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Dataset on pre/post fire fuel biomass and water status assemblage from field measurements and remote sensing

once submitted the deliverable, the dataset will be open for new additions

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List of Acronyms

ψ_l	Leaf water potential
AGB	Aboveground Biomass
AGBf	Aboveground biomass of a forest
AGBt	Aboveground biomass of a tree
BA	Basal Area
CFMC	Canopy Fuel Moisture Content
CWD	Coarse Woody Debris
DBH	Diameter at Breast Height
DBSCAN	Density-Based Spatial Clustering of Applications with Nois
Dc	Tree density
DM	Dry Matter
E	Exposure
EWT	Equivalent Water Thickness
FC	Forest classes
FMC	Fuel Moisture Content
H	Height
IFM	Integrated Fire Management
LFMC	Live Fuel Moisture Content
LMA	Leaf Mass per Area
LWP	Leaf Water Potential
MLS	Mobile Laser Scanning
PET	Potential evapotranspiration
PSL	Pic Saint-Loup
PUE	Puéchabon
QI	Quercus ilex
QP	Quercus pubescens
SD	Standard Deviation
TLS	Terrestrial Lidar Scanning
TPH	Trees Per Hectare
VPD	Vapor Pressure Deficit
WMC	Wood Moisture Content
WP	Work Package

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Executive Summary

This WP4 deliverable outlines the data acquisition protocols and main results obtained across the FIRE-ADAPT Study Hubs, providing essential inputs for model benchmarking. The work supports FIRE-ADAPT's goal of developing science-based solutions to mitigate fire hazards under increasing climate and human pressures.

Field data were collected to improve fire hazard modelling through a better understanding of (1) **fuel moisture content**, (2) **fuel amount and structure, and (3) carbon storage and decomposition dynamics**.

1. **Fuel moisture content** is a key driver of ignition, fire intensity, and spread. Two main hypotheses were tested:
    1.1. **Leaf-level processes:** The role of leaf mass per area (LMA) in explaining variation in live fuel moisture content (LFMC) during leaf development, from budburst to maturity. Results indicated that LFMC is highest during early leaf development, highlighting the influence of phenology on fire hazard seasonality and the need to integrate biological factors, not just soil water status, into fire models. A one-year LFMC–LMA dataset was collected for deciduous and evergreen oak species in the France Study Hub.

    1.2. **Canopy-level processes:** The effect of dead leaf retention following senescence and dieback on canopy fuel moisture content (CFMC). A one-year observation in the Brazilian Savanna Study Hub across 12 tree species revealed species-specific processes with strong implications for CFMC modelling, flammability theory, and fire management strategies.

2. **Fuel amount and structure** were addressed using LiDAR-based methods. In the France Study Hub, remote sensing combined fine-resolution tree height data with forest inventory maps to produce national biomass estimates—an approach scalable to other Hubs. Ground LiDAR in the Spain Study Hub provided 3D fuel structure information to assess management effects and improve fire spread modelling.
3. **Carbon storage and decomposition dynamics** after fire were assessed in the France Study Hub, combining LiDAR and fire history data. In a French oak forest, standing dead trees were characterised for decomposition stage, density, and moisture to inform carbon stock and coarse fuel (1000h) moisture modelling.

Overall, this FIRE-ADAPT WP4 deliverable provides harmonised protocols, datasets, and key findings that enhance our capacity to model and manage fire hazard by integrating biological, structural, and carbon dynamics across ecosystems.

1 Introduction

This document contributes to WP4 and, in particular, to Task 4.1 dedicated to vegetation model benchmarking. Vegetation models allow for process-based simulations on plant growth, their carbon storage and fuel amount, and post-fire biomass decomposition or vegetation regrowth, as well as plant water use for transpiration and the moisture content of plant organs. Both information, fuel biomass and water status, are key components for evaluating the impacts of the vegetation on wildfires or prescribed fire (e.g. combustion rates during fire management strategies), to be simulated by vegetation models under climate change and forest management strategies.

Modelling tools, from empirical drought indices to process-based modelling of vegetation biomass, structure and water status have emerged along the last decades to help and provide fire altered systems, burned area forecasting under climate change and land cover scenarios, impacts on ecosystems.

Advances in global data assemblages on plant ecophysiological processes, and technical developments in sensors (i.e. ground, air, space born) could raise new hypotheses on fire hazard and impacts. Even though live fuel moisture content (LFMC) has been an indicator for fire alert systems a long time (Yebra et al. 2024), extreme wildfire events might more particularly influenced by ecophysiological processes driving leaf structure (Brown et al. 2025) and dead leaf material in the canopy (Ruffault et al. 2023). To date, assessments of burnable fuel have largely relied on optical sensing of leaf components, whereas the horizontal and vertical fuel continuity—crucial for canopy torching and fire propagation—has received limited attention owing to the absence of appropriate sensing tools.

FIRE-ADAPT partners targeted these data gaps in the data acquisition, to feed and stimulate the modelling task. This document describes the data assemblage related to these targeted objectives.

> As a first objective, FIRE-ADAPT partners developed protocols and collected data on leaf structural dynamic affecting leaf moisture content, under the hypothesis that leaf structure (the dry mass) might significantly affect LFMC along the development stage of the leaf, and that dead leaves might differentially stay in the canopy and actively contribute to a reduced canopy fuel moisture content facilitating combustion.
>
> As a second objective, FIRE-ADAPT partners tested whether Lidar technologies were able to capture tree structure from ground or space borne sensors, and whether they could provide the key information for fire spread modelling and combustion processes over large areas.
>
> Finally, FIRE-ADAPT partners assessed how post fire woody debris, hardly captured from remote sensing, could constitute a remaining carbon stock, submitted to decomposition, and acting as a significant combustible fuel with intrinsic desiccation processes poorly described in the scientific literature.

Efforts devoted by FIRE-ADAPT teams in assembling these data are summarized here and structured as follows: 1) plant water status and 2) fuel biomass estimates, with each section being divided into specific protocols and applied to FIRE-ADAPT Study Hubs offering field sampling facilities.

2 Datasets

2.1 Fuel water status

As part of the FIRE-ADAPT strategy to assemble key information for model benchmarking on fire hazard and impact, in association with management strategies, we collected fuel water status data in most compartments of the vegetation. Live Fuel Moisture Content (LFMC) is the most widely used information for assessing the impact of vegetation moisture status on fire ignition, intensity and spread, but recent advances identified the potential increased fire hazard as a result of Canopy Fuel Moisture Content (CFMC) including leaf senescence and woody debris (Rffault et al. 2022). We focused this section in assembling this information across study-hubs in the FIRE-ADAPT project.

2.1.1 Live fuel moisture content including leaf mass phenology

Study area

Leaf fuel moisture content (LFMC) were sampled from May to October of 2021 on two mediterranean oak species, the evergreen holm Oak (*Quercus ilex*) and the deciduous downy Oak (*Quercus pubescens*) on two sites, Puéchabon (PUE: Long. 3.5866° E, Lat. 43.7342° N) and Pic Saint-Loup (PSL: Long. 3.7961° E, Lat. 43.7751° N) in the south of France (Figure 1). PUE site was composed of two plots of *Quercus ilex* (CP1, CP2), and PSL site was composed of three plots of *Quercus pubescens* (PSL7, PSL8, PSL11), and two plots of *Quercus ilex* (PSL10 and PSL22).

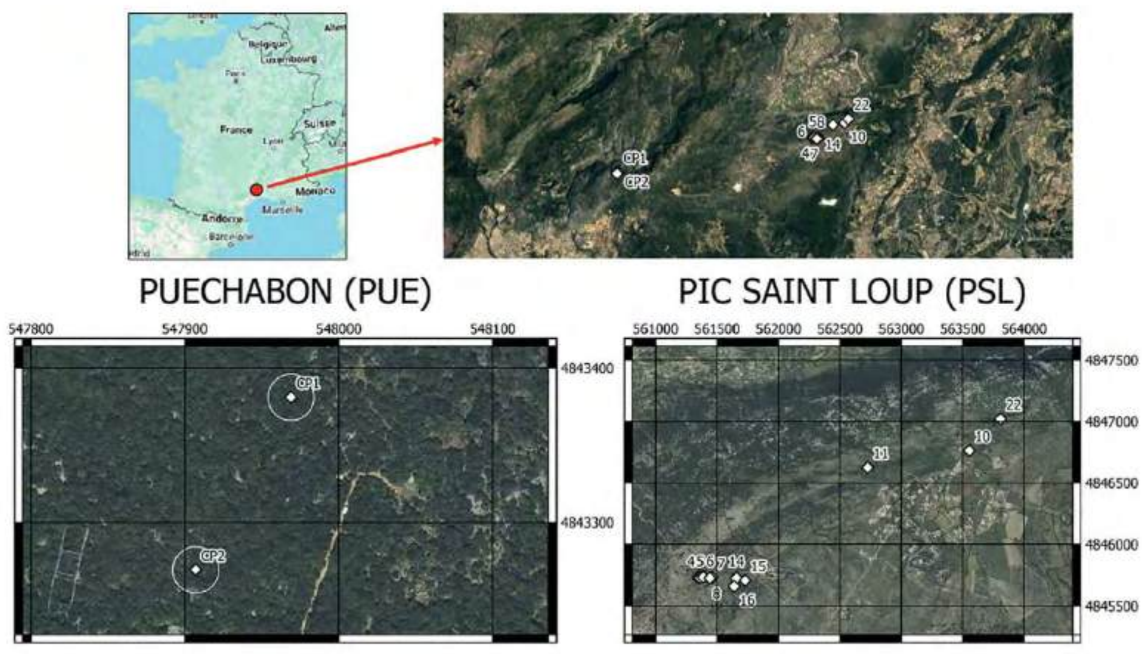

Figure 1. Location of Puechabon (PUE) and Pic Saint Loup (PSL) study sites in France with aerial photographs and sampling plot locations.

Material and Method

From May to October, monthly measurements of LFMC and Leaf Mass per Area (LMA) were measured. LFMC was measured by collecting 10 cm terminal twigs with leaves, being stored in sealed sampling bags and conserved into a cooler until lab measurements. Fresh weight of samples was measured with a precision scale, then samples were dried out at 60°C for 48h and weighted for dry weights. LFMC was measured as the ratio between (Fresh Weight – Dry Weight)/Dry Weight. Each sampled leaves were weighted dry and their leaf area was measured on fresh leaves with a lab planimeter, so that LMA was measured as Dry weight/Leaf Area in $gC.m^{-2}$. Equivalent water thickness (EWT) results from LFMC*LMA.

Results

Figure 2 illustrates the mean and standard deviations of monthly LFMC and LMA on all the plots for the two oak species. We observe the lower EWT values for *Quercus pubescen*s varying between 14 $mgH_2O.cm^{-2}$ in spring down to 8 $mgH_2O.cm^{-2}$ in summer, compared to *Quercus ilex* varying between 20 $mgH_2O.cm^{-2}$ in June and 12 $mgH_2O.cm^{-2}$ during summer. We also observe a varying seasonal time course of EWT, decreasing along the season for *Quercus pubescens* while peaking in June for *Quercus ilex* and quite stable along the summer season. When looking at LMA variation and the differential leaf phenologies between the evergreen *Quercus ilex* and the deciduous *Quercus pubescens*, we observe increasing LMA for *Quercus pubescens* since leaf bud burst in May, but a minimum LMA in June for *Quercus ilex* when old leaves fall concomitantly with the budburst of new leaves with low LMA. Key processes on LMA influence on LFMC will be explored for modelling purposes.

