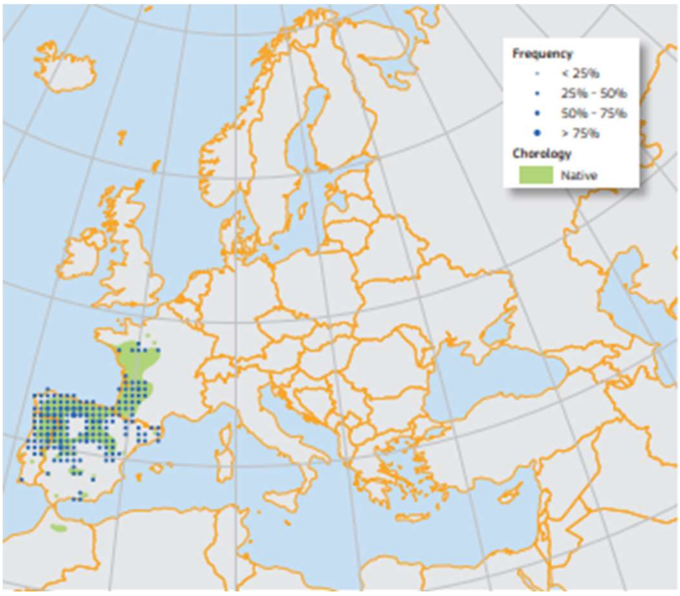

Figure 2. Quercus pyrenaica geographic frequency and simplified chorology distribution map (https://forest.jrc.ec.europa.eu/media/atlas/Quercus_pyrenaica.pdf).

Historically, the current QF oak forest area suffered two major wildfires, in 1984 and 1995, which heavily affected most of the current pilot area. Since then, the forest has undergone natural regeneration, partially assisted through planting, and is now managed for conservation, fire prevention purposes, wood production for fuelwood and grazing. Vegetation within QF is highly heterogeneous. The oak woodland includes unevenly distributed stands of varying size and age, interspersed with open areas such as pastures and rocky outcrops, as well as shrub dominated areas, mainly brooms (*Cytisus multiflorus* and *Cytisus scoparius)*. Hawthorn (*Crataegus monogyna*), Blackberry (*Rubus ulmifolius*) and Grey Willow (*Salix atrocinerea)* are also present. Some of the sparsely wooded or degraded areas have been replanted with pioneer conifer species, such as Maritime Pine (*Pinus pinaster*) and Cypress (*Cupressus sempervirens and Cupressus lusitanica*), selected for their high productive potential.

2.2. Forest Management Approach

Quinta da França (QF) is managed under the umbrella of sustainable agroforestry management, using several approaches of nature-based solutions such as grazing and closer-to-nature forest management practices to create a feedback loop for adaptive management for resilience against wildfires. This management framework is implemented methodologically in the following way (Figure 3):

- Intensive monitoring is conducted with real-time and continuous data collection using remote sensing and in situ IoT sensors;
- Field data collected are used for further modelling and calibration to support decision-making and improve the understanding of sustainable forest management practices;
- Modelling results and outputs are used to further improve the management of the area and guide the relevant strategies through optimization of actions and also actionable recommendations to create a continuous sustainable feedback loop.

Figure 3. Sustainable agroforestry management framework at Quinta da França.

2.3. The Context of the SILVANUS Approach

The forest management project at Quinta da França has been developed in the framework of the EU Horizon Europe SILVANUS project.

In the context of contemporary wildfire management, response agencies are actively involved in the exploration, development, and implementation of innovative approaches to improve the detection, monitoring, and response to wildfire incidents. The SILVANUS project, recognizing the need of the agencies for more advanced, efficient, and proactive strategies produced the Integrated Technological and Information Platform for Wildfire Management, a platform with the capability to assess input from various sources to results that support prevention, enhance situation awareness, support decision-making and provide guidance for restoration.

Aerial imagery systems, through satellites or UAVs, as well as ground-based sensors can allow the early detection of wildfires [78]. UAVs can support communication even in remote areas, providing the necessary technological means [79,80]. Nowadays, social media technologies [81] can support such kind of detection and allow for improved communication between citizens and emergency responders [82]. Satellite imagery allows easy and regular monitoring of vegetation, before and after wildfire, especially for post-fire rehabilitation but also for management purposes [77]. Various data combined in technological platforms that encompass modern GIS capabilities can support decision making [83,84].

The notion of IFM as adopted within SILVANUS is depicted in Figure 4.

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Figure 4. SILVANUS stakeholder involvement with the relevant phases in IFM. Phase A refers to Prevention and preparedness, Phase B refers to Detection and response and Phase C refers to Restoration and adaptation.

The overarching design of the SILVANUS Integrated Wildfire Risk Management (IWRM) is presented in Figure 5, that maps the data and information flow that has been identified within the risk assessment framework and further mapped into the list of 'user products (UPs)'. We introduce the notion of user products, to emphasise the design and the operations of the UPs have been conceived with a specific user persona. The role of UPs and the interoperability between those UPs have been conceptualised in close consultation with the end-users (also referred to as stakeholders). The IWRM framework workflow initiates from the need for enhancing the preparedness and prevention activities with the creation of fire danger index (FDI) maps along with the involvement of citizens. The knowledge gathered about the environmental assets with the creation and curation of the biodiversity indices assists in modelling the impact of wildfires on a region. Following the high-level of preparedness, the regions identified to be under threat will have enhanced surveillance monitoring either with the use of drones or through the deployment of IoT devices on the field. The data collected and aggregated from the field will be used to continually monitor the state of the forest environment and when a fire incident has been detected, the IWRM framework allows for the use of decision support system (DSS). The functionalities of the DSS bring together several components including deployment of appropriate resources based on the estimated fire spread, identification of relevant evacuation pathways and assess air quality monitoring. The IWRM framework extends beyond the fire suppression interventions with the ability to continually monitor the rehabilitation and restoration activities.

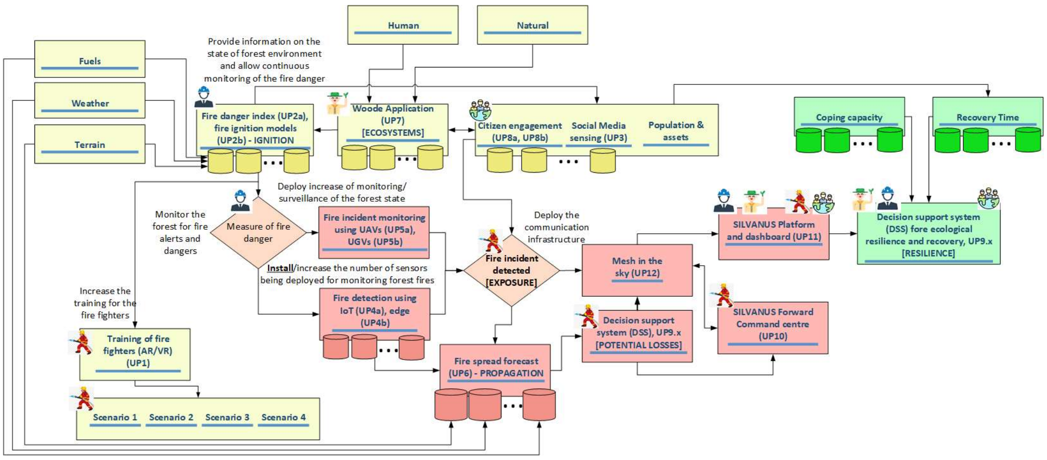

Figure 5. SILVANUS IWRM framework.

The Portuguese case study aligns with the Integrated Fire Management (IFM) objectives, following an annual cycle that includes Phases A, B and C, implementing a continuous action plan that covers all phases throughout the year, rather than concentrating efforts solely during the peak fire season (Figure 6).

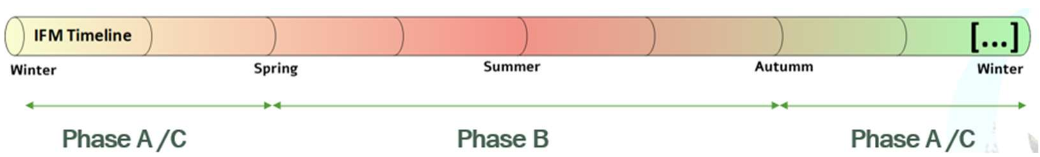

Figure 6. Integrated Fire Management (IFM) phase clustering within an annual cycle approach in the Portuguese case study.

