

TWENTY FIVE YEARS OF OBSERVATION OF THE OLD-GROWTH MASSANE FOREST DYNAMICS: A UNIQUE PERMANENT MONITORING SYSTEM

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ABSTRACT.- Located in southern France and bordering Spanish Catalonia, the Massane beech forest is one of the last old-growth forest of the Mediterranean basin and represents one of the southern populations of the European beech *Fagus sylvatica* in Western Europe. As such, it deserved special attention and a fine monitoring of its dynamics appeared especially relevant in the context of the ongoing climate change.

As the team responsible for managing the Massane National Nature Reserve, we initiated a comprehensive inventory of its unmanaged forest stands in late 1998. This article aimed at presenting the methodology and monitored traits in order to shed light on this exhaustive and long-term monitoring approach. This survey encompassed all standing trees—both living and dead—as well as fallen dead wood within a 9.4 hectares area known as the integral reserve. The study extended along a 5.25 km stretch of the Massane River, covering an additional 19.4 hectares. The primary objective was to establish a detailed baseline of the forest composition, predominantly consisting of European beech (*Fagus sylvatica*).

Collected data included dendrometric measurements, phenological stages, health assessments, and the presence and characteristics of various tree-related microhabitats (TreMs). These data were systematically stored in a Geographic Information System (GIS) and are regularly updated—semi-annually for tree decline and approximately every 12 years for dendrometric data.

To date, 70,794 items have been cataloged across the 28.8 hectares study area, comprising 61,532 standing trees (alive or dead) and 9,262 pieces of fallen dead wood. This extensive data collection provides valuable insights into forest structure, dynamics (such as growth, intra- and interspecific competition, regeneration and decay), and the presence of parasitic and

saprophytic fungi. It also allows for a nuanced understanding of dead wood distribution and various TreMs, including cavities and brown rot.

By correlating these observations with data from the on-site weather station, we can finely assess the impacts of climatic related events, such as drought stress and phenological anomalies. The weather station, operational since 1959, has documented a nearly 2°C increase in mean temperatures and a significant decline in precipitations since 2021, which may explain the changes observed in the stands, such as the decline of many trees.

This ongoing monitoring initiative, underpinned by a robust cartographic database, forms the core of a unique forest observatory. The choice to conduct comprehensive inventories over substantial areas ensures a thorough representation of the forest's richness and complexity. Although initially labor-intensive, the endeavor has yielded significant results, fostering numerous scientific collaborations and encouraging continued commitment to this invaluable research.

INTRODUCTION

In the second half of the 1990s, the growing interest in natural forests in Western Europe led researchers, managers, and naturalists to engage in a vast effort to inventory and characterize these complex ecosystems. The Massane forest National Nature Reserve (Argelès-sur-Mer, Pyrénées-Orientales, France) has for long been recognized as a outstanding example of an ancient forest in free evolution. The Reserve team then established a permanent monitoring system. Inspired by the European COST action E4 program (Parviainen J *et al* 2000) for the implementation of dendrometric and biodiversity surveys. Thanks to the extensive knowledge previously acquired on the site, it has been made possible to enrich the local protocol by identifying and targeting tree-related microhabitats (TreMs), saproxylic fungi, and heritage species such as certain lichens, etc.

Since the writing of its first management plan, the management team of the reserve was largely encouraged by the CSRPN (Conseil Scientifique Régional du Patrimoine Naturel) to establish a long-term monitoring system for forest ecosystems. Research efforts had until then mainly focused on inventory work of species, which were numerous and highly regarded, revealing the richness of the forest and particularly the importance of saproxylic communities for biodiversity. This work has led to the production of species lists, and this effort for comprehensiveness has never ceased. Nearly 5000 taxa were recognized in 1997 (nearly 12,000 today). These raw lists provide valuable information on the diversity and richness of environments, but not in terms of the dynamics and functioning of ecosystems. The permanence of a technical team attached to the site and the deployment of geographic information systems on

Catalan natural reserves have allowed the establishment since 1999 of a cartographic database for the dynamic study of forest tree populations.