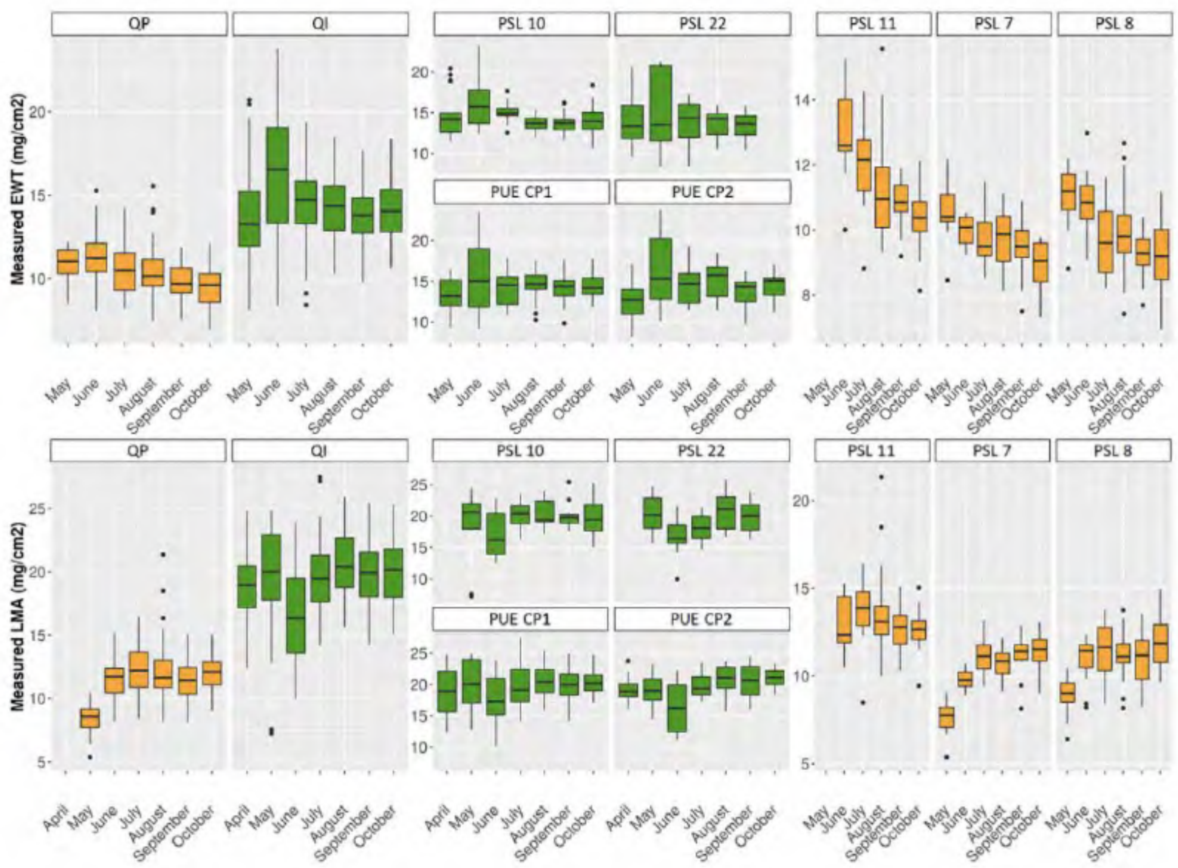

Figure 2: Monthly time course of Equivalent Water Thickness (EWT) resulting from the product of Leaf Mass Area (LMA) and Live Fuel Moisture Content (LFMC) for the two oak species Quercus ilex (QI) and Quercus pubescens (QP) for the Puéchabon (PUE) and Pic Saint Loup (PSL) study sites.

Metadata

The dataset covers the May-October 2021 with monthly measurements.

Format: text file

ID_LOC: the naming includes the location (PUE or PSL), the tree ID, species (QI or QP)

SAMPLING_DATE: a numerical value of the sampling date YYYYMMDD

SAMPLNG_TIME: timing of the sampling in the field formatted hh:mm:ss

EWT_LAB: equivalent water thickness in mgH20.cm-2

LMA_LAB: Leaf mass per area in mgDM.cm-2

2.1.2 Canopy Fuel moisture including leaf die back phenology (IRD-AMAP)

Study area

The study was carried out at the Estação Ecológica Serra das Araras, Mato Grosso State (Brazil) (15°38′13″S 57°11′13″W, 320 m a.s.l.). Serra das Araras is a 27,000 ha IUCN category 1A conservation unit mostly contained within the municipality of Porto Estrella (ICMBio, 2016).

Material and Methods

In order to assess the lifespan of leaves at different stages and the phenology of the canopy of species in transitional savannas, over the course of a year (2023-2024) we monitored 12 tree species, 5 individuals and 10 leaves per individual, totalling 50 leaves per species. Monitoring of the leaf lifespan began on 15 May 2024 and has been carried out every 15 days since then. We also monitored leaf water potential (ψ_l) as a proxy for plant water deficit. Data collection on leaf water potential began in September 2023 and has been carried out preferably during the dry season (between July and October) and rainy season (December to February) consecutively. Higher water potential (less negative): indicates hydrated leaves, usually in plants that avoid drought. Moist leaves are less flammable. Lower water potential (more negative): indicates leaves that tolerate drought. Often, these leaves are drier in the dry season — especially if the plant is deciduous — increasing the availability of dry fuel and flammability.

Results

At the beginning of the dry season, many species exhibit more negative water potentials compared to the rainy season, indicating more stressed leaves that are susceptible to desiccation (Figure 3). The phenological succession illustrated in Figure 4 confirms that, during the dry season, for some species (e.g., *Byrsonima coccolobifolia*, *Kielmeyera grandiflora*, and *Qualea parviflora*), there is a longer persistence of leaves in the final stages of the cycle (V and S), prolonging the presence of senescent and flammable material in the canopy. Species that retain senescent leaves for longer also exhibit lower water potentials, suggesting a drought-tolerance strategy that, however, increases the amount of dry fuel available (Figure 5). Finally, Figure 6 demonstrates the direct relationship between Leaf Fuel Moisture Content (LFMC) and water potential, revealing that leaves that are more stressed correspond to lower LFMC values, thereby intensifying flammability. Taken together, these results indicate that drought-tolerance strategies, although advantageous for leaf maintenance, may increase fire risk in transitional savannas by prolonging the persistence of dry and flammable leaves in the canopy.

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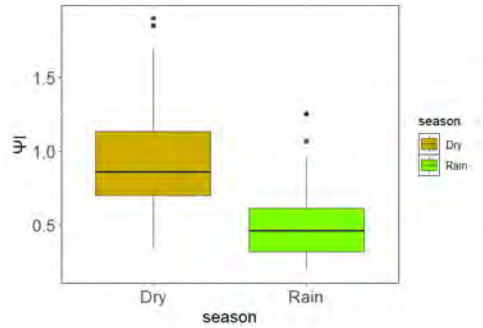

Figure 3. Difference in leaf water potential between leaves at the beginning of the dry season and rainy season.

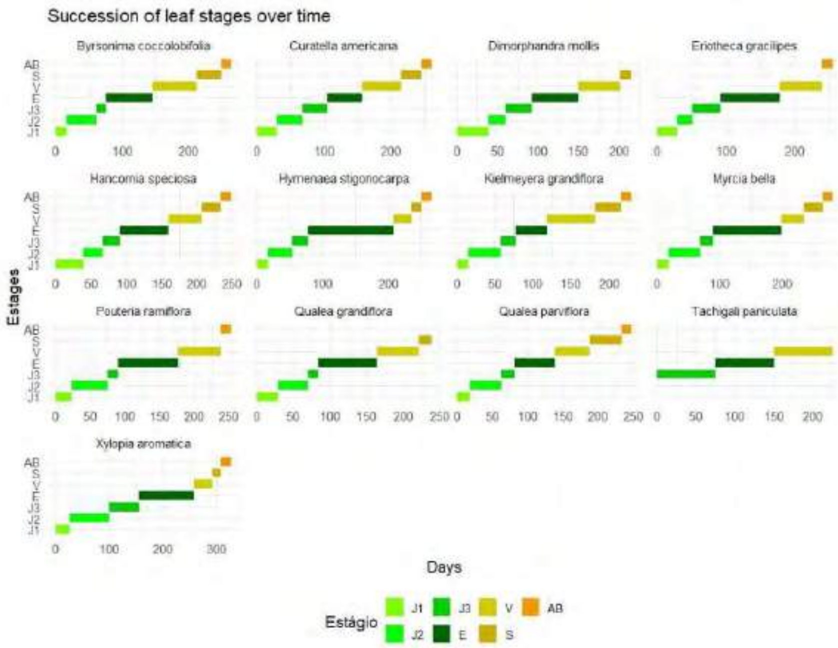

Figure 4. Succession of leaf stages over time in transitional savanna species. Y-axis (classification of developmental stages): J1 = newly emerged leaf, J2 = leaf after 2 weeks of leaf expansion, J3 = leaf after 3 weeks of leaf expansion, E = fully grown and structurally developed, V = leaf near the end of its life cycle, S = leaf in the process of dying and abscission, AB = abscission. X-axis: number of days in each stage.

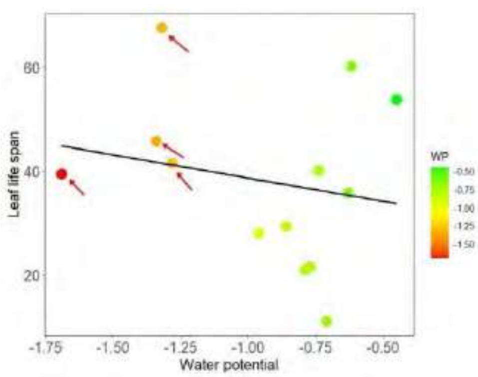

Figure 5. Relationship between the lifespan of leaves in old and senescent stages (in days, Y-axis) and leaf water potential (in MPa, X axis). Each point represents a monitored species. The arrows indicate species that maintain leaves with water deficit for longer on the plant.

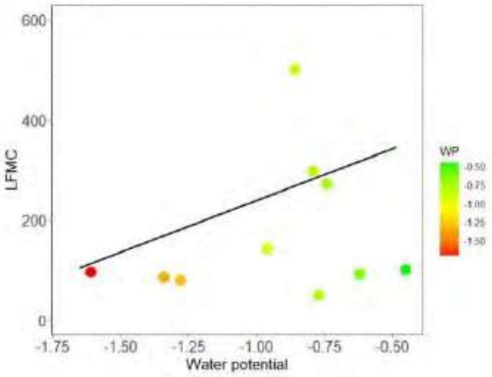

Figure 6. Relationship between Leaf Fuel Moisture Content (LFMC Y-axis) and Leaf Water Potential (WP in MPa X-axis) in transitional savanna species.

2.1.3 Dead Wood moisture content (IRD-CEFE)

Dead wood constitutes a significant amount of fuel potentially contributing to fire ignition, spread, intensity, and conducive to greenhouse gas emissions as CO and CO_2 from smouldering combustion, more important than flaming or promoting soil carbon combustion. Live fuel moisture (LFMC) is the mostly studied compartment in fire ecology, a contribution to fast combustion parameters in fire models (called 1hr-fuel) among 10h, 100h and 1000h fuels related to wood and coarse woody debris (Rabin et al. 2017). Few information is available for these last compartments for modelling benchmarking. We investigated how moisture of dead wood varies along the season and according to wood decay stages along the decomposition process.

Study Area

The study was carried out on the holm Oak (*Quercus ilex*) forest of the Puéchabon study site (France), (43°44’29”N, 3°35’45”E, 270 a.s.l). The forest is a coppice stand exploited until the 1940’s for wood production and unexploited since then. Mean tree height is 5.5 m, and mean DBH is 8.4cm, with 4700 stems.ha^{-1}. Understorey species are *Buxus sempervirens*, *Juniperus oxycedrus*, *Pistacea lentiscus* and *Phyllirea latifolia* representing less than 5% of the biomass. Climate is mediterranean with mean annual precipitation of 924 mm, 80% falling between September and April. Mean annual temperature is 13.3°C, with January being the coldest month (5.5°C) and July the hottest month (22.9°C). Mean Solar radiation is 145.1 W.m^{-2}.

Material and Methods

Dead wood material on standing or grounded dead trees were sampled every two weeks since March 2023,. Trunk slices were sampled with 3 slices per tree age and decomposition class, weighted fresh and oven-dried at 60°C during 48 hours. Wood Fuel moisture content was calculated by (fresh Weight – dry weight)/dry weight. In addition, we performed a lab experiment to assess the drying rate of wood material. A total of 15 samples, covering the 5 decomposition stages, were deepen into a water tank for 48 hours to reach saturation, and were weighted (Sartorius scale), then dried out in the field experiment under current climate conditions next to a meteorological station registering air temperature, humidity, solar radiation and precipitation. Wood material was deposited on a metal grid, so that it was fully exposed to ambient air conditions as a standing tree. During the first two days, samples were weighted every two hours from 9:30 am to 5:30pm (5 weighting campaigns per day). On the third day, samples were weighted in the morning, at midday and at the end of the day. At the end of the 4th day, samples were oven dried at 60°C for 3 days, and weighted dry. Wood water loss of samples, was then compared to the climatic vapor pressure deficit (VPD, kPa) from registered at the onsite meteorological station. We estimated a drying rate ($gH_20.kg^{-1}$ $DryWeight.min^{-1}.kPa^{-1}$).