During the peak fire season in summer, most forest management activities are restricted or prohibited, to comply with wildfire protection law. As a result, during this period, the IFM objectives at the pilot site Quinta da França (QF) in Portugal primarily focus on Phase B, emphasizing wildfire risk monitoring and preparedness for first response actions. These actions involve local equipment interventions, including portable fire extinguishers, water tanks, water cannons, and firebreak-maintenance tractors equipped with grader blades. From the perspective of this sustainable agroforestry management framework at QF site, some actions are accomplished in the different IFM Phases.

The specific actions followed for the sustainable agroforestry framework are the following, based on IFM and CTNFM approaches. Regarding the prevention and preparedness phase (Phase A) the following activities are carried out:

- Implementation of frequent remote sensing monitoring;
- Reduction in management costs through proactive planning of clearing activities;
- Identification of terrain characteristics that may constrain or ease wildfire combat;
- Maintenance of fire breaks;
- Selective tree cutting pruning and thinning;
- Livestock grazing and mechanical control to reduce fuel load; prescribed fire to control shrub biomass fuel;
- Personnel engagement for wildfire prevention and preparedness – good practices adoption on forest management activities.

Phase C activities focus on the mitigation of trade-offs by the use of grazing for biomass management, aiming at avoiding impacts on soil, biodiversity, tree regeneration and reducing GHG emissions; and selecting the right set of variables to assess restoration efforts.

2.4. Forest Planning

A sustainable forest management plan is essential for implementing IFM and CTNFM at QF. Management is carried out according into different zoning plan based on homogeneous land cover, biomass type and density. A fence was installed to divide the Pyrenean oak forest into two different main management areas: grazed and non-grazed. This zoning plan guides to promote sustainable utilization of forest products (timber and non-timber forest products), biomass control, such as thinning, mechanical shrub removal and prescribed burns. These operations are primarily conducted in areas not subject to grazing management, as such, in the grazed areas, animals contribute for the biomass control. In both areas, different levels of landscape discontinuities and biomass load, such as shrub cover, are created and managed to increase forest fire resilience (Figure 7). In Figure 8, an example of the differences in shrub cover in both grazed and non-grazed areas is presented.

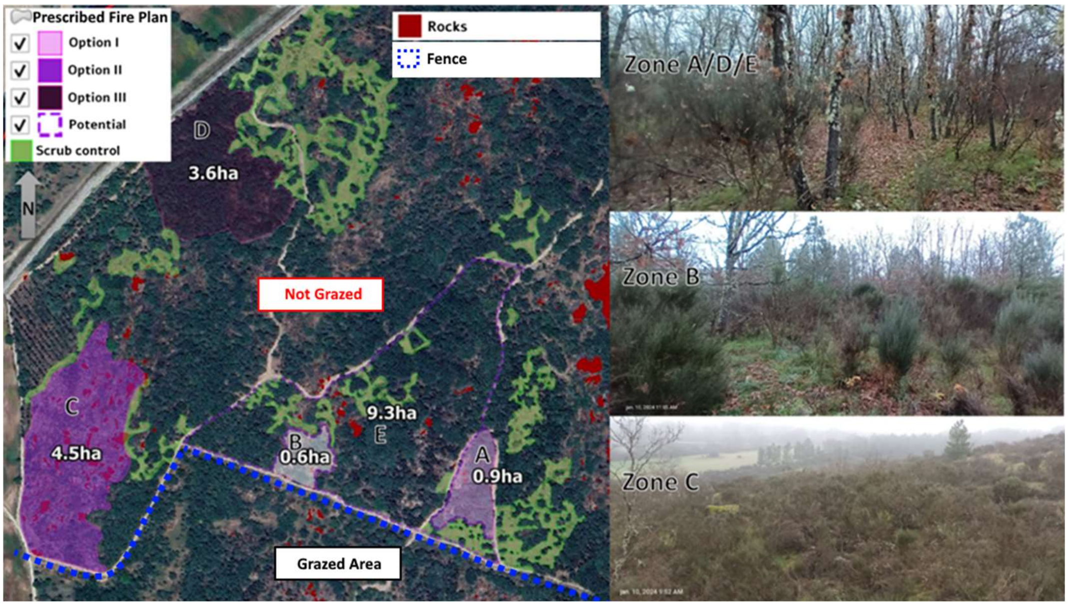

Figure 7. Forest zoning plan at Quinta da França, Portugal.

Figure 8. Grazed area vs. non-grazed area at Quinta da França, Portugal.

2.5. Non-Grazing Interventions

2.5.1. Firebreaks

Maintaining a clear and navigable network of firebreaks works as a prevention measure and is also essential for effective firefighting during the suppression phase. Quinta da França's forest features an extensive network of firebreaks, ranging from 5 to 10 meters in width, kept free of vegetation and obstacles. These firebreaks are typically aligned with fences network and bounders the forest management zones (Figure 9).

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Figure 9. Left: Firebreaks network at Quinta da França, Portugal. Right: Fire break example at Quinta da França, Portugal.

Firebreaks are part of the QF's forest road network and, together with fuel management plots, are considered part of the Integrated Forest Fire Defence Network (FFDN) as Fuel Management Strips (FMS), and is a legal obligation defined by Portuguese law (Article nº 46 of Decree-Law 82/2021, 13 October). The FMS are divided into three categories based on their function of regional interest (primary network), municipal interest (secondary network) or local interest (tertiary network). In the QF, the FMS networks are identified as municipal and local interest and the vegetation must be managed and controlled according to the definitions of the Municipal Forest Fire Defence Plan in order to reduce the spread of fire, protect communication routes and infrastructure, and isolate potential ignition sources. Legally, it is the responsibility of forest and agricultural landowners and managers and their organizations to carry out fuel management in the areas under their management. Thus, FMS is a legal requirement and a key component of the FFDN in QF to reduce fuel loads, slow fire spread, facilitate firefighting, and protect people, property, and ecosystems. Within the FFDN we can consider also the green fire belts as the agricultural parcels (rainfed and irrigated) that are part of the landscape heterogeneity of QF farm, but also the riparian vegetation corridors (trees grasses and shrubs) that goes along the two main rivers (Rio Zêzere and Ribeira de Caria) that border the farm, one on the North and other on the South.

2.5.2. Mechanical Shrub Control

Shrub control at Quinta da França's forest is performed as a prevention action, with a shrub shredder, to reduce the understory biomass and prevent intense forest fires whilst minimising soil perturbation (Figure 10).

Figure 10. Mechanical shrub control at Quinta da França, Portugal.

Mechanical vegetation treatments such as mastication, shredding, and thinning are increasingly used to reduce wildfire fuel loads and modify fire behaviour. These methods disrupt vertical and horizontal fuel continuity, lowering flame heights and the likelihood of crown fires. For example, [85] demonstrated that mechanical mastication in Australian shrublands significantly reduced predicted flame heights without harming native biodiversity. Long-term monitoring by [86] showed that shrub suppression and reduced fine fuel loads persisted up to nine years post-treatment. In forest ecosystems, early work by [87] confirmed that mechanical crushing effectively reduced fire hazards in ponderosa pine slash. Additional studies [88,89] found that combining mechanical thinning with prescribed burning offered the greatest reduction in fuel hazard, particularly in eucalypt and Mediterranean pine forests.

This type of work can only be done when there is no fire weather restriction because it involves heavy machinery working in the forest, such as tractors and coupled surface vegetation shredders with high-speed rotating iron chains, blades, or hammers. These mechanical operations can easily provoke sparks that can ignite a fire in a dry vegetation situation and when there are high air temperature and low humidity conditions. Therefore, the Portuguese law (Article n.º 68 and n.º 69, from the Decree-Law 82/2021, from 13th of October) recommends carrying out mechanical operations in forest areas only outside the season of hot summer days, especially if they occur in a classified as Priority Prevention and Security Areas (PPSA) with high, or very high, risk classification from the Fire Danger National Map, as happens in a significant part of the QF forest (https://www.dgterritorio.gov.pt/paisagem/ptp/carta-perigosidade-incendio-rural).