The Massane National Nature Reserve fully plays its role as a natural laboratory for observing the life and death processes of a freely evolving forest ecosystem. How does regeneration occur following the formation of windthrows? How do species distribute themselves and how does forest settlement get organized without human intervention? How are dead wood stocks composed—an essential component of forest biodiversity? How do TreMs and their associated species renew and evolve over time? And how does the forest respond to climatic disturbances—a particularly pressing question, given that the European beech *Fagus sylvatica*, a keystone species with likely glacial origins, is found here at the rear-edge of its range, deep within the Mediterranean biome?

Massane stands as a remarkable example of an old-growth forest in free evolution, and the establishment of this long-term monitoring system provides vital insights into these fundamental questions.

This article summarizes the elements presented as an Introduction to the conference organized for the 50th anniversary of the National Nature Reserve of the Massane Forest. Its objective is not to address in detail the questions raised above or to delve into a specific aspect. Above all, it aims at describing the method, at reporting on the quantity and quality of the data collected, and at providing the broadest possible overview of the opportunities offered by such a system.

STUDY SITE

The mapping inventory was carried out in two forested sections of the Massane Forest Nature Reserve: the *integral reserve* (9.4 ha) and the *riparian forest* (19.4 ha), representing over 15 % of the reserve's total forested area.

The so-called *integral reserve* zone is located in the northern part of the nature reserve and is easily accessible from the end of the dirt road at Roc del Corb (Fig. 1, Fig.2). It offers numerous advantages for conducting a comprehensive field survey. This section of the forest, situated between 640 and 735 meters above sea level on the right bank of the Massane River, was fenced off in 1954 by the Arago Laboratory (now the Observatoire Océanologique de Banyuls sur Mer – CNRS – Sorbonne Université) to protect it from grazing cattle. At the Laboratory's initiative, a closed shelter adjoining the integral reserve was built in 1957 to serve as a refuge and storage facility. In 1996, the original fence, which had become ineffective, was replaced with an electrified one, and the equipment is now regularly maintained to prevent cattle from entering. Finally, the 9.4 hectares area is quite representative of the whole Massane Forest,

thanks to the diversity of forest types, slope exposures, and the various development phases.