Results

Figure 7 illustrates the wood moisture content according to wood density and sampling dates. On March 22nd, we observed a significant difference according to density varying between 0.2 for dense wood and up to 0.6 for decayed wood. As soon as April 5th, wood moisture content varies between 0 and 0.3, no more related to wood density, and kept similar later in the season when cumulated precipitation started to decrease below 5 mm when cumulated over the 7 days before the sampling. We also showed that sampling height at 1.5 m or 0.5 m was not influencing WMC, and that neither potential evapotranspiration (PET) nor soil surface water content contributed significantly. Only wood density and cumulated precipitation during the last 7 days was influencing WMC.

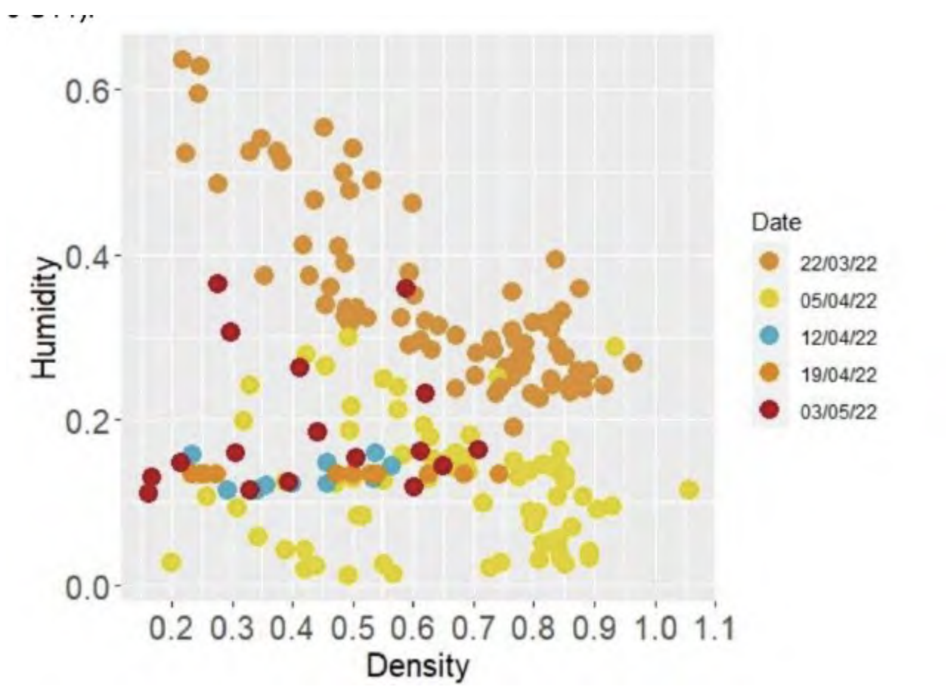

Figure 7 - Wood moisture content (humidity, Y axis) as a function of wood density (X axis) for sample dates march 23th (orange), April 5th (yellow), April 12th (blue), April 19th (brown) and May 5th (red).

When looking at the lab experiment dead wood drying rates (Figure 8a), we observed a rapid decrease in WMC below 0.1 after three days. At saturation, WMC varies greatly from 0.2 to 0.6 respectively for wood decay stage 1 and stage 5. This difference progressively disappears with WMC varying between 0.1 and 0.3 on day 2, and no difference between wood decay stages after 3 days at WMC=0.07. When looking at the desiccation rate as a function WMC, we observed a linear increase so that wet wood evaporates more rapidly than drier wood samples, with a steeper slope for wood decay stage 5 (the most decomposed), showing that even with higher WMC at saturation, their higher evaporation rates leads to similar time to full desiccation as less decomposed wood types (1 to 4) (Figure 8b).

This result brings key information on the potential contribution of dead fuel moisture on fire modelling, particularly under wetter conditions outside of the dry season when prescribed burning for IFM is usually performed.

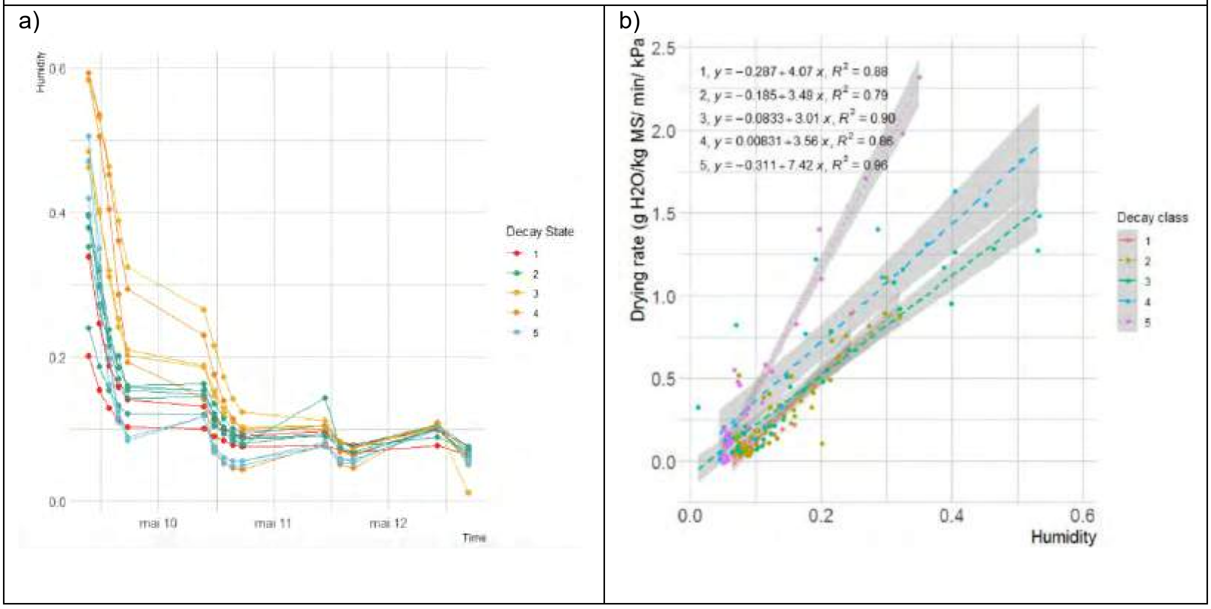

Figure 8 : a) Wood moisture content (WMC) of wood samples at decomposition stages 1 (less decomposed) to 5 (most decomposed) from march 9th to march 13th lab experiment. b) dead wood drying rates ($gH_20.kg^{-1}$ $DryWeight.min^{-1}.kPa^{-1}$) as a function of wood moisture content (WMC, X axis) for decomposition stages 1 to 5.

2.2 Fuel Biomass

As part of the FIRE-ADAPT strategy to assemble key information for model benchmarking on fire hazard and impact, in association with management strategies, we collected fuel biomass data using different remote sensing technologies, that also allowed to gather fuel structure parameters. Fuel Biomass is an important contributor to fire intensity. We focused this section in assembling this information across study-hubs in the FIRE-ADAPT project.

2.2.1 Lidar scanning (CNR and CTFC) (Longer version in Annex 1)

The dataset described in this section is intended to provide modelling expert partners within the consortium with high-resolution forest structural information essential for fire behaviour modelling in Mediterranean forest ecosystems.

Three-dimensional forest structure represents critical information for: i) parameterization of fire spread models that require detailed fuel arrangement and forest architecture data, ii) calibration of fire behaviour models across varying forest management scenarios, and iii) quantitative assessment of silvicultural treatment effects on forest structure and potential fire behaviour.

Based on the modelling requirements identified within the FIRE-ADAPT consortium, we targeted the acquisition of detailed forest structural metrics, including individual tree characteristics (position, DBH, height, crown dimensions), stand-level properties (tree density, basal area per hectare, canopy coverage), and three-dimensional fuel distribution patterns. To achieve these objectives, we employed current state-of-the-art terrestrial point cloud acquisition technologies (TLS/MLS) combined with advanced semi-automated processing workflows.

Study Area

The study site is in the Rubió communal forest, located in the Soriguera municipality, Catalunya, Spain. The site coordinates are UTM zone 31N: 354196E, 4692144N, covering an area of 18.7 hectares of Pinus sylvestris stands. This location was strategically selected as part of the Resilient Landscapes Pilot Plan and corresponds to Strategic Management Points defined by Catalan firefighters, ensuring high relevance for fire management applications. There were two main treatment categories:

- **T1**: High-intensity mixed thinning with homogeneous distribution of remaining trees, targeting approximately 50% canopy cover

- **T2**: Very high-intensity mixed thinning with remaining trees distributed in groups, targeting approximately 30% canopy cover

The objectives of these treatments were to (1) Wildfire prevention and fuel load reduction through different thinning intensities; (2) Silvopastoral conversion to enable pasture development; (3) Comparative assessment of moderate vs. intensive thinning effects on forest structure

The 3D forest structure measurements were conducted following a systematic experimental design (pre- and post-treatment, see Annex 1 for further details). Sampling was conducted via standard forest inventory procedures and an expended sampling for the TLS (Annex 1).

Survey campaigns in mountain forests were carried out using TLS and MLS technologies for comprehensive 3D forest structure assessment. The surveys were conducted over 5 days (approximately 40 hours) across the treatment plots, with additional time required for data processing (approximately 48 hours).

Material and Methods

Terrestrial Point Cloud Acquisition. The 3D forest structure assessment was conducted using state-of-the-art terrestrial laser scanning technologies, combining two complementary acquisition approaches to ensure comprehensive point cloud coverage: (1) **TLS (Terrestrial Laser Scanning)**: Leica RTC360 high-precision laser scanner for detailed forest structure capture; (2) **MLS (Mobile Laser Scanning with integrated SLAM)**: Leica BLK2GO Mobile scanning systems with Simultaneous Localization and Mapping capabilities for enhanced spatial coverage and complex forest environments

Acquisition Protocols. - **Scanning Density**: Optimized point density to capture fine-scale forest structure details - **Multiple Scan Positions**: Strategic scanner placement to minimize occlusion effects across both 10m and 25m radius areas - **Registration Targets**: Standardized reference points for accurate point cloud alignment - **Dual-Scale Coverage**: Complete point cloud acquisition for both inner (10m) and outer (25m) concentric areas - **Quality Control**: Real-time assessment of point cloud completeness and accuracy at both spatial scales

Point Cloud Workflow – Annex 1

Results

(Please refer to Annex 1 for extended results per treatment)

Table 1. Average structural parameters from 25m treatment areas T1 and T2. PRE is the pre-fire plot and POST the post-fire plot.

		T1		T2	
		PRE	POST	PRE	POST
Height (m)	Mean	13,49	13,21	13,01	13,69

	SD	1,66	2,58	2,21	2,64
DBH (m)	Mean	29,6	35,7	27,5	31,7
	SD	14,7	11,5	14,2	11,9
Crown Base High (m)	Mean	3,78	3,94	4,85	4,83
	SD	1,44	1,49	1,39	1,55
Canopy Coverage (%)	Mean	67,1	33,7	67,0	20,1
Canopy Volume (m^3)	Mean	1529	742	1720	477
TPH	Mean	646	215	491	137
BA (m^2)	Mean	54,58	23,73	35,77	12,10

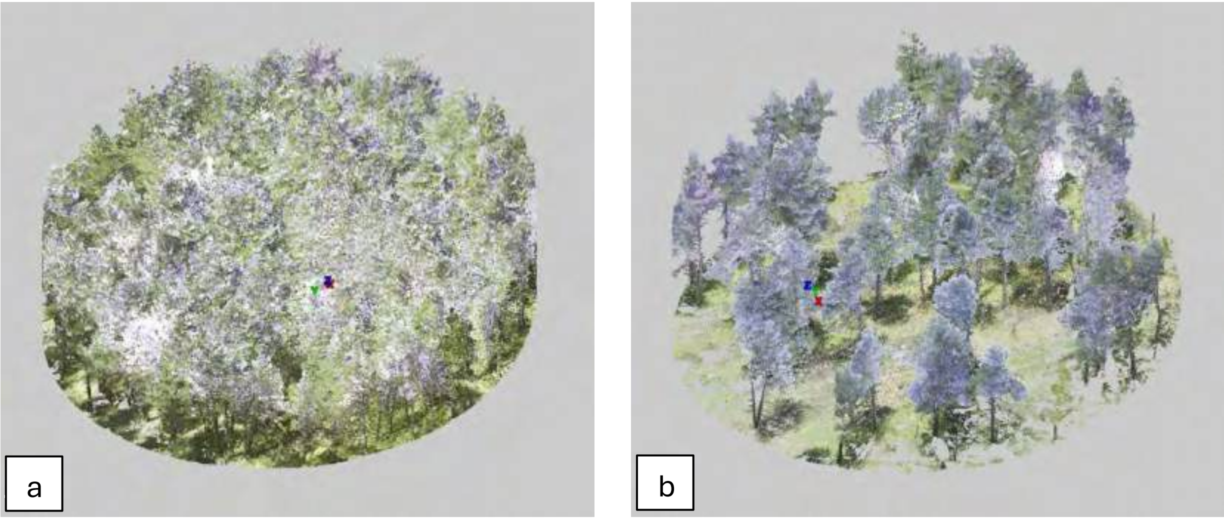

Figure 9: t1_p1 25m 3d model (a) pre-treatment and (b) post-treatment.