Also, mechanical biomass control in a forest environment needs to fulfil some terrain and vegetation conditions; namely it is not possible to operate in high slope or rocky surfaces, especially to avoid machinery rollover and non-optimized route path, with obstacles bypass or inaccessible areas. It is also not possible to work in a dense forest where the machine cannot pass.

The criteria for mechanical brush control in QF's forest is, firstly, to follow the legal permission for forest mechanical operations, taking into account the weather conditions for low fire danger, secondly, to avoid operations in the forest during the nidification season, mainly in spring, and, thirdly, to follow an integrated forest management plan for biomass control, in accordance with the biophysical characteristics of the farm parcels and the zoning plan, alongside with the grazing and prescribed fire plan, this, as a complementary and/or overlapping approach. The objective is to have multiple approaches to forest biomass management that can adapt to the biophysical conditions (weather, vegetation and terrain) and the inter-seasonal and intra-annua parcel rotational intervention planning, aiming at a more cost-effective and environmental benefit, always with a low fire risk for the forest.

Mechanical shrub control allows greater selectivity and is a good practice for places where other techniques cannot be used, either because of the morphological conditions of the area or the presence of protected or ecologically sensitive species or plant communities.

Mechanical shrub control techniques should also consider labour and fuel costs. Its cost is higher than that of grazing but lower than that of prescribed fire, but in QF a combined solution seems to be the most efficient, because is possible to implement different approaches to reduce fuel biomass, according to the different terrain and vegetation conditions.

Several studies have evaluated the combined effects of mechanical treatments (e.g., thinning or mastication) with prescribed fire and/or grazing on reducing biomass and mitigating wildfire risk. The utilisation of integrated approaches frequently results in the attainment of more effective and sustained outcomes in comparison to those achieved by single-method treatments [90–92].

It is very important to emphasize that QF management does not use tillage as a mechanical shrub control, only surface cutting of biomass with no (or very little) soil disturbance. All shredded biomass and fine debris are spread and left in the field, not piled, on the topsoil layer, for organic decomposition, contributing to and transforming into soil organic carbon. In this way, there are several ecosystem benefits, such as protection against soil erosion and increased soil carbon input. Also, that the fact that this is done rotationally, in widely spread areas each area, ensures that any additional temporary fire risk does not exist.

The retention of fine woody debris following mechanical forestry treatments has been demonstrated to enhance soil moisture, organic carbon, and microbial activity, thereby promoting soil health and augmenting carbon sequestration [93,94]. While the implementation of fine woody debris can lead to an augmentation in surface fuel loads in the short term, the distribution of fuel, heightened moisture content, and the suppression of shrub regrowth contribute to a reduction in fire risk over time [95].

The implementation of optimal practices, such as the avoidance of accumulations of vegetation (i.e., piles), the utilisation of prescribed fire, and the monitoring of fuel accumulation, is conducive to the preservation of soil integrity and the enhancement of forest fire resilience.

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2.5.3. Prescribed Burning

Prescribed fire can be described as a planned use of fire to achieve a defined and precise objectives, in a more appropriate and controlled manner, evolving less risk approach when compared with the traditional agricultural burnings [96].

The use of prescribed fire during the cold season seems to be an efficient and good practice for fire prevention, to control the biomass and reduce fire risk and fire severity during the hot and dry season, contributing also for other ecological benefits by maintaining open habitats, promoting the renewal of dominate vegetation by controlling invasive species, not effecting the soil properties [96–98]. Moreover, prescribed fire appears to have higher cost-effectiveness compared to other fuel treatments [97,99,100] and could be used in various fire-adapted vegetation types worldwide [97,101–104].

Quinta da França had a forest management trial with prescribed fire, with the presence of fire experts and the authorization of the local competent authorities in January 2024 (Figure 11).

Figure 11. Prescribed fire at Quinta da França, Portugal, in January 2024.

The use of prescribed fire in the cold season, under adequate weather conditions (air temperature, moisture and wind speed), allows for the implementation of controlled burning with low fire intensity and lower fire temperature, which does not affect the living trees and the soil organic matter (Figure 12).

Figure 12. Controlled fire not affecting alive trees and soil organic matter. Example at Quinta da França, Portugal, January 2024.

As a result of the prescribed fire, the understory biomass is reduced and the vegetation loses its vigour for the next germination season, but the trees are not affected (Figure 13).

Figure 13. Prescribed fire outcome at Quinta da França's forest, Portugal, September 2024.

2.5.5. Selective Tree Pruning and Thinning

A selective tree cutting and tree pruning is done at Quinta da França's forests for fire prevention Phase-A, and for restoration Phase-C, and is manly applied in the non-grazed area. The tree pruning and thinning was intensively done in all QF's forest, under two main forest projects in 2001 and 2002. In the subsequent years, these operations were done manly in the North area of the forest, non-grazed area, under a regular basis, more focus in the coniferous curtain spots (Cupressus sp.), alongside the forest paths and fire breaks (Figure 14), also in some patches of mix oak forest groves, for firewood production.

Figure 14. Tree selective cutting and pruning at Quinta da França, Portugal.

The mechanical pruning technique involves the use of machinery, such as chainsaws, so it also applies the same principles for forest management interventions period that was described for the mechanical shrub control. The objective for this intervention is to reduce the biomass in a vertical layer, by cutting the lower branches of the trees, creating a discontinuity of fine biomass from the ground to the canopy.

This operation is complemented by a selective tree cutting - thinning, with two main objectives, one is to reduce the tree density in some areas, reducing the canopy contact and creating open areas

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and forest clearings, another is to promote the formation and faster growth of some tree specimens. Finally, there is the selective cutting of dead or visibly diseased or weakened trees.

The rationale behind these operations is mainly to reduce the biomass, either in a vertical or horizontal discontinuities, by introducing discontinuities in the forest landscape mosaic that, on one hand, contribute for hindering the fire propagation and, in another, facilitate the firefighting and the mobility. Ecological and hunting aspects are also benefiting from these interventions, as it creates open areas and promotes natural pastures for wildlife and cattle grazing.

In the South area of the forest - grazed area, the livestock produces an effect of biological thinning, which is a natural process that mimics or complements human thinning efforts in forest management.

The sustainable management of the QF forest through closer-to-nature silviculture treatments, should facilitate sustained tree growth and forest biomass over time, leading to a more mature forest with greater resilience to forest fires.

2.6. Grazing

In 2018, livestock grazing was implemented in half of the forest area, aims to extend the farming grazing areas to the forest and reducing fuel load. In this period, the forest provides abundant green grasses, young tree shoots from tree growth and regeneration, and acorns, which serve as highly nutritious food resources for cattle in the extensive beef-calf production system. Additionally, the forest offers a natural refuge for cattle, sheltering them from harsh winter conditions (Figure 15).

To allow a comparative study of the effect of grazing, however, it was implemented only in half of the forest: one area open to cattle (a herd of approximately 60 beef cows, during part of the year), under free grazing on one side of the fence (south area); and one area without grazing on the other side (north area). In order to evaluate the effects of cattle grazing, field data on the vegetation structure were collected in both grazed and non-grazed sites, from 2018 to 2021, and remotely sensed data were analysed for the period of from 2016 to 2021 (two years before and three years after grazing began).

Figure 15. Cattle grazing in forest areas at Quinta da França, Portugal.

Livestock grazing acts as a nature-based solution (NbS) contributing to a more a cost-effective control of fire hazard, by regulating vegetation quantity and spatial distribution, and maintaining fuel discontinuity [105]. This discontinuity should occur both horizontally, in the form of open pastures (i.e., the silvo-pastoral mosaic) and vertically, by reducing understory vegetation and limiting ladder fuels that can facilitate fire spread [106,107].

3. Methods

3.1. Remote Sensing

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Land surface and land cover is primarily monitored through remote sensing imagery. Remote sensing, and data imagery collection for land cover mapping, stands as a fundamental tool for vegetation assessment. The literature commonly refers to remote sensing as a primary source of data in terms of vegetation mapping, and the range of applications in vegetation assessment is very diverse, covering vegetation monitoring for ecosystem structure and function, plant communities, biodiversity, health condition, and restoration status, for instance, in the evaluation for forest resilience from a pre and post forest fire situation point of view [108]. In this sense, remote sensing is a valuable tool for forest management, planning and decision making. Remote sensing is manly done by Earth Observation (EO) equipment, such as satellite imagery, with a major potential to cover large areas at a lower cost, continuously and regular data collection. However, satellites face limitations, mainly due to insufficient spatial, spectral and temporal resolution, but also, from cloud cover light reflectance blocking and suitable imagery failure [108]. This can be mitigated with the use of UAVs for low-altitude imagery data collection.