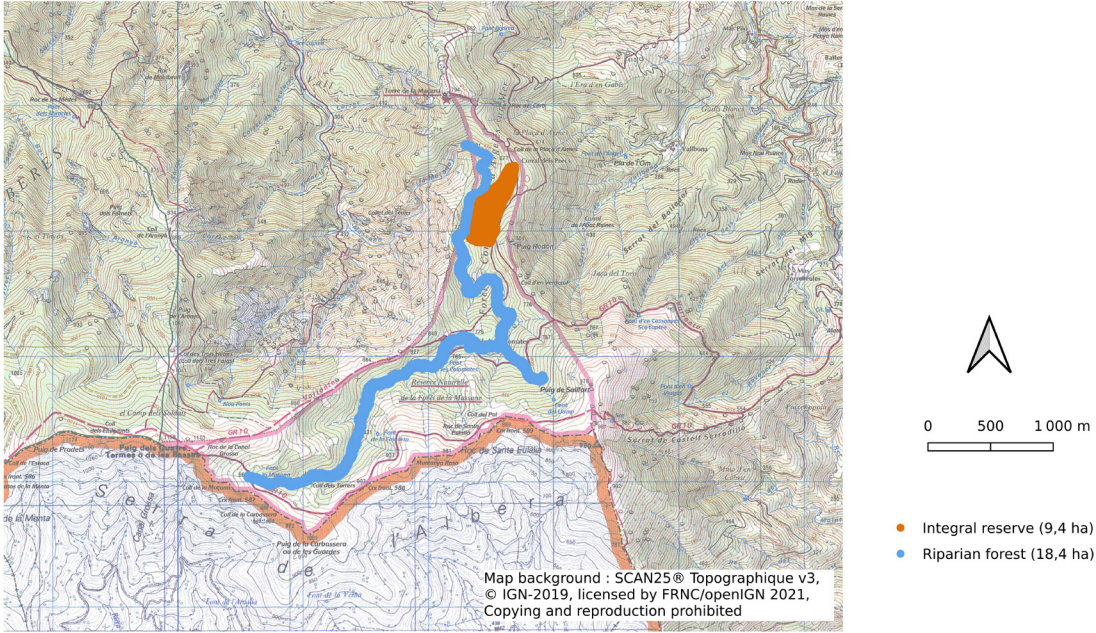
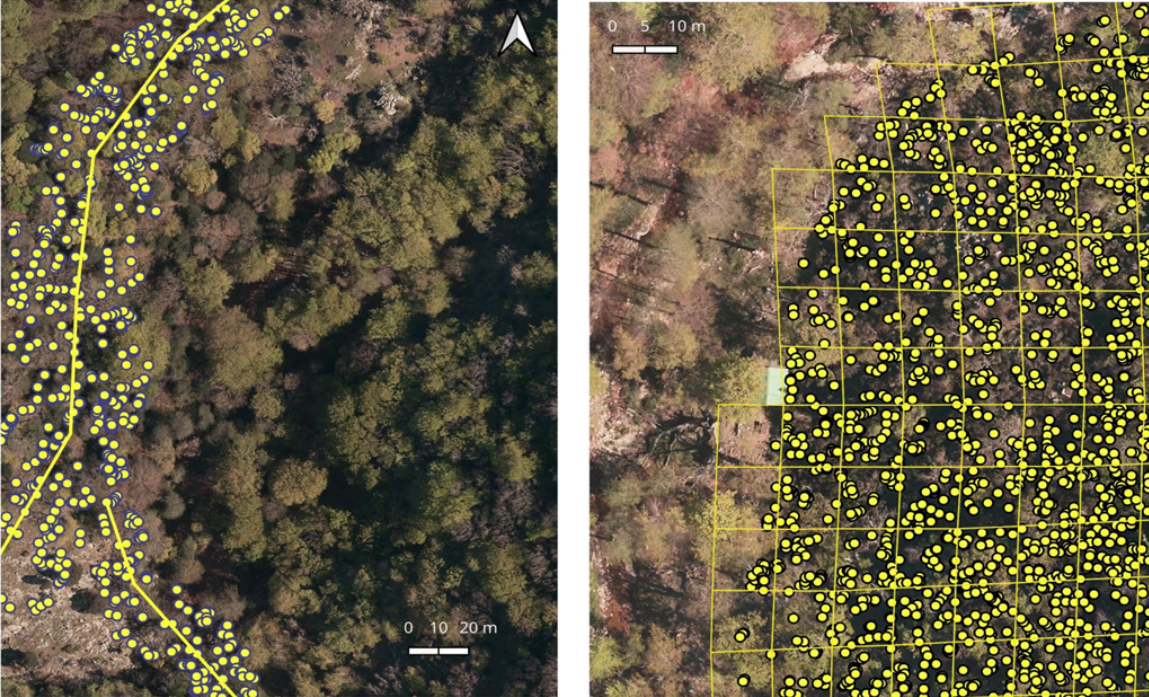


Fig.1.-The two study areas within the national nature reserve (Argelès-sur-Mer, Pyrénées-Orientales, France)



Map background : RNN Massane, Orthophoto 2016 Sintegra

Fig. 2.-Left: survey in the riparian forest along 50 m transects, using a compass, measuring tape, and range-finder. Right: location of individuals within 10×10 m plots, marked on the ground with rebar stakes oriented north–south using a compass and string line.

The area known as the riparian forest follows the banks of the Massane River for a stretch of 5.25 km, from the Font dels Alemanys (610 m altitude) up to its source at the Font de la Maçana (970 m) (Fig. 1, Fig.2). An additional 0.5 km is included to account for a section of vegetation along a tributary, the “Còrrec de la Font del Llamp.”