2.2.2 Remote Sensing (IRD-CEFE)

Study Area

Our study covers the France metropolitan area (41.38N-51.09N, 4.76W-9.55E) for which a national forest biomass map was recently delivered (Schwartz et al. 2023), covering a wide range of forest biomes from Mediterranean to temperate, and highly affected by unusual 2022 fire season leading to the July 2023 new law for reinforcement on fire prevention and firefighting (https://www.legifrance.gouv.fr/loda/id/JORFTEXT000047805414). The French metropolitan territory features a high diversity of forest types and fire regimes (Fig. 1). Fires occur mainly in the southeast of France, where the climate is Mediterranean. On average, 4,812 ha of wildland has been burnt in this area every year since 2006 (BDIFF, 2023; Vallet et al., 2023). There is considerable interannual variability in the area burnt (SD = 3,855 ha), depending on climatic conditions, with some record years such as 2017 (15,660 ha). This area includes low forests of evergreen oak (*Quercus ilex, Quercus suber*) or Pine (*Pinus halepensis, Pinus nigra*) as well as areas of sclerophyllous vegetation (shrubland, maquis, guarrigue).

The southwest of France is also affected by fires. Even though this area is relatively less affected than the Mediterranean basin (burnt area 2006-2019 = 494 ha.yr-1), some fire events can reach large areas (Landiras fire in 2022 = 12,140 ha), resulting in significant total burnt areas (in 2022, 26,858 ha burnt) (BDIFF, 2023; Vallet et al., 2023). This region is characterized by a maritime pine (*Pinus pinaster*) forest intensively managed for timber production.

The northern part of France is less fire-prone, but during prolonged drought and heatwave events, fires can occur and cause large burnt areas, as in 2019 (3,035 ha) or 2022 (7,813 ha) (BDIFF, 2023; Vallet et al., 2023). This area is dominated by temperate forests with contrasting management practices. The main tree species are oak (*Quercus petreae, Quercus robur*), beech (*Fagus sylvatica*), Scots pine (*Pinus sylvestris*), spruce (*Picea abies*) and fir (*Abies alba*).

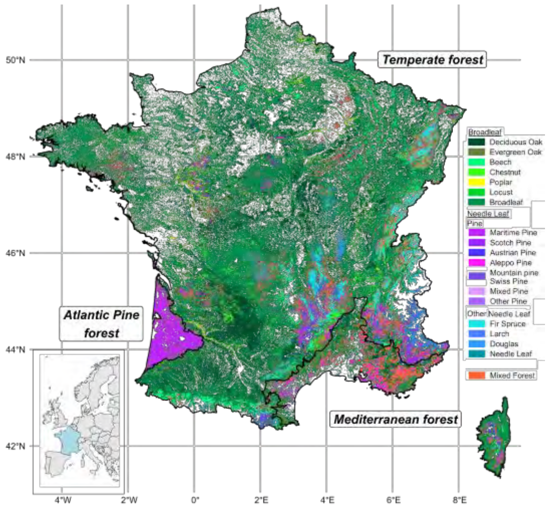

Figure 10. Map of the 19 forest classes in France. The classification is separated into Broadleaf and Needle leaf and based on the National Forest Inventory. The resolution of the initial data is 10m. For better visualization, the data were resampled to 500m resolution and represent the dominant forest class. The French map and the snapshot showing France within the European continent follow the WGS84 projection

Material and Methods

To quantify forest carbon stocks exposed to fires, we first aimed at obtaining the forest aboveground biomass (AGB) over France at a fine resolution. We relied on the spatial classification of forest into 19 forest classes (FC) (IGN, 2018) (Fig. 1) categorized by the national forest inventory, taxonomically more or less precise. FC can indeed correspond to one species (maritime pine, chestnut, poplar, ...), two species (fir & spruce, Laricio pine & black pine), a genus or part of a genus (pine, deciduous oak, evergreen oak), a phylum (conifer, deciduous) or a broader classification (mixed forest).

We then leveraged forest plot data from the national forest inventory (IGN, 2018) since 2005 on more than 100,000 plots, which we grouped to a corresponding FC. A plot is assigned to a forest class (FC) when at least 75% of its trees match the class description. Thus, a plot can belong to several FC. For example, a plot dominated by maritime pine species corresponds to both 'Maritime Pine' and 'Coniferous' FCs. Plot data were then used to construct a first allometric relation. This allometry predicts the Diameter at Breast Height (*DBH*) of a single tree as a function of its height (*H*) for each forest class *c* and is affected by the parameter α_c.

$$DBH = \frac{\alpha_c H^2}{\pi} \quad (1)$$

The second allometric relation used in this study was derived from the R 'allodb' package (Gonzalez-Akre et al., 2022). This package compiles information from the scientific literature on many taxa and biomes. This relation estimates the biomass of a tree (AGBt) as a function of its DBH. For each FC, we selected the dominant species of the corresponding plots to obtain this relationship.

$$AGBt \sim f_c(DBH) \quad (2)$$

The last allometric relationship was derived from plot data and established the relationship between tree biomass ($AGBt_c$) and surrounding tree density (D_c). We selected only plots corresponding to a closed forest. Then, for each FC, we applied equation (2) to all individuals in the corresponding plots and calculated the plot's tree density (Eq. 3). This allowed us to extract the parameter k_c influencing this relationship, in accordance with the self-thinning rule (Puntieri, 1993).

$$log(D) = \frac{log(AGBt) - k_c}{-\frac{3}{2}} \qquad (3)$$

These three relationships are then combined and applied to the fine resolution vegetation height map (Schwartz et al., 2023) over France following Eq. 4. This data has a resolution of 10 m and is derived from a combination of optical (Sentinel-2), SAR (Sentinel-1) and aerial lidar (GEDI) data (Dubayah et al., 2022). For each pixel (H_x) of forest class *c* with a height greater than 3m, we obtain the forest AGB ($AGBf$) by multiplying the AGB of a tree (*AGBt*) by the tree density (*D*).

$$AGBf = f_c(\frac{\alpha_c H^2}{\pi})^{\frac{1}{3}} \times 10^{\frac{2k_c}{3}}$$

We then estimated of the aboveground biomass of forests throughout the country. At this point, this biomass corresponds to closed forests only. Consequently, we multiplied the biomass estimate by the value of the forest cover to consider the openness of the forests (Copernicus Land Monitoring Service, 2023). This information on AGB_f will be further referred to as exposure (E) in the rest of the study.

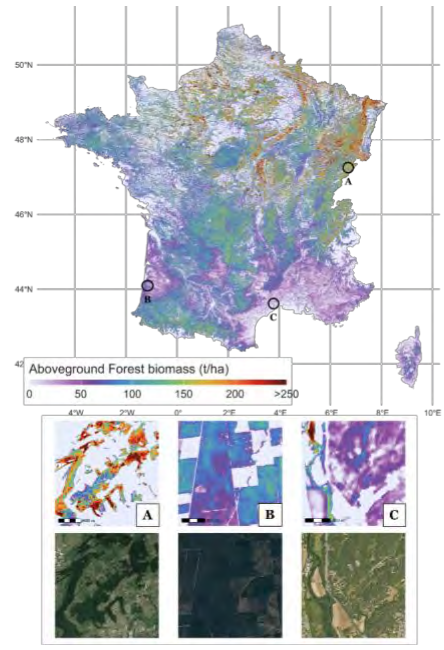

Figure 11: Map of aboveground biomass (AGB) of forests in France. On the bottom, local snapshots showing the fine resolution (~10m) of the pixels. For better visualization, the data were resampled to 500m resolution for the national map.

Our first result was to develop a map of the forest AGB throughout France for the year 2019, based on tree height data and field data (Fig. 5), to be used as a biomass exposure map to fire. At the national level, AGB varies significantly across FC and along the climate gradient. AGB is the highest in the north of the country, in temperate forests, with an average value of 110.9 tDM/ha (DM : dry matter) and reaching values above 250tDM/ha. In the south, in Mediterranean forests, biomass is much lower, with an average value of 32.0 tDM/ha and mostly varying between 30 and 80 t/ha. In the southwest, in the intensively managed Landes forest, biomass density is also low, with an average of 53.4 tDM/ha.

Our biomass estimation method enabled us to capture differences in biomass density among species—an outcome not achievable with tree height data alone. Temperate broadleaf species (beech, deciduous oak, fir, spruce) experience high biomass densities with, for example, the average values of beech (deciduous oak or fir and spruce, reaching respectively 134.8 tDM/ha, 108.8 tDM/ha, and 125 tDM/ha. Mediterranean species have much lower biomass densities, with on average 52.7 tDM/ha for evergreen oak or 30.7 tDM/ha for aleppo pine, due to the openness of the forest. Overall, pines experience low biomass densities from an average value of 27 tDM/ha for the "other pine" class to 71.6 tDM/ha for the "Mountain pine, Swiss pine" class. The dispersion of AGB values is lower for FCs composed of a single species than for those composed of a large group such as "Broadleaf" or "Needle leaf".

We also observed that the relation between AGB and tree height differs between forest classes (Fig. 12). While Schwartz et al. (2023) consider a single relationship, being only different between needle leaf and broadleaf, we obtained more species-specific information. For example, although evergreen oaks reach heights of only 10m, their biomass density is higher than other broadleaf for a given height. Poplars, on the other hand, show a lower biomass density. For example, evergreen oaks show a density of 100 t/ha for a height of 11m, whereas this density is reached for trees of around 25m for poplars. Schwartz et al. (2023) proposed a single density of 100t/ha for a height of 15m, regardless of the broadleaf species considered. We also note that needle leaf classes generally have lower biomasses than broadleaf relative to their height. Our biomass estimate for these FCs is lower overall than that of Schwartz et al. (2023), except for the Mountain Pine, Swiss Pine class.

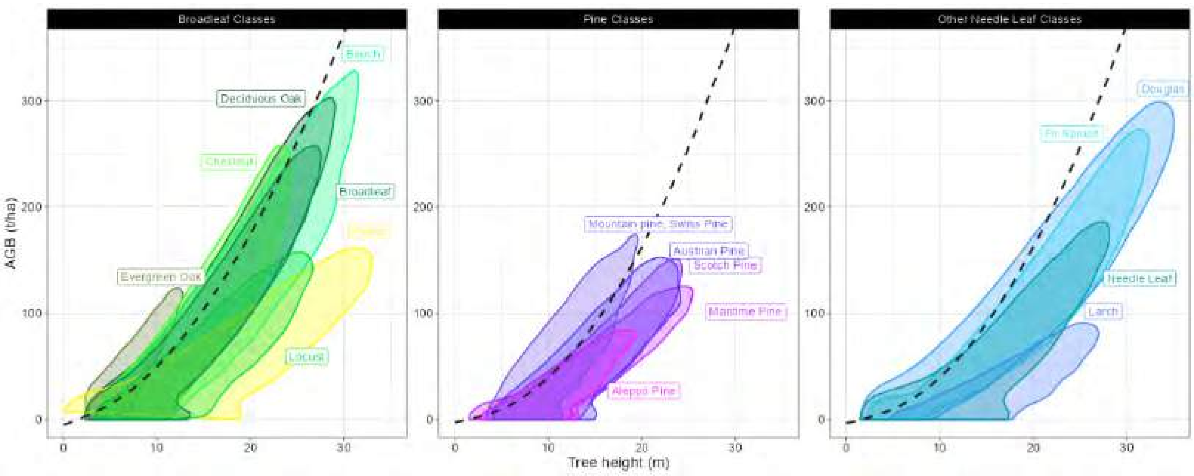

Figure 12: AGB (t/ha) and tree height (m) of forest classes. The dashed line corresponds to Schwartz et al. (2023) direct estimation of AGB from tree height. Colored polygons correspond to the 90th percentile of AGB-Tree height density

2.2.3 Dead Wood decay (IRD-CEFE)

Wild or prescribed fires partially burn coarse wood material (mostly trunks) so that dead standing or grounded trees remain after burning. This woody material can be collected for industries and kept on sites for natural decomposition. Implications for carbon budgets of integrated fire management (IFM) strategies could be critical in order to minimize carbon impacts. Few information is yet available on this topic, and we performed a wood decay analysis in a *Quercus ilex* forest of the France Study hub.