3.1.1. Satellite Monitoring

Sentinel-2 is a powerful tool for Earth Observation (EO) and land cover mapping production, especially appropriated for vegetation and soil monitoring. The Sentinel-2 mission, developed by the European Space Agency (ESA) under the Copernicus Programme, is an EO mission. The mission comprises two satellites (Sentinel-2A and Sentinel-2B) that capture high-resolution optical imagery across 13 spectral bands. The primary objective of the mission is land monitoring, with additional applications including agriculture, forestry, land use, and disaster response. With a spatial resolution of 10–60 m and a swath width of 290 km, Sentinel-2 provides global coverage at a rate of once every five days. The satellite's open data policy has facilitated extensive utilisation in scientific and operational contexts, particularly in the domain of environmental monitoring [109,110].

Remote sensing data acquisition of Sentinel-2 imagery for the QF site is an automatic procedure implemented with two main objectives: first, for real time data mapping and land cover monitoring, and, second, for historical time-series analysis and for modelling. A large volume of gathered data is critical for land cover mapping evolution, training of machine learning models, biomass assessment and forest management planning. At Quinta da França, this is carried out with weekly satellite imagery acquisition. All Sentinel-2 satellite bands are stored in a database, from which multiple combinations are obtained, like the combination of visible Red, Green and Blue (RGB) bands for true and false composite colour images or the calculation of vegetation indices such as the Normalized Difference Vegetation Index (NDVI). The RGB False colour image is appropriate for vegetation and NDVI is a widely used metric for assessing vegetation health and density, as an indicator of greenness vigour [111] (Figure 16).

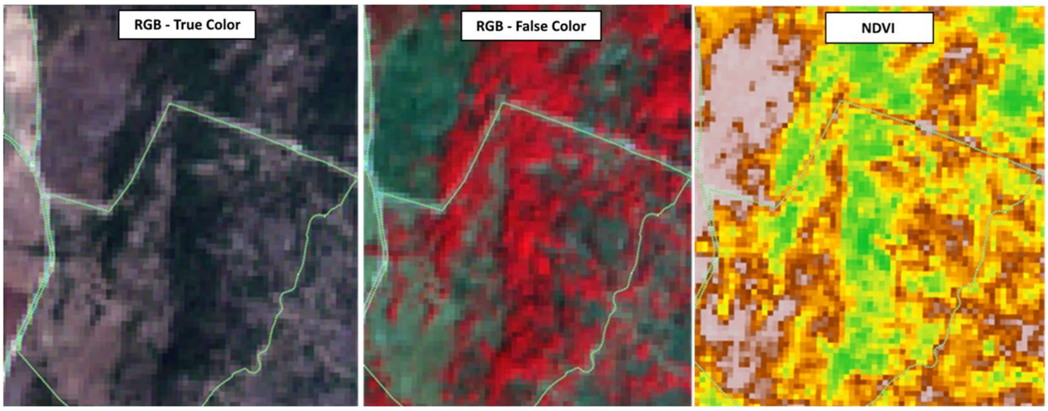

Figure 16. Satellite (Sentinel-2) imagery data collection. Examples for composite imagery. Left: VIS True color; Middle: VIS False color and Right: NDVI index production, at Quinta da França, Portugal.

3.1.2. UAV Monitoring

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Seasonal drone (or unmanned aerial vehicle UAV) flights are carried out at low-altitude in Quinta da França in order to collect hight resolution surface imagery. The cameras in the payload collect visible (RGB) and near-infrared (NIR) images. This image data collection contributes to hi-resolution visible true-color and false-color ortophotomap images, and hi-resolution NDVI products (Figure 17). The drone flights are done in different time seasons, to capture the vegetation phenology cycles. LiDAR (Light Detection and Ranging) data acquisition is done for biomass assessment.

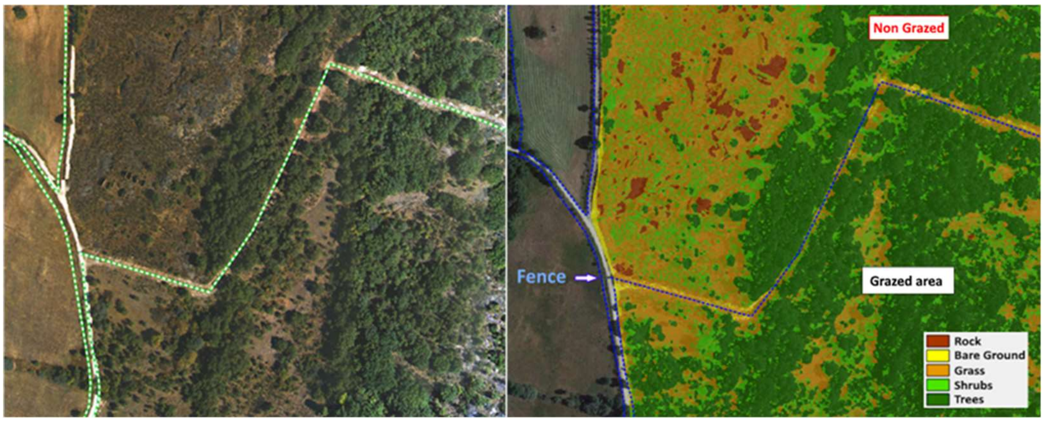

Figure 17. Left: Hi-resolution visible true-color ortophotomap; Right: Hi-resolution land cover map.

3.1.3. Land Cover Maps

Land cover maps have particular importance in forest monitoring and management, especially regarding wildfire prevention. Hi-resolution land cover mapping and shrub cover mapping is an efficient tool to address vegetation evolution and condition, mainly in Mediterranean ecosystems and, in particular, in the pilot region, characterized with a fine-grained heterogeneous land cover, with shrub encouragement after land abandonment and fire [112].

Earth Observation (EO) and satellite (Sentinel-2) imagery collection and time series data analysis, crossed with the validation from the hi-resolution land cover map (drone flights outcome), were used for the development of machine learning models for shrub cover percentage mapping in QF [108,112] (Figure 18). Areas of 0% cover where also identified and mainly correspond to the rocky or bare ground. The shrub cover map does not identify the understory cover, that corresponds to the trees in the land cover map.

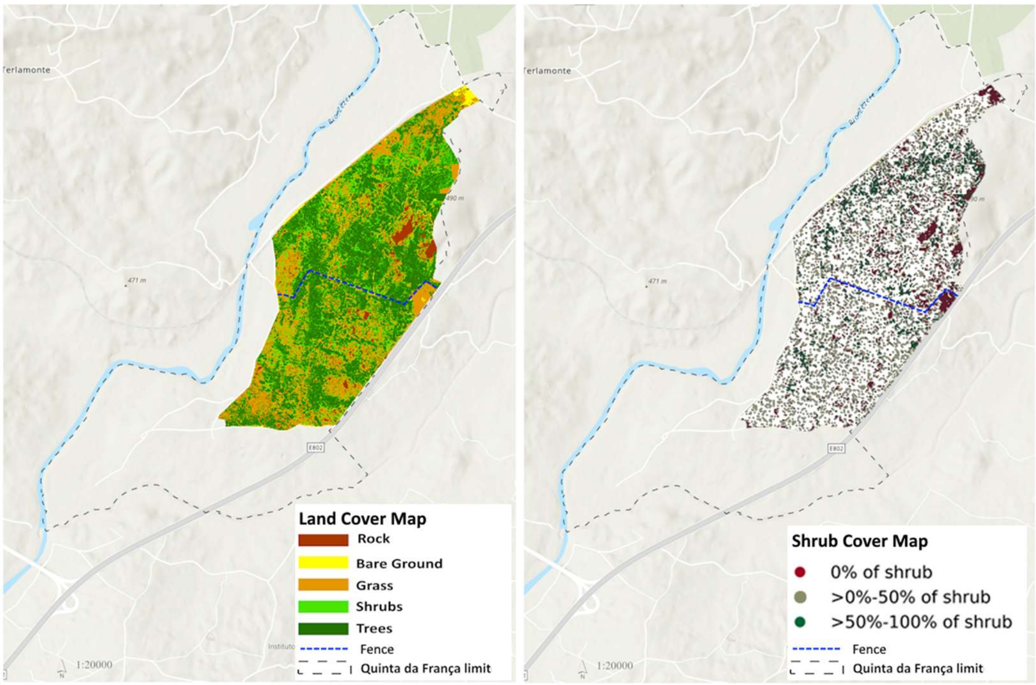

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Figure 18. Left: Hi-resolution land cover map, from drone flights (4 cm x4 cm). Right: Shrub cover map from satellite Sentinel-2 (10 m x 10 m).