The choice to monitor this riparian zone is based on several factors, notably the topography of the nature reserve, which encompasses the upper valley of the Massane River. This habitat is also the exclusive environment for many species and plays a key role in regulating the microclimate of the upper valley.

The area is accessible to livestock and studying it provides useful comparisons with the strict nature reserve—an enclosure where grazing is excluded due to fencing.

Throughout its course, the vegetation in the riparian zone is shaped by the Massane’s hydrological regime. This influence is especially evident in the lower sections, where a more typical riparian vegetation thrives, including numerous alder trees (*Alnus glutinosa*) and other species adapted to temporarily waterlogged soils.

MATERIALS AND METHODS

The study consists of mapping the tree populations along with various parameters recorded in the field during comprehensive inventories.

Acquisition of Geographical Information

Field data were transcribed as graphical objects (points or polygons) with geographic coordinates (x, y), depending on their type, and organized into separate layers within a Geographic Information System (initial operations were carried out using MapInfo Professional software):

Points were used for standing trees, whether alive or dead. Systematic inventories were conducted for all living woody plants (excluding shrubs) at least 0.3 meters tall, measured from the base to the apical bud. Standing dead trees were also recorded: those taller than 1.3 meters were classified as *snags*, while shorter ones were referred to as *stumps*.

Polygons were used to represent dead wood lying on the ground. Only logs with a base diameter of at least 10 cm and a minimum length of 40 cm were included.

The initial survey in the strict nature reserve was conducted within a grid physically laid out in the field, using a 10-meter square mesh marked by rebar stakes, string lines, and a topofil (measuring tape device). Due to the lack of a high-precision GPS device available at the time, the grid was georeferenced manually using compass bearings and tape measurements,

oriented north-south from the laboratory shelter. Advances since then have enabled the acquisition of precise GPS points, and subsequent translation and warping of the GIS layers have now resulted in near-meter accuracy.

The initial survey in the riparian forest was carried out using transects due to the linear nature of the habitat along the river. The field survey was structured around a 50-meter baseline stretched with a cord, with its endpoints anchored in the middle of the river. The study area was defined as the *floodplain*, i.e., the area covered by a 100-year flood event. For reference, the initial survey was conducted two years after the November 12, 1999 flood, which falls into this category. The broader survey zone (15 meters on either side downstream) gradually narrows upstream to about 5 meters on either side near the source. The alignment of the various GIS layers using newly acquired precise GPS points is currently underway.

Attribute Data

Each mapped object is associated with a set of attribute data, recorded at varying frequencies. The table I below summarizes the main fields used, their nature, and the frequency of data collection.

Main categories:

General identification: Unique code, object type (living tree, stump, snag, downed dead wood), date of appearance/disappearance, species.

Dendrometric data: DBH (diameter at breast height i.e. at 1.3 m), height, end diameters for dead wood, degradation stage (from 1 to 4).

Ecological characteristics: Phenology (e.g., early leaf-out), ground cover (mosses, litter, rocks), shrub density.

Tree-related microhabitats: TreM types, cavity types (basal, trunk, branches, water-filled rot holes), presence of wood mould, brown rot, saproxylic beetles presence indices.

Other variables: Presence of lignicolous fungi (with identification attempts), *Hedera helix*, *Lobaria pulmonaria*, signs of decline (browning, parasitic infestations, browsing damage).

This data is entered into a GIS-compatible database, enabling detailed temporal and spatial monitoring, particularly improved since the implementation of geographic correction in 2022.

Graphic objects are integrated into different MapInfo layers. Attribute data is stored in an Access database. The historical structure of this database has been preserved, even though in recent years many operations have been carried out using Qgis and Qfield software.