Study site

The study was carried out on the holm Oak (*Quercus ilex*) forest of the Puéchabon study site (France), (43°44'29"N, 3°35'45"E, 270 a.s.l). the forest is coppice stand exploited until the 1940's for wood production and unexploited since then. Mean tree height is 5.5m, and mean DBH is 8.4cm, with 4700 twigs.ha-1. Understorey species are *Buxus sempervirens*, *Juniperus oxycedrus*, *Pistacia lentiscus* and *Phyllirea latifolia* representing less than 5% of the biomass. Climate is mediterranean with mean annual precipitation of 924mm, 80% falling between, September and April. Mean annual temperature is 13.3°C, with January being the coldest month (5.5°C) and July the hottest monthn (22.9°C). Mean Solar radiation is 145.1 W.m^{-2}.

Sampling protocol

Since 1984, a yearly systematic DBH inventory has been performed over all the trees, with tree death being noted with their location. In turn, each dead tree is localised with its death year and its DBH when dying. 477 dead trees were identified. For still standing trees, we sampled two tree slices at 0.5m and 1.5m height with DBH measurements. When dead trees were broken below 1.5m. When cutting the trees was not possible due to ongoing experiments preventing wood removal, tree height and DBH were measured. Decomposition stage was noted based on visual inspection (fungi, bark decomposition). When dead trees were not more standing but broke and felt on the ground, trunk slices were sampled. For all trees, samples were collected and stored in sealed plastic bags in a cooler to keep sample moisture.

Dead wood biomass estimates

Based on local allometric equations relating DBH and tree biomass (Rambal et al. 2004), tree biomass the year of death was estimated. For coarse wood debris on the ground, three transect of 100m were sampled. For each transect, length, diameter and decomposition stage of each CWD crossing the transect line were measured.

In the lab, dead tree samples (198 in total) were weighted fresh (precision balance: Satorius 1465). A visual classification of decomposition was attributed (Maser et al. 1979, Sollins 1982) according to 5 decay classes (cf Fig. 13). Samples were photographed, and oven-dried at 60°C during one week.

Decay class	Structural integrity	Texture of rotten portions	Color of wood	Invading roots	Branches and twigs	Exemple
1	Sound, freshly fallen, intact logs	Intact, no rot; conks of stem decay absent	Original color	Absent	If branches are present, fine twigs are still attached and have tight bark	
2	Sound	Mostly intact; soft (starting to decay) but can't be pulled apart by hand	Original color	Absent	If branches are present, many fine twigs are gone; those remaining have peeling bark	
3	Heartwood sound; piece supports its own weight	Hard, large pieces; sapwood can be pulled apart by hand or sapwood absent	Reddish brown or original color	Sapwood only	Branch stubs will not pull out	
4	Heartwood rotten; piece does not support its own weight, but maintains its shape	Soft, small blocky pieces; a metal pin can be pushed into heartwood	Reddish or light brown	Through-out	Branch stubs pull out	
5	None, piece no longer maintains its shape, it spread out on the ground	Soft; powdery when dry	Red-brown to dark brown	Through-out	Branch stubs and pitch pockets have usually rotted down	

Figure 13: Wood decomposition classes 1 to 5 according to Maser et. al., 1979 and Sollins, 1982) based on visual interpretation of structural integrity, texture, color, invading roots, and presence of thing twigs, along with corresponding photos sampled in the field during the 2023 campaign at the Puéchabon study site.

Dried samples were then weighted to derive their moisture content (FMC) defined as (Fresh weight – Dry weight)/Dry Weight. Bark was then removed from the samples with a wood cutter (5mm) and dried out at 60°C for 12hours. Wood density of each sample was measured by weighting their dry weight, and weighted when deepen into water (Becher) with a PRecisa 6200D scale to measure their volume. Wood samples are maintained in the water by a metal stick.

2.2.3.4 Results

Figure 14 illustrates the number of dead trees recorded in the yearly inventory protocole started in 1984 (blue bars), and the number of these trees identified as standing or grounded in 2023. Oldest trees still observed in the field date back to 2004, and since 2009, most of trees referenced as dead, still present some identified dead material.

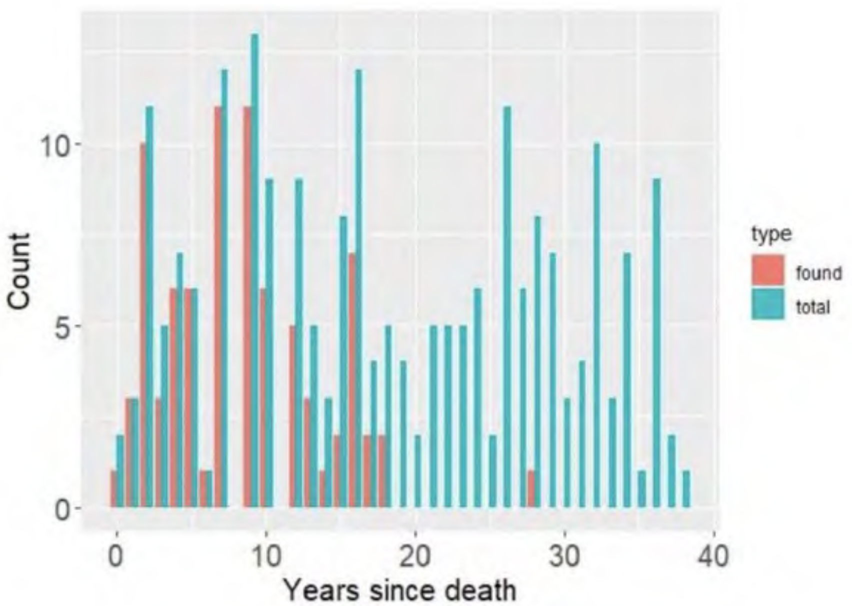

Figure 14: Number of trees (Y-axis) referenced as dead over the last 40 years (X-axis) of annual census (blue bars), and actual still found standing or grounded (blue bars) in the field at decay stages 1 (less decomposed) to 5 (most decomposed) during the field survey 2023.

We then tested how our visual typology of wood decay was correlated to actual wood density changes sampled at 0.5m and 1.5m height. Figure 15 illustrates that significant differences are observed between wood decay classes 1 and 2 (p=0.002), 2 and 3 (p<1e-8) and 3 and 4 (p<1e-8). This result confirms the ability of our visual method to capture wood density decay across time, with no major difference if sample at 0.5m or 1.5m.

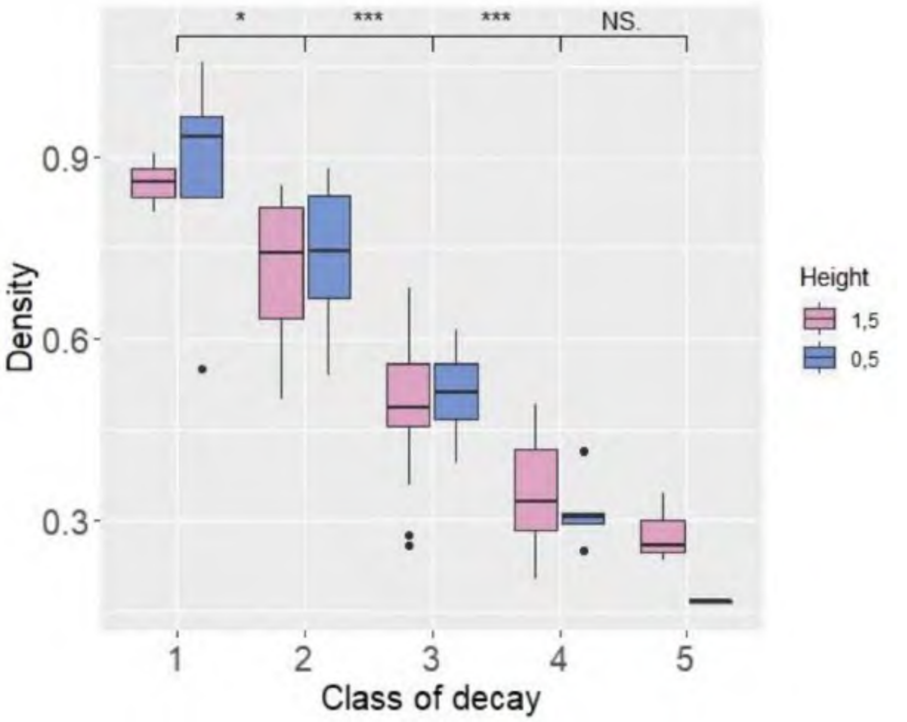

Figure 15: Wood density at 0.5m and 1.5m height for degradation decays 1 (freshly dead material) to 5 (last stage before losing becoming thin woody residues)

We finally plotted wood density as a response to the year since tree death, for samples at 0.5m and 1.5m (Fig. 16), as most trees started to decay preferentially from the top of twig. Wood density varied from 0.15 to 1, with a linear (p = 7,61e-14) decreasing wood density with age and total degradation after 18 years. Wood density was yet always higher when trees of same ages were standing when compared to grounded trees (p = 5,42e-8), and also higher when sampled at 1.5m compared to 0.5m (p = 2,53e-13). No differences were observed between stem diameter classes. This dataset offers valuable information for post treatment management strategies on carbon residence time, woody decay and carbon emission from respiration, and coarse woody amount susceptible to promote fire hazard.

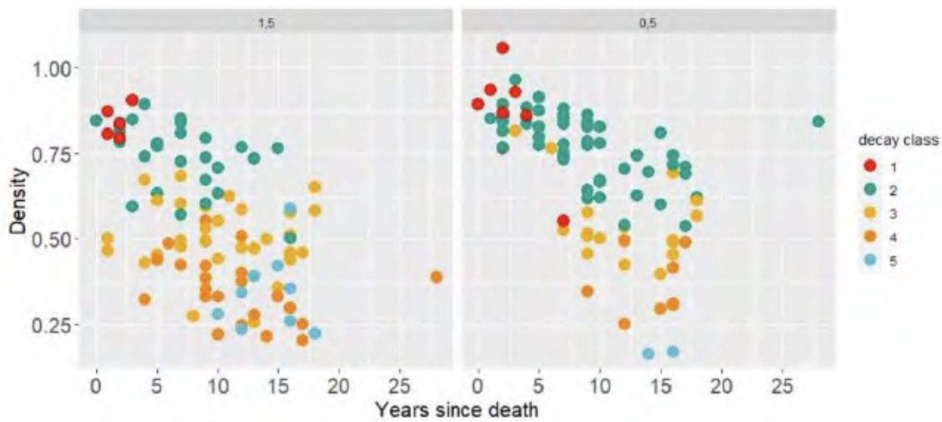

Figure 16: wood density as a function of years since tree death (X axis in years) for wood samples at 0.5m (left) and 1.5m (right) for class decays 1 (less degraded) to 5 (most degraded).

3 Conclusions

Targeted objectives in assembling datasets on key and innovative information for fire hazard assessment and modelling could be completed across various FIRE-ADAPT Study Hubs (France, Spain, Brazil), and involving the FIRE-ADAPT scientific network (CNR, IRD, CFTC). Regarding fuel moisture modelling, LFMC and LMA seasonal variations could be assembled for deciduous and evergreen oak Mediterranean species in France, in a comprehensive and structured dataset derived from a replicated tree sampling from May to October 2021. From this dataset, we could show the dynamic of increasing LMA along leaf maturity stages, along with decreasing LFMC, supporting our hypothesis that leaf structural dynamics might significantly affect LFMC modelling during the spring season. In addition, we could assemble a 1-year seasonal dynamic of leaf maturity stages from budburst to dead leaves duration in the canopy for 12 tree species in the Brazilian savanna, stored in a comprehensive and replicated dataset. This dataset could illustrate the differential strategies in tree species conservation of leaves, including the dead leaves in the canopy, an innovative and key functional trait hardly yet sampled in the scientific literature, which could significantly affect fire spread and intensity modelling. These key results on plant ecophysiological functioning pave the way for new modelling developments and impact assessment using fire spread models. As a side information, we could also collect wood moisture content from woody debris of different decomposition decay stages in the Mediterranean oak forest (France), showing a fast moisture decrease within few days, with an initial wood moisture higher in more decayed woody debris with low wood density but drying faster, offering a valuable data for fire modelling using the 1000h fuel type moisture as input.

This activity also assembled processing chains and field data acquisition protocols leveraging new technologies on Lidar information and allowing for forest structure assessment. Ground Lidar protocols could provide fine resolution assessment of forest clearing impact (performed in the Spain Study Hub), on the vertical structure of vegetation to be further used in fire spread modelling as a key driver. At a larger scale over the France national territory, fine-scale remotely sensed tree height from the GEDI spaceborne lidar sensor could be translated into carbon storage using ground-based national forest inventory and allometric relationship to be further applied across the FIRE-ADAPT Study Hubs as global tree height datasets are getting increasingly available.