3.1.4. Vegetation Vigour

Indexes can be driven from remote sensing data (EO and UAV) by the combination of bands and used for describing land cover conditions, water, vegetation and soil. One of these indexes is the Normalized Difference Vegetation Index (NDVI).

NDVI is a metric used to quantify vegetation greenness. It is a valuable tool for understanding vegetation density and assessing changes in plant condition. The NDVI makes use of two Sentinel-2 bands, namely the red (R) and near-infrared (NIR) values [113,114]:

$$NDVI = \frac{NIR - R}{NIR + R}.$$

NDVI is a widely used indicator for measuring various factors related to ecological parameters, including canopy density, biomass, plant health, and vegetation productivity [115–117]. Furthermore, the same studies also found NDVI to be effective in the assessment of vegetation damage, stress, and recovery. NDVI time series monitoring using remote sensing images can be used to determine vegetation growth and recovery.

3.1.5. Biomass Estimation

Models can be trained to match satellite imagery detection to the high-resolution LiDAR data obtained in UAV flights, estimating vegetation volume [118].

The model training process is based in three steps:

1. In a given area, vegetation classes (species present in the area) are identified.
2. Vegetation volume is extracted per class, in the area, overlapping LiDAR data.
3. ResNet machine learning models make use of satellite images to produce the volume per class.

LiDAR data of biomass volume with spatial resolution of 1m X 1m were extrapolated. These maps feed a machine learning image segmentation model that uses 10m resolution Sentinel-2 images to infer the vegetation volume maps.

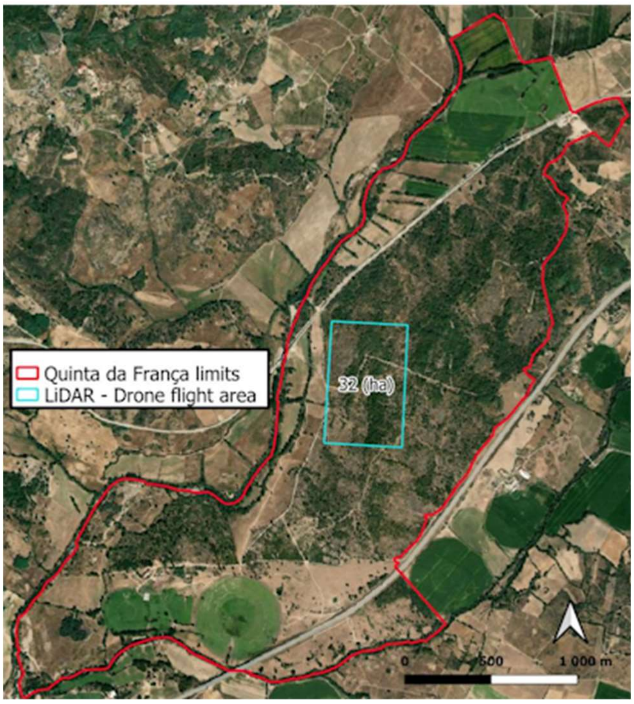

Figure 19. Drone flight area for LiDAR data collection, at Quinta da França, Portugal.

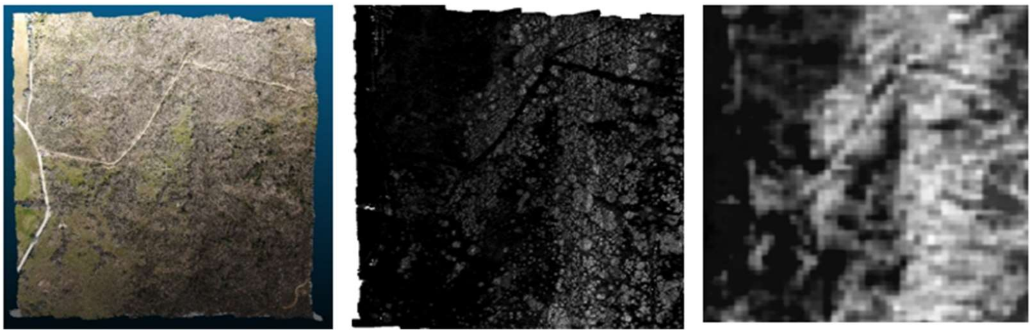

Figure 20. Left: LiDAR cloud points; Middle: Biomass volume from LiDAR; Right: Model inference.

The ResNet architecture is typically used for image classification. CNN (Convolutional Neural Network) and FCNN (Fully Convolutional Neural Network) were also tested with weaker results. Several other architecture experiments were made to optimize the amount of pixels passing into the model.

3.2. Fieldwork

3.2.1. Forest Inventories

The Quinta da França forest is subject to regular monitoring through forest inventories (FI). These FI are conducted on a regular 250 m x 250 m point grid within the forest (with higher resolution in smaller parcels), with the aim of measuring tree dendrometric variables, including total height, diameter at breast height (DBH), used in allometric equations for tree density and biomass calculation. In addition, the forest's condition and tree health are monitored during the FI (Figure 21).

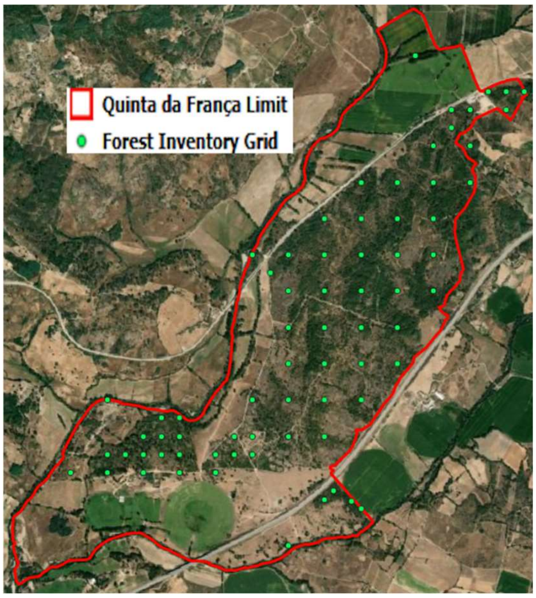

Figure 21. Forest Inventory point grid at Quinta da França, Portugal.

3.2.2. Vegetation Survey

Vegetation structure is surveyed in 10 m x 10 m sampling plots (Figure 22): vertical vegetation profile is surveyed in four perpendicular transects of 5 meters from the centre (maintaining a 90º angle, or as close as possible, between them). Vegetation type (grasses, forbs, shrubs, trees) and height class (0-0.25 m; 0.25-0.50 m; 0.5 -1.3 m; 1.3 - 2m; 2 - 4m; >4m) or bare soil, were registered at the centre and at every meter of the transects (i.e., in a total of 21 registration points per sampling plots).