Type	Data	Comment	Frequency
Object	Unique code Type of object Date appearance Date disappearance	A unique identifier is assigned to each object. standing tree / tree or branch on the ground	Once only Once only Once only Once only
Species	Species	Botanical identification	Once only
Tree measurement	Stump Snag DBH Diameter base Diameter top Height Decay stages	True/False True/False The diameter at breast height is measured using a tape. This measurement is systematically taken for all individuals with a height of 1.3 meters or more and when the DBH is greater than or equal to 1 cm. Measurement of the diameter at both ends of the dead wood pieces. – Measurement taken using a forestry caliper Measuring height with a 5-meter stadia rod or a clinometer systematically for individuals between 0.3 m and less than 1.3 m tall (measured at the base of the apical bud), and non-systematically for all others. Stage from 1 to 4 for downed dead wood. 1 (intact) . 2 – the bark begins to degrade. The middle of the trunk starts to rot (less than a tenth of the diameter)»3» - the trunk has rotted well in the middle (more than a third of the diameter). 4 (advanced decay – indistinguishable from forest humus)	2 yearly inspections 2 yearly inspections Update every 12 years for the full reserve (2000, 2012, ongoing) – not carried out for the riparian forest. same same
Phenology	Early	True/False (concerns the earliness of budburst in beech trees)	Once only
TreMs	Cavity Type of cavity Accessibility Wood mould Indicators presence Brown	True/False Trunk cavity, basal cavity, branch cavity or dendrotelm (water-filled tree cavity) True/False (Can the contents of the cavity be controlled?) True/False (contains wood mould?) Presence of the hermit beetle (<i>Osmoderma eremita</i>): larvae or adults, body remains or frass. True/False (presence of the Lucanid beetle <i>Aesalus scarabaeoides</i>)	Once only (2000 - 2002) – To be updated 12-year update including a new dead wood inventory

Fungi	Lignicolous fungi Species	True/False Identification of fungus species	2 yearly inspections 2 yearly inspections
Ivy	Ivy	True/False	The 2000 survey campaign, followed by occasional surveys (not systematically conducted)
Lichen	<i>Lobaria pulmonaria</i>	True/False (only <i>L. pulmonaria</i>)	The 2000 survey campaign, followed by occasional surveys (not systematically conducted)
Tree health status	Browning Parasitic attack Browsing impact	True/False (Premature browning of foliage following recent branch dieback or crown decline) True/False (If true, identify the parasite) True/False	2 yearly inspections 2 yearly inspections Ongoing (taking roe deer presence into account)

Table I.- Field data, nature and frequency of surveysType

In the case of the strict reserve, the delineation of 10 x 10 m plots on the ground allowed for a visual estimation of ground cover percentages (%) by grasses, mosses, bare soil, rocks, or litter. Shrub density (*Erica arborea*, *Juniperus communis*, and *Cytisus scoparius*) was also taken into account -classified into three categories: fewer than 5 shrubs individuals, 5 to 20, and more than 20 - during the initial assessment. During the new survey campaigns, to save time, ground cover rates and shrub densities were not taken into account.

Since the major drought and heatwave climatic event of 2003, a bioclimatic monitoring protocol has been implemented. It is based on two annual survey campaigns, conducted in spring and autumn, aimed at recording new cases of tree mortality as well as visible symptoms of decline (branch dieback, crown thinning, emergence of wood-decay fungal fruiting bodies, etc.). These observations were systematically cross-referenced with data from the local weather station, enabling a dynamic analysis of climatic impacts over the short, medium, and long term.

RESULTS

A total of **70,794 individual items** were recorded (61,532 standing trees, whether alive or dead, and 9,262 pieces of dead wood on the ground) over an area of 28.8 hectares during the various survey campaigns.

In order to gauge the intensity of the inventory, we note that for the integral reserve, two agents spent 264 days (between 1999 and 2000) carrying out grid mapping in the field with stakeouts and recorded the initial state. One agent then spent 80 days entering the data into the computer. Only 64 days were needed to map the riparian forest. The vegetation densities were lower and the establishment of transects rather than grid mapping was much less labor-intensive.