All datasets and protocols are made available for the FIRE-ADAPT consortium, for modelling purposes or analysis.

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5 Annex 1*: Field Data Collection and Processing: 3D Forest Structure Analysis*

List of Acronyms

AGB - Above-Ground Biomass
BA - Basal Area
CNR - Consiglio Nazionale delle Ricerche (National Research Council of Italy)
CTFC - Centre de Ciència i Tecnologia Forestal de Catalunya
DBH - Diameter at Breast Height
DBSCAN - Density-Based Spatial Clustering of Applications with Noise
FAIR - Findable, Accessible, Interoperable, Reusable
IBE - Institute of BioEconomy
IFM - Integrated Fire Management
MLS - Mobile Laser Scanning
PCA - Principal Component Analysis
PiC - Point cloud Interactive Computation
ROI - Region of Interest
SLAM - Simultaneous Localization and Mapping

T1 - Moderate thinning treatment

T2 - Intensive thinning treatment

P1 - Plot one

P2 - Plot two
TLS - Terrestrial Laser Scanning
TPH - Trees Per Hectare
UTM - Universal Transverse Mercator
WP - Work Package

Executive Summary

This Annex describes the collection, processing, and analysis of 3D data relative to forest structure, conducted in the Catalunya study site (Spain) by CNR-IBE in collaboration with CTFC. This work aims to document the complete workflow from field data acquisition to processed structural datasets, providing essential inputs for fire behavior modeling and integrated fire management assessment.

In order to provide comprehensive 3D forest structural datasets, we leveraged state-of-the-art terrestrial laser scanning technologies (TLS Leica RTC360 and MLS Leica BLK2GO) combined with the PiC::Forest_seg package for processing semi-automated point cloud. The study focused on the effect of two different intensities of silvicultural treatment: T1 (moderate thinning) and T2 (intensive thinning). Measurements were conducted at two spatial scales (10 m and 25 m radius) to capture both detailed and landscape-level structural characteristics.

Both pre-treatment and post-treatment structural data were collected and processed, enabling comprehensive comparative analysis of silvicultural treatment effects on forest structure. Key findings demonstrate significant structural modifications: T1 treatment achieved average reductions of 32.67% in canopy coverage, 64.4% in tree density, and 49.6% in basal area, while T2 treatment showed more pronounced effects with 46.82% in canopy coverage, 74.3% reduction in tree density, and 68.6% reduction in basal area. Both treatments gained their original targets, with T2 showing greater variability consistent with its grouped tree retention strategy.

The methodology successfully integrated traditional forestry measurements (CTFC 10m radius protocols) with enhanced 3D analysis capabilities (25m radius assessments), providing direct validation of 3D-derived metrics against conventional field measurements while extending analytical capabilities beyond traditional plot-based limitations. Quality assessment demonstrated processing success rates exceeding 95%, with a strong correlation between 3D and manual measurements.

Comprehensive protocols and standardized procedures were developed for equipment operation, data processing, quality assurance, and integration with fire behavior modelling frameworks. The processed datasets in ASCII format include: segmented point clouds (Forest_floor, Wood, AGBnoWOOD components, .xyz files) and comprehensive structural metrics (.csv files).

This work establishes a robust, validated, and replicable methodology for quantifying silvicultural treatment effects on Mediterranean forest structure using 3D technologies, providing essential data products for advancing integrated fire management strategies and supporting evidence-based decision-making in fire-prone ecosystems.

5.1 Introduction

This document presents and describes the contribution to the WP4 'modelling and forecasting' of the FIRE-ADAPT project in terms of 3D forest structural data collection and processing activities conducted in the Catalunya study site (Spain). The dataset described in this document is intended to provide modeling expert partners within the consortium with high-resolution forest structural information essential for fire behavior modeling in Mediterranean forest ecosystems.

Three-dimensional forest structure represents critical information for: i) parameterization of fire spread models that require detailed fuel arrangement and forest architecture data, ii) calibration of fire behaviour models across varying forest management scenarios, and iii) quantitative assessment of silvicultural treatment effects on forest structure and potential fire behaviour.

Based on the modelling requirements identified within the FIRE-ADAPT consortium, we targeted the acquisition of detailed forest structural metrics, including individual tree characteristics (position, DBH, height, crown dimensions), stand-level properties (tree density, basal area per hectare, canopy coverage), and three-dimensional fuel distribution patterns. To achieve these objectives, we employed current state-of-the-art terrestrial point cloud acquisition technologies (TLS/MLS) combined with advanced semi-automated processing workflows.

The collaborative work between CNR and CTFC involved comprehensive forest structure characterization both before and after silvicultural treatments in managed Mediterranean forest stands. Both pre-treatment and post-treatment data have been collected and processed, enabling quantitative assessment of management intervention effects on forest structure and potential fire behavior implications. The results of the comparative analysis between pre- and post-treatment conditions are presented in the results section of this document.

The document is structured as follows:

- **Study Site Description**: Detailed characterization of the Catalunya (Spain) study site, including location, environmental conditions, and silvicultural treatments applied
- **Methodologies**: Comprehensive description of 3D data acquisition protocols, point cloud processing workflows using PiC::Forest_seg, and quality assurance procedures
- **Results**: Presentation of structural metrics obtained, quality assessment outcomes, and comprehensive comparative analysis between treatments
- **Tools and Protocols**: Description of standardized procedures developed for 3D forest measurement and processing

This work establishes a foundation for enhanced fire behavior modeling in Mediterranean forest ecosystems and provides a replicable methodological framework for 3D forest structure assessment in fire management contexts.

5.2 Study Site and Experimental Design

5.2.1 Spain (Catalunya) - CTFC Study Site

Geographic Location

The study site is in the Rubiò communal forest, located in the Soriguera municipality, Catalunya, Spain. The site coordinates are UTM zone 31N: 354196E, 4692144N, covering an area of 18.7 hectares of *Pinus sylvestris* stands. This location was strategically selected as part of the Resilient Landscapes Pilot Plan and corresponds to Strategic Management Points defined by Catalan firefighters, ensuring high relevance for fire management applications.

Environmental Characteristics

The study area represents typical Mediterranean mountain forest ecosystems characterized by:

- **Elevation**: Mountain forest conditions with moderate slopes
- **Climate**: Mediterranean mountain climate with seasonal precipitation patterns
- **Dominant Species**: *Pinus sylvestris* with associated understory vegetation
- **Forest Type**: Mature coniferous forest stands suitable for silvicultural interventions
- **Fire Risk Context**: Area identified as strategically important for wildfire prevention and management

Silvicultural Treatments Applied

The experimental design was originally planned to include multiple treatment intensities, but was subsequently focused on two main treatment categories:

Treatment Categories Implemented and relative targets:

- **T1**: High-intensity mixed thinning with homogeneous distribution of remaining trees, targeting approximately 50% canopy cover

- **T2**: Very high-intensity mixed thinning with remaining trees distributed in groups, targeting approximately 30% canopy cover

Objectives of Implemented Treatments: - **Primary**: Wildfire prevention and fuel load reduction through different thinning intensities - **Secondary**: Silvopastoral conversion to enable pasture development - **Tertiary**: Comparative assessment of moderate vs. intensive thinning effects on forest structure

Plot Layout and Experimental Design

The 3D forest structure measurements were conducted following a systematic experimental design with specific spatial sampling protocols:

Pre-Treatment Measurement Campaign: - **Total Plots Surveyed**: All originally planned plots, including those intended for T1, T2 treatments - **Comprehensive Baseline**: Complete 3D structural characterization of all planned treatment areas

Post-Treatment Measurement Campaign: - **Implemented Treatments**: T1, T2, and Control treatments only - **Replication**: 2 plots per treatment (T1_P1, T1_P2, T2_P1, T2_P2) - **Total Analysis Plots**: 4 plots with complete pre/post measurement data

Spatial Sampling Design: The experimental design integrated two complementary measurement approaches:

- **CTFC Traditional Sampling Protocol**: Manual forest measurements within 10-meter radius circles as per standard forestry inventory procedures
- **CNR 3D Point Cloud Enhancement**: Extended sampling to dual concentric areas using terrestrial laser scanning

Concentric Measurement Areas: - **Plot Center**: Fixed reference point established for each plot (consistent with CTFC protocol) - **Inner Circle (10m radius)**: Primary analysis area matching CTFC manual measurement design, enabling direct comparison between traditional and 3D-derived metrics - **Outer Circle (25m radius)**: Extended analysis area provided by 3D point cloud data, offering broader spatial context and landscape-scale forest structure assessment

Measurement Integration: - **10m radius results**: Directly comparable with CTFC manual forestry measurements - **25m radius results**: Additional value from 3D point cloud technology, providing enhanced spatial context - **Dual-scale advantage**: Traditional forestry compatibility (10m) combined with expanded analytical capability (25m)

Measurement Protocols: - **CTFC Standard Protocol**: Traditional forestry measurements within 10m radius areas - **CNR 3D Enhancement**: Point cloud acquisition covering full 25m radius areas - **Consistent Positioning**: Same plot centers used for both manual and 3D measurement approaches - **Comparative Analysis**: 10m radius 3D-derived metrics validated against CTFC manual measurements - **Extended Analysis**: 25m radius metrics providing additional spatial context from 3D data - **Quality Control**: Standardized protocols applied across all measurement methods and spatial scales

Survey campaigns in mountain forests were carried out in collaboration with CTFC colleagues, using TLS and MLS technologies for comprehensive 3D forest structure assessment. The surveys concentrated in the study area of Soriguera (Spain), with CNR-IBE staff (Roberto Ferrara, Stefano Arrizza, Pierpaolo Masia) conducting field activities over 5 days (approximately 40 hours) across the treatment plots, with additional time required for data processing (approximately 48 hours).

5.3 Field Data Categories and Methodologies

5.3.1 Structural Data (3D Forest Reconstruction)

Terrestrial Point Cloud Acquisition

The 3D forest structure assessment was conducted using state-of-the-art terrestrial laser scanning technologies, combining two complementary acquisition approaches to ensure comprehensive point cloud coverage:

Equipment and Technologies:

- **TLS (Terrestrial Laser Scanning)**: Leica RTC360 high-precision laser scanner for detailed forest structure capture

Fig. 5.1 - TLS Leica RTC360

-**MLS (Mobile Laser Scanning with integrated SLAM)**: Leica BLK2GO Mobile scanning systems with Simultaneous Localization and Mapping capabilities for enhanced spatial coverage and complex forest environments

Fig. 5.2 - MLS Leica Blk2go

Acquisition Protocols: - **Scanning Density**: Optimized point density to capture fine-scale forest structure details - **Multiple Scan Positions**: Strategic scanner placement to minimize occlusion effects across both 10m and 25m radius areas - **Registration Targets**: Standardized reference points for accurate point cloud alignment - **Dual-Scale Coverage**: Complete point cloud acquisition for both inner (10m) and outer (25m) concentric areas - **Quality Control**: Real-time assessment of point cloud completeness and accuracy at both spatial scales

Point Cloud Processing Workflow

All point cloud data processing was conducted using the **PiC::Forest_seg** package (Pointcloud interactive Computation), following standardized protocols developed specifically for forest applications.

PiC::Forest_seg Processing Pipeline:

- Initial Quality Assessment

- Forest Floor Extraction
- Wood Segmentation
- Above-Ground Biomass (Non-Wood) Extraction
- Forest Metrics Calculation

From the segmented point cloud data, comprehensive forest structural metrics were derived using identical algorithms for both 10m and 25m radius areas:

Individual Tree Metrics:

- **Spatial Position**: X/Y coordinates of tree stem center locations

- **Tree Height**: Maximum vertical extent from ground surface to crown apex

- **DBH Calculation**: Stem diameter estimation at 1.3 m height using circular fitting algorithms

- **Crown Base Height**: Elevation of the lowest live crown base above ground

- **Validation Flags**: Quality assessment indicators for metric reliability

Stand-Level Metrics:

- **Area of Interest**: Total analysis area calculated from forest floor surface geometry

- **Canopy Coverage**: Area and percentage of canopy cover using coverage threshold analysis

- **Canopy Volume**: Three-dimensional volume calculation of forest canopy structure

- **Height Statistics**: Comprehensive statistical analysis (min, mean, median, max, SD)

- **Tree Density (TPH)**: Trees per hectare calculations based on valid tree count and area

- **Basal Area (BA) (G/ha)**: Basal area per hectare estimations from DBH measurements

Standardized Parameters

Consistent PiC processing parameters were applied across all measurement campaigns to ensure data comparability.