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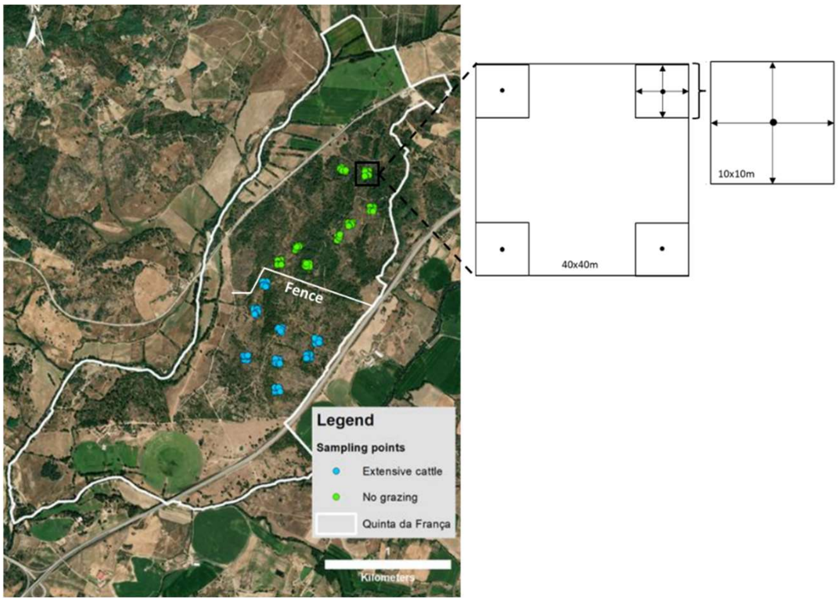

Figure 22. Spatial arrangement of survey plots (40 m x 40m) at Quinta da França (left). Schematic drawing of a 40 m x 40 m survey plot, composed of four 10 m x 10 m sampling plots (right).

4. Results and Discussion

4.1. Overall Forest Characteristics

The tree species composition of QF's forest in the last forest inventory report (2021) is mostly composed by broadleaves trees, from Pyrenean oak (87%), and in much lower significance, followed by coniferous trees of Maritime pine and Cupressus (12%), and some residual other broadleaves of Ash, Willow and Eucalyptus (Figure 23).

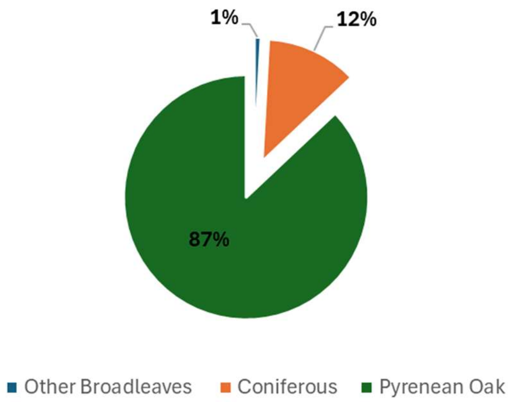

Figure 23. Tree fractions composition in the QF forest (FI 2021).

Diameter at breast height (DBH) and tree height (H) is a key indicator of forest maturity and health in *Quercus pyrenaica* (Pyrenean oak) stands, with studies in Portugal and Spain having shown that higher DBH values are associated with more advanced forest structure, higher biomass accumulation and greater carbon storage [119–121].

Figure 24. shows that, over approximately fifteen years of forest management at QF, the average DBH and H increased by almost 50%.

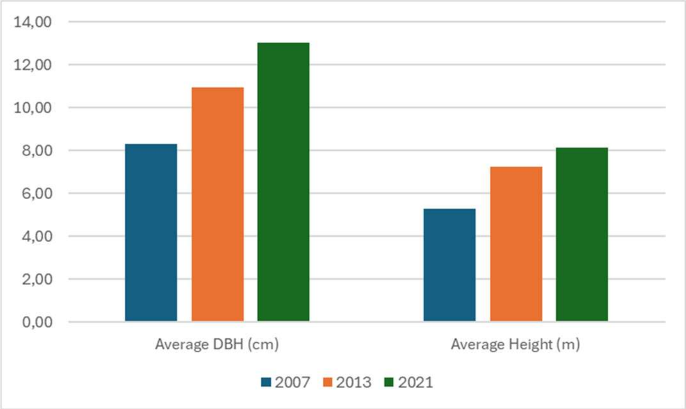

Figure 24. Tree diameter at breast height (cm) and tree average height (m) along Forest Inventories (2007, 2013 and 2021).

The literature indicates that mature *Quercus pyrenaica* forests with higher biomass values have structural characteristics that confer greater stability and resilience. In addition, accumulated biomass is directly related to stand maturity [122].

4.2. Grazing

Regarding tree density and tree biomass, Figure 25 indicates that has been a general increase along the years for both areas (South area – grazed and North area – non-grazed), with approximately 26% more (101 trees per hectare) in 2021, compared to 2007. When looking into the tree density simple average growth per year, since grazing was introduced, in the grazed area, it is much larger than in the non-grazed area, i.e., 7.0% (grazed area) *vs* 1.4% (non-grazed area).

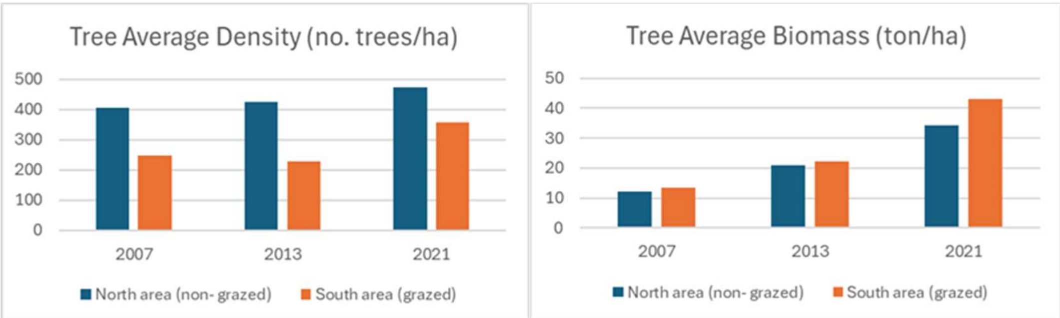

Figure 25. Tree average density (no. trees/ha) and biomass (ton/ha) along FIs (2007, 2013 and 2021), for the grazed and non-grazed areas.

Results show that, in 2007 and 2013 the South area, then non-grazed, had lower tree density but the same biomass (hence higher average biomass per tree) (Figure 25). With the introduction of grazing in 2018, with an effect we observe in 2021, the number of trees increases in the grazed area increases. This finding may be indicative of the effect of the cattle on the trees' natural regeneration, nevertheless it does not appear to exert a similar influence on fully mature trees.

Field monitoring results (Figure 26) demonstrate the effects of cattle grazing and trampling on vegetation structure. These effects indicate distinct vegetation trajectories between the grazed and ungrazed areas. In the ungrazed area, vegetation evolved towards greater structural complexity, with an increase in vertical continuity due to greater coverage across multiple strata. In particular, there was an accumulation of herbaceous biomass in the lower layers (<0.5 m), along with an increase in tall grasses and shrubs in the intermediate and upper strata (0.5 – 2 m), contributing to vertical fuel connectivity and potentially increasing susceptibility to fire spread.

In contrast, the grazed area exhibited more constrained vegetation growth and a simplified vertical structure. Vegetation cover in the intermediate strata declined, likely reflecting reduced recruitment of oak saplings and a thinning of lower tree branches due to browsing (<2 m). There was also a decrease in the cover of tall grasses. Regarding shrub cover, the animals showed more constrained effects, as it increased slightly over time. At ground level (<0.25 m), herbaceous cover increased, yet a higher proportion of bare soil was observed, compared to the ungrazed parcel, potentially indicating localized soil disturbance associated with cattle presence.

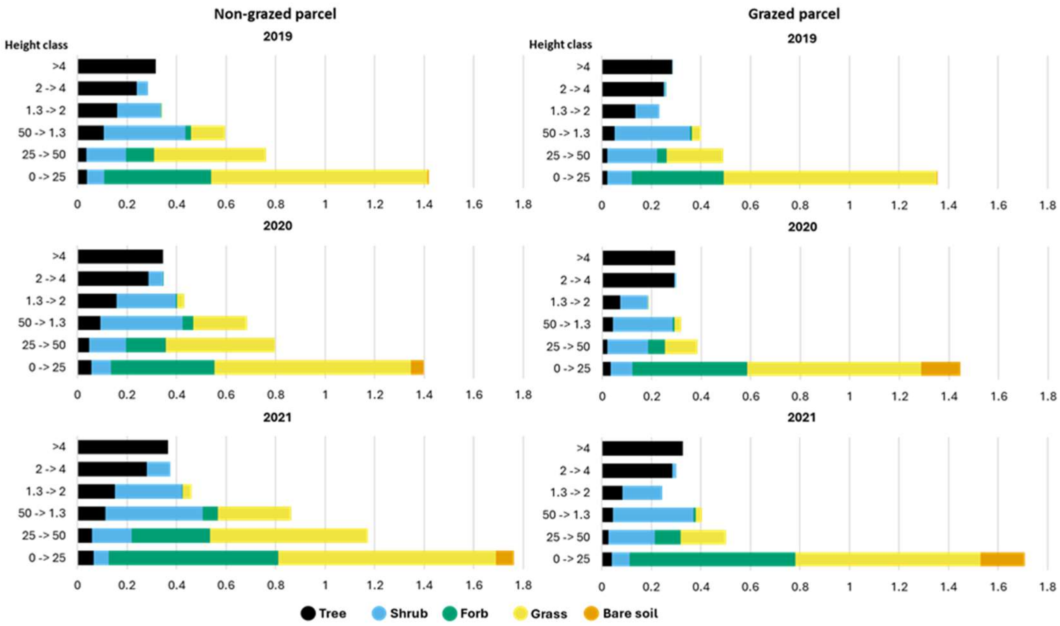

Figure 26. Changes in the relative coverage of the vegetation life forms in different vertical strata, in the monitoring areas. The cumulative coverage value can be greater than 1.