Forest stand structure characterization

Thirty-one (31) out of thirty-two (32) tree species present (Table II) in the whole nature reserve were identified): only one species *Juglans regia* (an introduced species)—was not observed in the integral reserve or the riparian forest.

<i>Acer campestre</i>
<i>Acer monspessulanum</i>
<i>Acer opalus</i>
<i>Alnus glutinosa</i>
<i>Arbutus unedo</i>
<i>Castanea sativa</i>
<i>Corylus avellana</i>
<i>Crataegus monogyna</i>
<i>Evonymus europaeus</i>
<i>Fagus sylvatica</i>
<i>Fraxinus excelsior</i>
<i>Ilex aquifolium</i>
<i>Phillyrea latifolia /media</i>
<i>Pinus nigra subsp. nigra</i>
<i>Populus nigra</i>
<i>Populus tremula</i>
<i>Prunus avium</i>
<i>Prunus spinosa</i>
<i>Pyrus spinosa/amygdaliformis /Pyrus sp.</i>
<i>Quercus pubescens</i>
<i>Quercus ilex</i>
<i>Salix alba</i>
<i>Salix purpurea</i>
<i>Sambucus nigra</i>
<i>Sorbus aria</i>
<i>Sorbus domestica</i>
<i>Sorbus torminalis</i>
<i>Taxus baccata</i>
<i>Tilia platyphyllos</i>
<i>Ulmus minor</i>

Table II.- List of trees and shrubs included in the inventory

In 2000, in the strict nature reserve (Fig. 3), the stand density—considering only living standing trees taller than 1.3 m—was 945 stems per hectare, with a mean basal area of 32.5 m²/ha. The maximum DBH (Diameter at Breast Height) recorded for a living tree in the strict nature reserve was reached by a European beech (*Fagus sylvatica*) with a diameter of 115.5 cm. By 2012, a new survey showed a decline to 739 stems/ha and a basal area of 29.5 m²/ha. This decline can be partly attributed to tree dieback following the unprecedented combination of drought and heatwave in the summer of 2003 (Magdalou JA *et al.* 2005).

During this period, canopy openings caused by dieback facilitated natural regeneration. The number of *Fagus sylvatica* individuals between 0.3 m and 1.3 m in height increased from 1,772 to 3,720 on this 9.4-hectare study area (i.e., from 189 per hectare to 396). A new round of dendrometric surveys is currently underway. *Fagus sylvatica* is the dominant species, accounting for 70 % of the stand, followed by *Quercus pubescens* and *Ilex aquifolium*, each representing 12 %.