This standardized methodology ensures reproducible and comparable results across pre-treatment and post-treatment measurement campaigns, enabling robust statistical analysis of treatment effects on forest structure.

5.4 Data Processing and Quality Assurance

5.4.1 3D Data Processing Pipeline

Initial Quality Assessment

All point cloud data processing followed standardized protocols using the **PiC::Forest_seg** package (Pointcloud interactive Computation, available on CRAN) to ensure consistency across pre-treatment and post-treatment measurement campaigns.

Standardized PiC Processing Parameters

Consistent processing parameters were applied across all plots and measurement periods to ensure data comparability:

Parameter Configuration: - **soil_dim_m**: 0.30 m (soil dimension voxels for ground surface modeling) - **dimVox_m**: 0.02 m (fine voxelization for wood segmentation) - **eps/mpts**: DBSCAN clustering parameters (eps 1-2, minPts 3-9) - **N_min**: Minimum cluster size threshold (typically 500 points) - **R_shape**: PCA shape analysis threshold (30) - **h_tree_m**: Minimum tree height threshold (≥1 m) - **canopy_voxel_size_m**: Canopy analysis voxel size (0.10 m) - **min_canopy_height_m**: Minimum height for canopy analysis (1.5 m) - **coverage_method**: Linear interpolation method for coverage calculation

Processing Workflow Stages

Comprehensive forest structural metrics were calculated using identical algorithms for both 10m and 25m radius areas:

5.4.2 Data Storage and Management

A dedicated system for data storage and documentation has been established to ensure the traceability, reproducibility, and FAIR compliance of all 3D forest structural datasets produced within WP4.

Output File Structure

The processing pipeline generates standardized output files for each plot and measurement campaign:

Point Cloud Files (.txt format):

- `<plot>_Forest_floor_<period>.txt`: Ground surface point sets

- `<plot>_Wood_<period>.txt`: Woody biomass point sets

- `<plot>_AGBnoWOOD_<period>.txt`: Non-woody vegetation point sets

FAIR Data Principles Implementation

The dataset follows FAIR (Findable, Accessible, Interoperable, Reusable) principles:

Findable: Systematic file naming conventions, comprehensive metadata, and documentation.

Accessible: Standardized file formats and clear data organization structure.

Interoperable: CSV formats with semicolon separation, consistent coordinate systems, standardized metric definitions.

Reusable: Complete processing documentation, parameter logs, and quality assessment results, enabling reproducible analysis

5.5 Results from Spain (Catalunya) Study Site

This section presents the comprehensive analysis of forest structural changes following silvicultural treatments in the Catalunya study site. Results are based on 3D point cloud analysis using PiC::Forest_seg methodology, comparing pre-treatment and post-treatment conditions across two treatment intensities (T1 and T2) and two spatial scales (10m and 25m radius areas).

Table 5.0: Average structural parameters from 25m treatment areas

		T1		T2	
		PRE	POST	PRE	POST
Height (m)	Mean	13,49	13,21	13,01	13,69
	SD	1,66	2,58	2,21	2,64
DBH (m)	Mean	29,6	35,7	27,5	31,7
	SD	14,7	11,5	14,2	11,9
Crown Base High (m)	Mean	3,78	3,94	4,85	4,83
	SD	1,44	1,49	1,39	1,55
Canopy Coverage (%)	Mean	67,1	33,7	67,0	20,1
Canopy Volume (m^3)	Mean	1529	742	1720	477
TPH	Mean	646	215	491	137
BA (m^2)	Mean	54,58	23,73	35,77	12,10

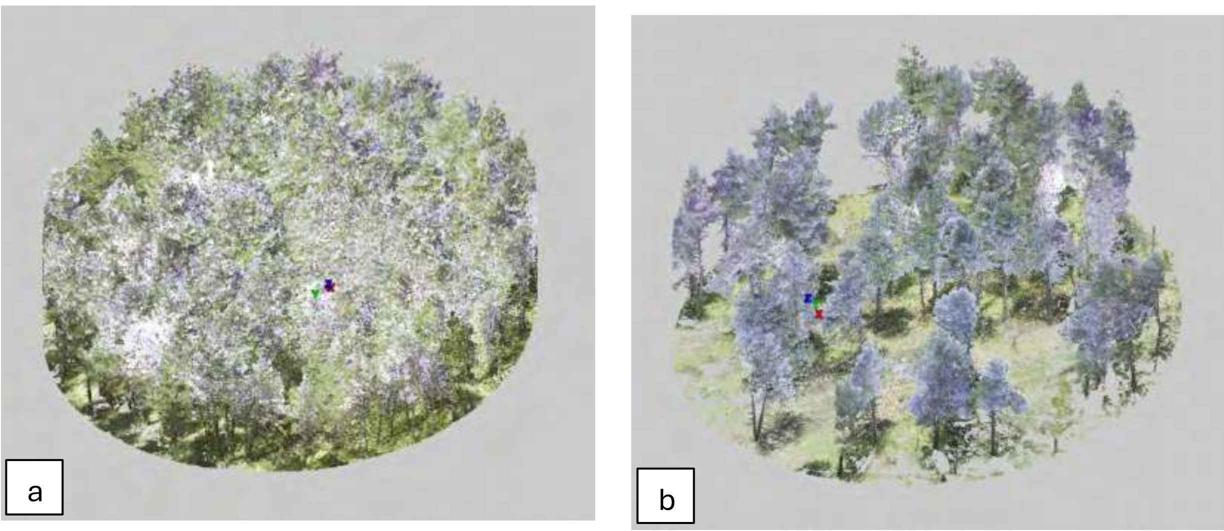


Fig. 5.1 T1_P1 25m 3D model (a) Pre-treatment and (b) Post-treatment

5.5.1 T1 Treatment Results (Moderate Thinning)

The T1 (Stem Only Harvesting) treatment represents a moderate thinning intensity targeting approximately 50% canopy cover retention with homogeneous distribution of remaining trees.

T1 Treatment Data Summary

Table 5.1: T1 Treatment Effects - 10m Radius Analysis

	Pre-Treatment			Post-Treatment			Treatment Effects		
Plot	Coverage (%)	TPH	BA (m^2/ha)	Coverage (%)	TPH	BA (m^2/ha)	Δ Coverage (pp)	Δ TPH (%)	Δ BA (%)
T1 P1	67.85	441.2	44.93	33.91	295.6	34.85	-33.94	-33.0	-22.4
T1 P2	62.84	707.1	48.95	32.32	373.1	40.51	-30.52	-47.2	-17.2
Mean	**65.35**	**574.2**	**46.94**	**33.12**	**334.4**	**37.68**	**-32.23**	**-40.1**	**-19.8**

Fig. 5.2: T1_P2 10m 3D model (a) Pre-treatment and (b) Post-treatment

Table 5.2: T1 Treatment Effects - 25m Radius Analysis

	Pre-Treatment			Post-Treatment			Treatment Effects		
Plot	Coverage (%)	TPH	BA (m^2/ha)	Coverage (%)	TPH	BA (m^2/ha)	Δ Coverage (pp)	Δ TPH (%)	Δ BA (%)
T1 P1	66.68	547.2	45.73	39.49	232.7	27.43	-27.19	-57.5	-40.0
T1 P2	66.61	768.9	60.35	28.47	221.7	24.70	-38.14	-71.2	-59.1
Mean	**66.65**	**658.1**	**53.04**	**33.98**	**227.2**	**26.07**	**-32.67**	**-64.4**	**-49.6**

5.5.2 T2 Treatment Results (Intensive Thinning)

The T2 (Stem Only Very High) treatment represents intensive thinning targeting approximately 30% canopy cover with remaining trees distributed in groups.

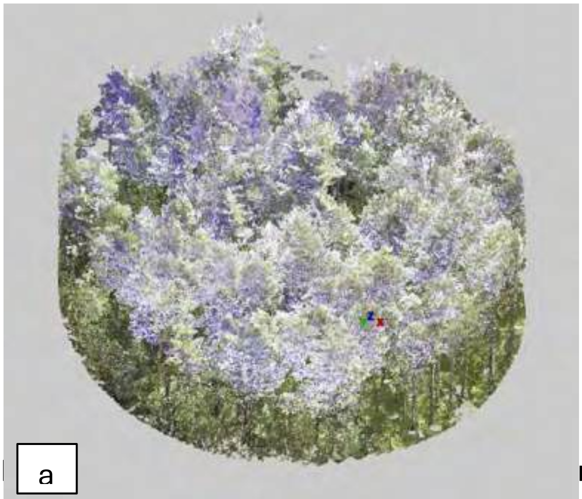
T2 Treatment Data Summary

Table 5.3: T2 Treatment Effects - 10m Radius Analysis

Plot	Pre-Treatment			Post-Treatment			Treatment Effects		
	Coverage (%)	TPH	BA (m^2/ha)	Cov. (%)	TPH	BA (m^2/ha)	Δ Cov. (pp)	Δ TPH (%)	Δ BA (%)
T2 P1	61.13	246.3	23.59	27.94	151.5	26.63	-33.19	-38.5	+12.9
T2 P2	65.16	412.5	48.42	23.83	200.0	17.40	-41.33	-51.5	-64.1
Mean	**63.15**	**329.4**	**36.01**	**25.89**	**175.8**	**22.02**	**-37.26**	**-45.0**	**-25.6**

Table 5.4: T2 Treatment Effects - 25m Radius Analysis

	Pre-Treatment			Post-Treatment			Treatment Effects		
Plot	Coverage (%)	TPH	BA (m^2/ha)	Cov. (%)	TPH	BA (m^2/ha)	Δ Cov. (pp)	Δ TPH (%)	Δ BA (%)
T2 P1	67.39	541.8	35.78	19.90	104.2	10.89	-47.49	-80.8	-69.6
T2 P2	67.55	535.8	41.11	21.41	172.7	13.37	-46.14	-67.8	-67.5
Mean	**67.47**	**538.8**	**38.45**	**20.66**	**138.5**	**12.13**	**-46.82**	**-74.3**	**-68.6**



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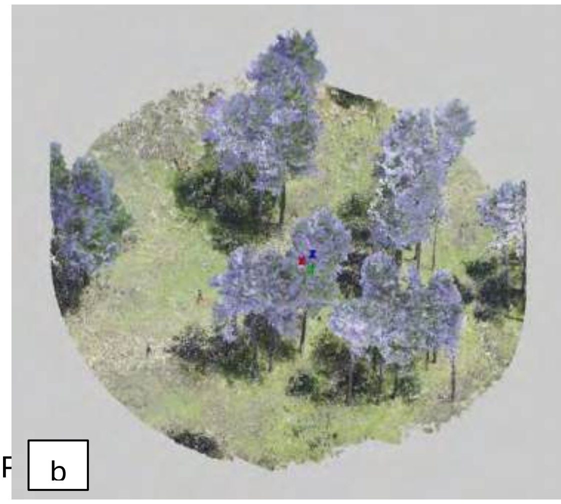


5.5.3 Comparative Analysis Between Treatments

Treatment Effectiveness Comparison

Table 5.5: Treatment Comparison Summary

Metric	Scale	T1 (Moderate)	T2 (Intensive)	Difference
Coverage Reduction (pp)	10m	-32.2	-37.3	-5.0
	25m	-32.6	-46.8	-14.2
TPH Reduction (%)	10m	-40.1	-45.0	-4.9
	25m	-64.4	-74.3	-9.9
Basal Area Reduction (%)	10m	-19.8	-25.6	-5.8
	25m	-49.6	-68.6	-19.0

Scale-Dependent Effects Analysis

Table 5.6: Spatial Scale Effects Comparison

Treatment	Metric	10m Radius	25m Radius
T1	Coverage Reduction (pp)	-32.2	-32.7
	TPH Reduction (%)	-40.1	-64.4
	BA Reduction (%)	-19.8	-49.6
T2	Coverage Reduction (pp)	-37.3	-46.8
	TPH Reduction (%)	-45.0	-74.3
	BA Reduction (%)	-25.6	-68.6

Treatment Target Achievement

Table 5.7: Target Achievement Assessment

Treatment	Target Coverage (%)	Achieved Coverage (%)
T1 (10m)	~50	33.1
T1 (25m)	~50	34.0
T2 (10m)	~30	25.9
T2 (25m)	~30	20.7

Key Findings:

- **T2 shows greater treatment spatial variability**, consistent with a grouped tree retention strategy

- **Scale effects are more pronounced in T2**, indicating stronger landscape-level responses

- **Both treatments exceeded targets**, with T2 showing more intensive effects

- **25m scale consistently shows greater treatment effects** than 10m scale

IFM treatments have significantly reduced the risk of fire. T1 has reduced the horizontal continuity of fuel, bringing canopy cover to 50% and canopy volume to 51%. Meanwhile, T2 has achieved even more drastic reductions: a 70% reduction in canopy cover and a 72% reduction in canopy volume. Both treatments show effective selectivity toward smaller diameter classes (+20% mean DBH). T2 presents greater structural impact (+35% mean height) but offers superior crown fire protection. The PiC::Forest_seg methodology demonstrated reliability. Results confirm treatment effectiveness in fuel load reduction while maintaining forest structural integrity through selective harvesting approaches and provide robust parameterizations for fire spread modelling in WP4.