Additionally, fieldwork results suggest that, although cattle grazing does not prevent shrub growth in grazed areas, shrub biomass in these areas accumulated at a slower rate compared to non-grazed areas [107]. The shrub cover map also shows a higher fraction in the non-grazed area, with higher shrub cover percentage class (>50% - 100%) when compared to the grazed area, (>0% to 50% cover) [112].

The analysis of remotely sensed data [77] indicates also an increase in herbaceous vegetation productivity in the grazed areas at the start of the autumn growing season, as well as higher annual peak productivity, in the early spring. Additionally, a decline in shrub peak productivity was observed in grazed areas, though without changes in phenology patterns.

The physical impact of cattle, including trampling and grazing, contributes to reducing both horizontal and vertical biomass, creating discontinuities that are critical for fire prevention [106]. This activity helps maintain forest clearings and pathways, contributing to a diverse landscape mosaic that enhances fire prevention. Furthermore, grazing plays a vital role in the forest soil nutrient cycle through the addition of organic matter, acting as a natural fertilizer. Grazing activity supports biodiversity and fosters phytosociological synergies between native grasses, shrubs, and trees [123,124]. These contributions are particularly relevant for forest management and restoration efforts (Figure 27).

Figure 27. Forest clearing from cattle grazing at Quinta da França, Portugal.

4.3. Prescribed Fire

In order to assess the impact of the prescribed fire event on the reduction of the understory biomass the Prescribed Fire Area was compared to a Control Area, where there was no fire (Figure 28).

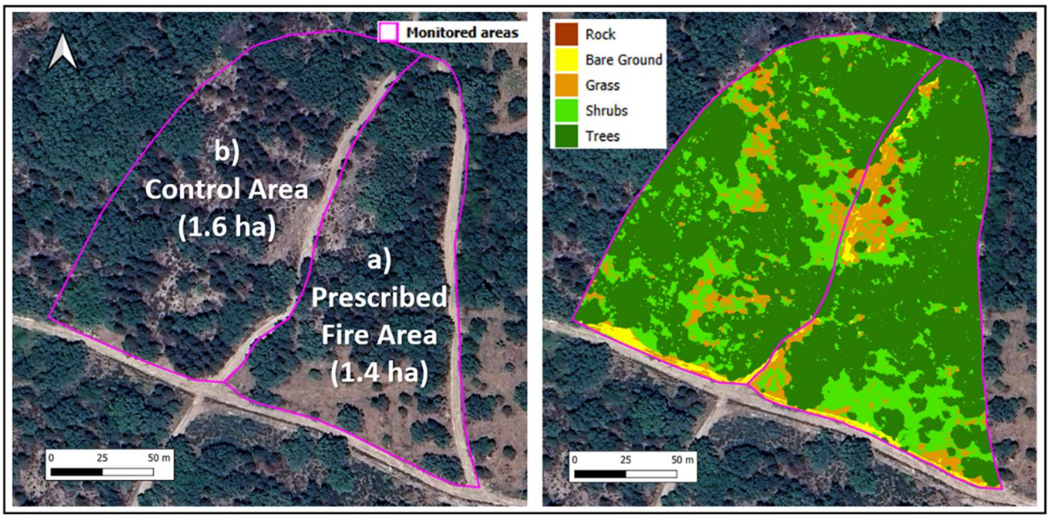

Figure 28. Monitored areas to evaluate the prescribed fire effect: a) Prescribed Fire Area; b) Control Area (image on the left), and corresponding high resolution Land Cover classes (image at the right).

The two monitored areas had a similar land cover structure, prior to the prescribed fire event, (as assessed with the high-resolution land cover map - 4 cm x 4 cm - obtained through UAV imagery and orthophoto map classification). The land cover structure is composed of a minor percentage of rocky and bare ground, less than 3% coverage, approximately 10% of annual grasses, around 20% of shrub vegetation, mostly composed by White Broom (*Cytisus multiflorus*), Blackberry (*Rubus spp.*) and Ferns (*Pteridium aquilinum*), and the largest area is covered by a mature mix trees of deciduous Pyrenean Oak (*Quercus pyrenaica*) and coniferous Maritime Pine trees (*Pinus pinaster*), covering more than 65% of the area (**Table 1**).

Table 1. Land cover composition in the two monitored areas: a) Prescribed Fire Area; b) Control Area.

	a) Prescribed Fire Area		b) Control Area	
Land Cover	**Area (ha)**	**%**	**Area (ha)**	**%**
Rock	0,01	0,5	0,00	0,3
Bare Ground	0,04	2,7	0,03	1,7
Grass	0,13	9,8	0,13	8,1
Shrubs	0,30	21,9	0,35	21,7
Trees	0,89	65,1	1,11	68,3
Total	**1,37**	**100,0**	**1,62**	**100,0**

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We emphasise that the land cover map results from a horizontal classification of the orthophoto map and does not take into account grasses and shrubs in the trees' understory.

The effect of the prescribed fire was evaluated by comparing the NDVI ratio for the land cover biomass classes, before and after the burning event, in the two monitored areas. The NDVI for the two monitored areas was assessed with a raster spatial zone statistics tool (QGIS - Zonal Statistics), applied over the land cover vector map, for a total of 22 Sentinel-2 images with dates in 2023 and 2024 (Table 2), one cloudless image per month (for December 2023 and March 2024, it was not possible to get clear sky images – NDVI values for these two month were calculated by linear interpolation). Note that in the oak-covered areas the satellite is receiving reflected light from under the canopy for half of the year, since these oaks are deciduous, without leaves from mid-autumn until mid-spring.

Table 2. Sentinel-2 tile number and images dates for the NDVI calculation.

Sentinel-2 Tile	2023	2024
T29TPE	04/01/2023	24/01/2024
	03/02/2023	03/02/2024
	15/03/2023	23/04/2024
	19/04/2023	23/05/2024
	14/05/2023	12/06/2024
	23/06/2023	12/07/2024
	13/07/2023	16/08/2024
	12/08/2023	15/09/2024
	26/09/2023	05/10/2024
	01/10/2023	09/11/2024
	25/11/2023	09/12/2024

Figure 29 presents the evolution of NDVI for 2023 and 2024, i.e., before and after the prescribed fire event at Quinta da França (30/01/2024) for each control area and prescribed fire area (below, we analyse each vegetation stratum separately). Figure 29 shows that the control area was adequately chosen: the two NDVI curves are quite similar until the prescribed fire and then start to differ. Also, right after the prescribed fire event, in the beginning of 2024, and the starting of the vegetation resurgence season, the NDVI signature curves seems to capture the greenness of the vegetation growth signal, but more intensely in the prescribed fire area, when compared to the controlled area. This NDVI signature curves inverts their position in the second half of spring season and in the summer, for both prescribed fire area and controlled area, but with lower vegetation signal vigour in the first one. Since during summer there are no grasses and the trees are the same from 2023 to 2024, the NDVI decrease in the prescribed fire area indicates a reduction in shrubs.