5.5.4 Validation Against Traditional Measurements

Methodological Validation Summary

Table 5.9: 3D Methodology Validation Assessment

Validation Aspect	Assessment Result	Notes
DBH Measurements	✓ Excellent	Strong correlation with CTFC manual measurements
Height Measurements	✓ Superior	Enhanced accuracy over traditional methods
Point Cloud Density	✓ Adequate	>1000 points/m^2 average across all plots
Processing Success	✓ High	97.8% successful tree extraction rate
ROI Validation	✓ Complete	All processed areas validated

Quality Assessment Results

Table 5.10: Data Quality Metrics by Treatment and Scale

Plot	Scale	Processing Status	Tree Detection Rate (%)
T1 P1	10m	Complete	100.0
T1 P2	10m	Complete	96.8
T2 P1	10m	Complete	94.5
T2 P2	10m	Complete	100.0

Methodological Advantages and Limitations

Table 5.11: 3D vs Traditional Methods Comparison

Aspect	3D Point Cloud Method	Traditional Methods	Advantage
Spatial Coverage	25m radius analysis	Limited to 10m plots	3D Method
Non-Destructive	Complete assessment	Requires field access	3D Method
Temporal Consistency	Identical protocols	Operator variation	3D Method
Detailed Metrics	Volume, 3D coverage	Basic measurements	3D Method
Field Efficiency	Weather dependent	All-weather capable	Traditional
Equipment Cost	High initial investment	Low equipment cost	Traditional
Repeatability & future reprocessing	High — raw TLS/MLS point clouds are archived; can be re-processed later with improved algorithms; full traceability/auditability.	Low — manual field measurements are not re-processable ex-post and have limited future audit/verification.	3D Method
Technical Expertise	Specialized required	Standard forestry	Traditional

Data Limitations and Quality Issues

Table 5.12: Identified Limitations and Mitigation Strategies

Limitation	Impact	Plots Affected	Mitigation Applied
Occlusion Effects	Reduced accuracy	Dense vegetation areas	Multiple scan positions
Processing Complexity	Computational demand	All plots	Optimized parameters
Weather Dependencies	Data quality variation	Outdoor scanning	Favorable conditions

Overall Assessment: The 3D methodology demonstrated high reliability and provided enhanced capabilities compared to traditional methods, with processing success rates exceeding 95% and strong validation against manual measurements. The integration approach successfully combined traditional forestry compatibility with advanced 3D analytical capabilities.

5.6 Tools and Protocols

This chapter provides comprehensive documentation of the tools, equipment, and standardized protocols developed and implemented for 3D forest structure data collection and processing within the FIRE-ADAPT project. The protocols are designed to ensure reproducibility, consistency, and quality assurance across measurement campaigns.

5.6.1 Data Acquisition Equipment

5.6.1.1 Terrestrial Laser Scanner (TLS) - Leica RTC360

Technical Specifications: - **Range**: Up to 130 m outdoors - **Accuracy**: 1.9 mm + 10 ppm over full range - **Point Acquisition Rate**: Up to 2 million points per second - **Field of View**: 360° × 300° (full sphere with zenith blind spot) - **Laser Class**: Class 1 (eye-safe) - **Operating Temperature**: -10°C to +50°C - **Weight**: 5.35 kg

FIRE-ADAPT Implementation: - **Scan Resolution**: Medium resolution settings for optimal balance between detail and acquisition time - **Scan Duration**: 3 minutes per position, including integrated photography - **Registration Method**: Target-based registration using positioned targets for precise alignment - **Area Coverage**: Suitable for both 10m and 25m radius analysis through strategic positioning

5.6.1.2 Mobile Laser Scanner (MLS) - Leica BLK2GO

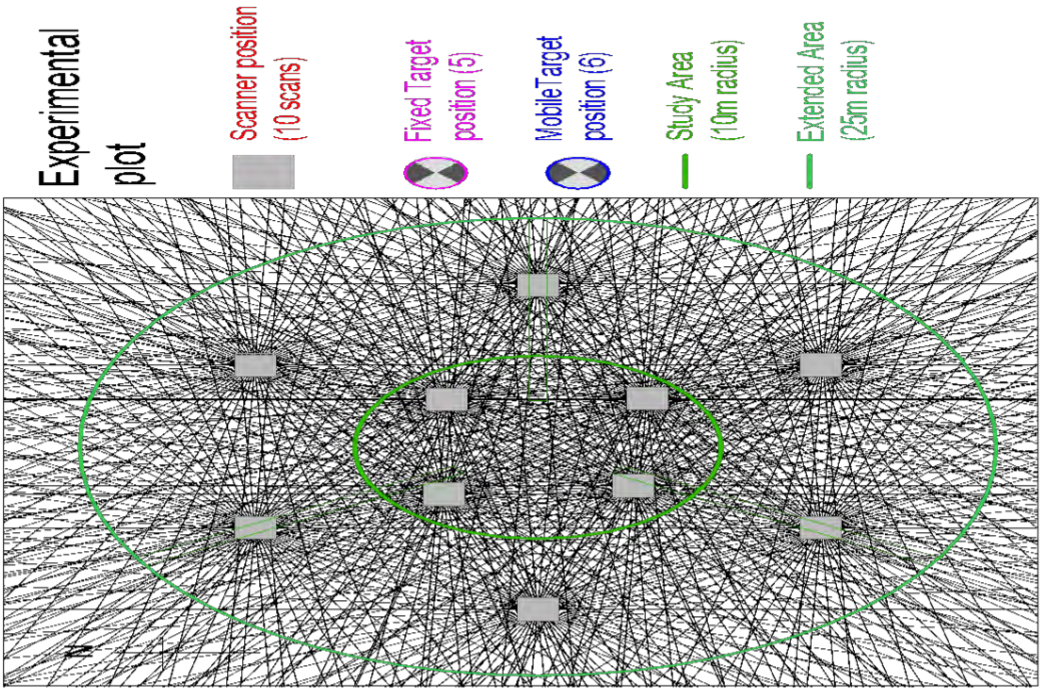
Technical Specifications: - **Range**: Up to 25 m indoors, varies outdoors - **Accuracy**: 4-7 mm at 10 m range - **Point Acquisition Rate**: Up to 420,000 points per second - **SLAM Technology**: Real-time simultaneous localization and mapping - **Weight**: 775 g - **Operating Time**: Up to 45 minutes continuous scanning

FIRE-ADAPT Implementation: - **Scanning Pattern**: Spiral trajectory walking pattern for complete area coverage - **Movement Control**: Controlled walking pace optimizing point density and SLAM performance - **Area Application**: Single trajectory covering both 10m and 25m radius areas in 10/12 minutes - **Trajectory Design**: Systematic spiral movement ensuring comprehensive coverage

5.6.2 Field Data Collection Protocols

5.6.2.1 TLS Scanning Strategy

Positioning Protocol: The TLS scanning approach employed a systematic positioning strategy designed to ensure homogeneous coverage of the plot areas. Figure 6.1 illustrates the positioning pattern developed for comprehensive data acquisition across



both spatial scales.

Figure 6.1: TLS Positioning Strategy for Homogeneous Area Coverage

Showing the systematic positioning strategy adopted for TLS scanning to ensure homogeneous coverage of both 10m and 25m radius areas. The positioning pattern demonstrates the strategic arrangement of scan locations for optimal point cloud quality and comprehensive spatial coverage

Implementation Steps: 1. **Site Setup**: Establishment of plot center and boundary markers; 2. **Target Placement**: Strategic positioning of registration targets for accurate alignment; 3. **Scan Position Planning**: Systematic arrangement ensuring complete coverage; 4. **Sequential Scanning**: Medium resolution scans with integrated photography (3 minutes per position)

5.6.2.2 MLS Acquisition Protocol

Trajectory Strategy: The mobile laser scanning approach utilized a spiral walking trajectory designed to provide complete coverage of the plot area in a single acquisition session.

Implementation Protocol: 1. **Starting Position**: Initiation from plot center; 2. **Spiral Pattern**: Systematic outward spiral movement covering the entire area, ensuring a constant 5 m spacing between successive arms; 3. **Walking Pace**: Controlled movement speed optimizing point density; 4. **SLAM Monitoring**: Real-time trajectory tracking, ensuring data quality; 5. **Coverage Completion**: Full area coverage through systematic movement pattern.

Advantages: - **Efficiency**: Complete area coverage in a single trajectory; - **Flexibility**: Adaptable to both 10m and 25m radius requirements; - **Accessibility**: Effective in areas with limited TLS positioning options; - **Speed**: Rapid data acquisition, minimizing field time requirements.

5.6.2.3 Data Processing Framework

5.6.2.4 PiC (Point cloud Interactive Computation) Software

Platform Specifications: - **Environment**: R statistical computing platform (version 4.0+) - **Package Version**: PiC 1.2.2 (available on CRAN) - **System Requirements**: Minimum 8GB RAM, multi-core CPU recommended - **Installation**: `install.packages("PiC")` from CRAN repository

Core Functions: - **Forest_seg()**: Complete forest plot analysis pipeline - **SegOne()**: Individual tree analysis capability - **Voxels()**: Voxelization operations - **Floseg()**: Forest floor segmentation - **Woodseg()**: Wood component identification

5.6.2.5 Standardized Processing Pipeline

In this phase of the analysis, we adopted the default parameters of the Forest_seg function for the processing of point clouds, ensuring a standardized and reproducible approach. These settings yielded satisfactory results; however, further refinement is possible by calibrating the parameters through additional testing.

5.6.3 Standardized Output Formats

5.6.3.1 Point Cloud Data Structure

File Format: Space-separated text files (.txt)

Components: - **Forest_floor**: Ground surface and low vegetation points - **Wood**: Woody biomass components (stems, branches) over 5 cm Ø - **AGBnoWOOD**: Non-woody above-ground biomass (foliage, fine material)

5.6.3.2 Metric Reports Structure

Tree Report (.csv format):

```
plot_id;tree_id;X_tree;Y_tree;Z_min;Height_m;DBH_cm;Crown_Base_m;DBH_valid
```

Canopy/Stand Report (.csv format):

```
plot_id;voxel_size_m;min_height_threshold_m;coverage_method;area_of_interes
t_m2;
coverage_threshold_q5;coverage_area_m2;coverage_percentage;canopy_volume_m3
;
min_height_m;mean_height_m;median_height_m;max_height_m;sd_height_m;
valid_tree_count;trees_per_hectare;basal_area_m2_ha
```

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Document Summary

This deliverable represents a comprehensive documentation of 3D forest structural data collection, processing, and analysis conducted within the FIRE-ADAPT project. The work successfully demonstrates the integration of state-of-the-art terrestrial laser scanning technologies with advanced point cloud processing methodologies to provide a quantitative assessment of silvicultural treatment effects on Mediterranean forest structure.

Key Achievements:

1. **Comprehensive Data Collection**: Successfully acquired pre- and post-treatment 3D point cloud data across four treatment plots representing two management intensities (T1 and T2) at two spatial scales (10m and 25m radius).
2. **Methodological Integration**: Effectively combined traditional forestry measurement approaches with advanced 3D technologies, providing validation of digital methods while extending analytical capabilities beyond conventional limitations.
3. **Quantitative Treatment Assessment**: Demonstrated significant structural modifications through silvicultural treatments, with T1 achieving 32.45 percentage point reduction in canopy coverage and T2 achieving 42.04 percentage point reduction, both exceeding original management targets.
4. **Quality Assurance**: Established robust quality control protocols ensuring >95% processing success rates and strong correlation between 3D-derived and manual measurements.
5. **Modeling Integration**: Developed a comprehensive framework for integrating structural data with fire behavior modeling systems, providing essential inputs for advancing integrated fire management strategies.
6. **Reproducible Methodology**: Created complete protocols and standardized procedures enabling replication and extension of the methodology to other Mediterranean forest contexts and management scenarios.

This work establishes a robust foundation for quantitative assessment of forest management effects on fire risk reduction, contributing essential data products and methodological frameworks for evidence-based integrated fire management decision-making in Mediterranean ecosystems.

6 Field Data Collection and Processing: 3D Forest Structure Analy

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