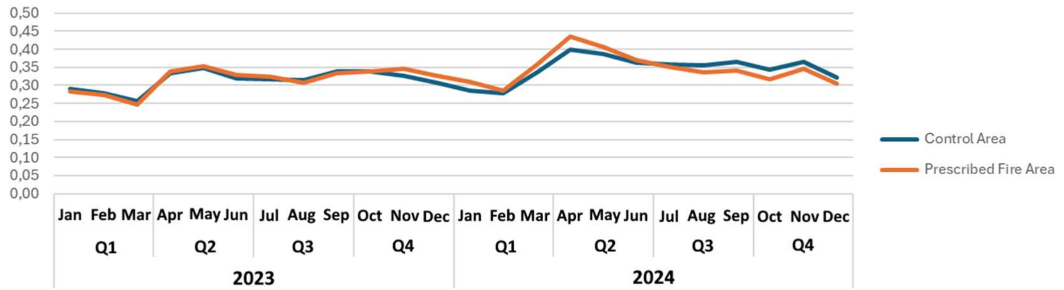

Figure 29. NDVI in the monitored areas: a) Prescribed Fire Area; and b) Control Area, per month in 2023 and 2024.

In **Table 3** is possible to find the analysis of the NDVI ratio (NDVI in the prescribed fire area divided by NDVI in the control area) for each landcover stratum in the summer period, when the

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grasses have dried out, but the shrubs and trees have not. Comparing the summers of 2023 and 2024, we see a significant reduction in the grasses and shrubs, with no significant change in the trees.

Table 3. NDVI ratio (Prescribed/ Control), in 2023 and 2024, for the summer period and its change.

Land Cover	2023	2024	Δ
Grass	4.8%	1.1%	-3.7%
Shrubs	1.5%	-2.5%	-4.1%
Trees	-6.4%	-6.8%	0.4%

5. Conclusions

Quinta da França (QF) has successfully implemented Integrated Forest Management and Closer-to-Nature Forest Management through a Sustainable Forestry 4.0 approach, in a Planning – Intervention – Modelling – Evaluation cycle. By developing a mixed oak dominated forest ecosystem, with a complex mosaic, including coniferous tree, shrubland and pastures, it has promoted ecological processes that lead to a more resilient forestry ecosystem, promoting biodiversity conservation, soil protection, water cycle regulation, carbon sequestration, climate adaptation and livestock production. Quantitative evaluation of the interventions has shown that prescribed fire leads to decreased fuel loading and that grazing leads to decreased horizontal and vertical vegetation continuity, reducing fire risk and increasing biomass, hence carbon sequestration.

The silvicultural treatments implemented in QF adhered to closer-to-nature principles, focusing on sustainable and ecologically sound management. This involved several key strategies:

i) Promotion of natural regeneration, partially assisted through planting: After two major wildfires, the area of where QF's forest currently lies underwent significant natural regeneration, with native oak, shrubs, and other vegetation returning. However, regeneration quality was hindered by factors such as the absence of mature trees, and pockets of invasive species like *Acacia dealbata, Acacia melanoxylon, Ailanthus altissima or Opuntia ficus-indica*. To support recovery, human assisted interventions, including thinning and pruning of the natural regeneration of oaks and targeted planting of pine and cypress saplings, have accelerated growth, stabilized soil, and improved biodiversity, bolstering ecosystem resilience

ii) Partial Selective Thinning for High-Value Trees: Low-intensity thinning was employed, prioritizing the retention and promotion of trees possessing the highest economic or ecological value. This meant favouring well-shaped, valuable broadleaf trees with high market potential while also conserving trees offering significant ecological benefits.

iii) Maintaining Species Diversity: A crucial element was the retention of all existing tree and undergrowth species. No species were removed solely based on their identity; instead, the focus was on optimizing the overall composition and structure of the forest.

iv) Promotion of multi-Stratified Structure for Wildfire Resilience: The silvicultural treatments actively promoted a multi-stratified forest structure. This means creating a forest with multiple layers of vegetation – from the understory to the canopy – rather than a uniform, *even-aged, single-layered, monoculture stands*. This complex structure is strategically important for reducing the risk of large wildfires. Specifically, the layered structure breaks the continuity of fuel, reducing the ease with which fire can spread through the vegetation. Thus, the fire would play only its naturally ecological role.

v) Selective Understory Clearing: In addition to the above, the understory vegetation was subject to partial, selective clearing. This was not a complete removal of the undergrowth but rather a targeted approach to manipulate the understory density and composition, potentially to improve light penetration for desirable species, reduce competition, or further enhance wildfire resilience by creating fuel breaks.

This paper reinforces the importance of conserving and promoting mature *Quercus pyrenaica* forests, not only for their capacity to store biomass, promote ecosystem services such as carbon

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sequestration, soil protection from erosion processes, water cycle regulation, air quality, natural quality scenic and landscape attributes, for other multiple socio-economic services, namely agroforestry uses, with natural pastures for extensive grazing, and societal forest recreational/tourism uses. Finally, their contribution to foster the stability and resilience of Mediterranean forest ecosystems in the face of challenges posed by desertification and forest fires is also instrumental.

The integrated fire management (IFM) approach is characterized in the literature as a holistic, multi-disciplinary strategy that synthesizes scientific research, operational tactics, and socio-economic considerations to address the challenges posed by wildfires [29,37]. This approach moves beyond traditional fire suppression methods by incorporating all the phases of disaster management cycle, i.e., Phase A – Prevention and preparedness, Phase B – Detection and response and Phase C – Restoration and adaptation within a unified framework. Key to the IFM approach is the recognition that wildfires are complex socio-ecological phenomena influenced by natural processes and human activities. As such, effective management requires the integration of diverse data sources—such as historical fire records, remote sensing information, and climate projections—with on-the-ground ecological assessments and local knowledge. This synthesis allows for the development of predictive models that not only forecast fire behaviour but also assess vulnerabilities across different landscapes and communities. Furthermore, the IFM approach emphasizes the importance of collaborative governance. It calls for the active involvement of multiple stakeholders, including government agencies, local communities, scientists, and land managers. By fostering partnerships and leveraging a broad range of expertise, this approach aims to enhance decision-making processes, promote adaptive management practices, and ensure that fire management strategies are both contextually relevant and sustainable over the long term. In essence, the literature underscores that an integrated fire management approach is essential for mitigating wildfire risks in an era of changing climate and land-use patterns. It offers a pathway to balance ecological integrity, community resilience, and economic stability, thereby paving the way for more effective and comprehensive wildfire management strategies. In the literature a framework for wildfire risk assessment has been published [125,126].

The IFM framework has been implemented by the SILVANUS project, integrating multiple components to support both risk evaluation and the development of risk reduction and adaptation strategies. The framework is structured to amalgamate diverse data inputs—such as fire behaviour metrics, fuel characteristics, meteorological variables, and topographical information—into a coherent modelling system that simulates fire dynamics. These models are further augmented by vulnerability and exposure assessments, which account for ecological, social, and economic factors that modulate the overall risk profile. At its core, the conceptual scheme emphasizes an iterative feedback mechanism whereby outputs from the predictive models and vulnerability analyses inform and refine risk management strategies. This dynamic loop facilitates continual improvement of the risk assessment process, ensuring that it remains adaptive to new data and evolving environmental conditions. The integration of these components not only provides a robust foundation for assessing wildfire risk but also offers a versatile platform that can be extended to guide risk reduction and adaptation measures in the face of changing wildfire regimes. Extending beyond the risk assessment framework to include the components that will empower the relevant stakeholders to be able to undertake interventions to mitigate against wildfires.

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Abbreviations

The following abbreviations are used in this manuscript:

CNN	Convolutional Neural Network
CTNFM	Closer-to-Nature Forest Management
DBH	Diameter at Breast Height
DSS	Decision Support System
EO	Earth Observation
ESA	European Space Agency
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FCNN	Fully Convolutional Neural Network
FDI	Fire Danger Index
FFDN	Integrated Forest Fire Defence Network
FI	Forest Inventories
FMS	Fuel Management Strips
GIS	Geographic Information System
H	Height
IFM	Integrated Fire Management
IWRM	Integrated Wildfire Risk Management
LFG	Landscape Fire Governance Framework
LiDAR	Light Detection and Ranging
NbS	Nature-based Solution
NDVI	Normalized Difference Vegetation Index
NIR	Near-Infrared
PPSA	Priority Prevention and Security Areas
QF	Quinta da Franca
QGIS	Quantum GIS software
RGB	Red, Green and Blue
UAV	Unmanned Aerial Vehicle
UP	User Products
WUI	Wildland Urban Interface

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