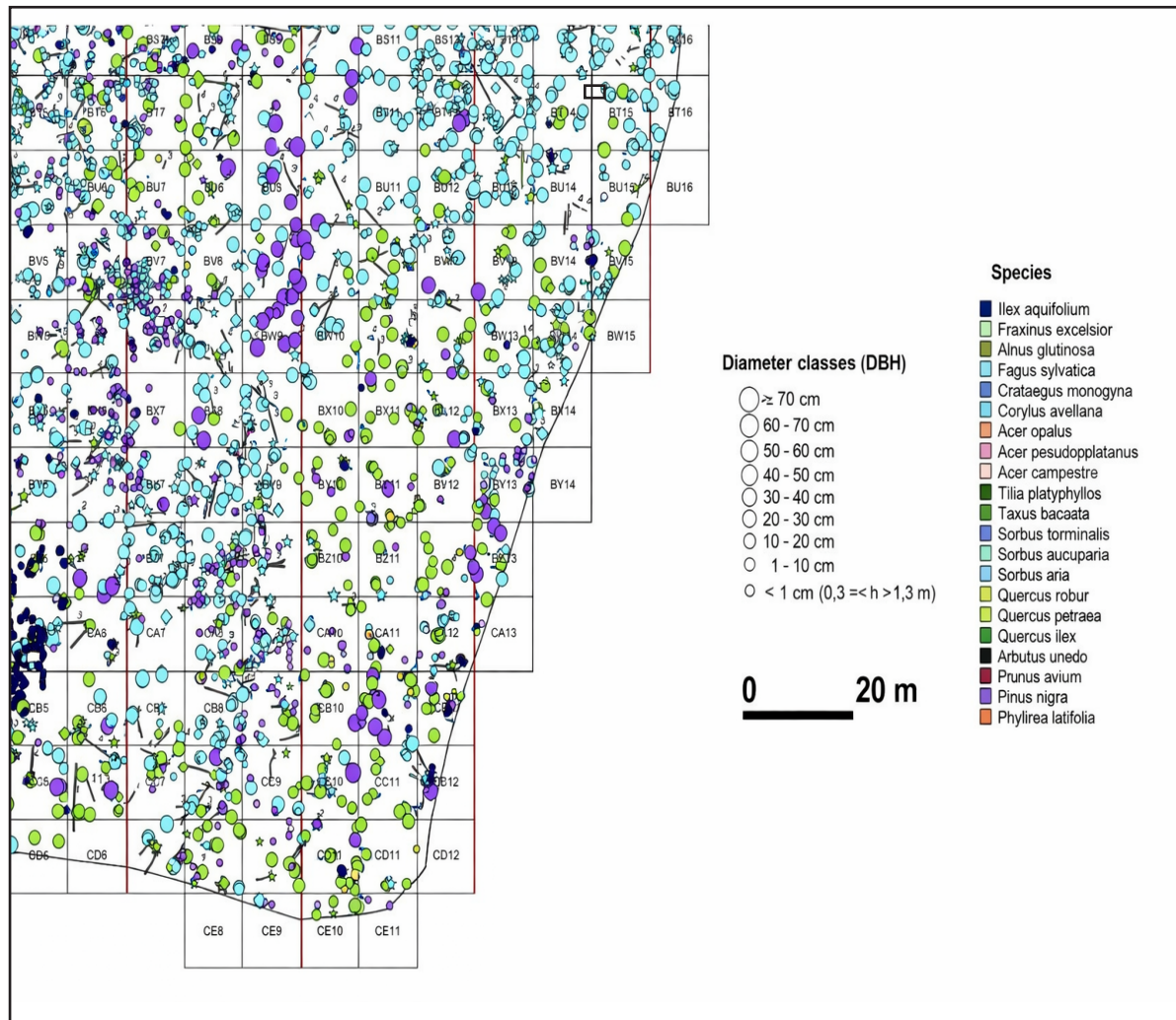


Fig. 3.- Structure of the forest stand in the strict nature reserve (except with visualization of two variables: species represented by color and DBH by size variation), RNN Massane

In 2002, the density of the riparian stand was 437 stems per hectare, with a basal area of 32.5 m² per hectare. The largest diameter belonged to a *Fagus sylvatica* measuring 160 cm. This basal area is comparable to that of the integral reserve, although it corresponds to a stand density that is only half as high. This portion of the stand falls within the active floodplain, meaning the area subject to a 100-year flood event, and is therefore influenced by the torrential hydrological regime of the small coastal river, the Massane. The relatively high basal area can be explained by the presence of very large-diameter beech trees in mature stages of the

stand, particularly in the upstream sections of the mapped inventory. Dendrometric data have not been updated since 2002; only annual surveys of dieback have been conducted. *Fagus sylvatica* is the dominant species (56 %), followed by *Ilex aquifolium* (24.7 %). *Alnus glutinosa*, a characteristic riparian species, accounts for 4.7 %. It is completely absent from the upper third of the 5.4-kilometre stretch of river covered by the mapping inventory.

Taking ground cover rates into account made it possible to clearly delineate and characterize the different facies of the beech forest in the integral reserve. Let's give a concrete example with the “beech forest with mosses” facies (Fig. 4).

	Integral reserve		Moss-dominated facies*	
	2000	2012	2000	2012
Density	930 tiges/ha	754 tiges/ha	1094	919
Basal area	32,5 m ² /ha	29,5 m ² /ha	36,3	30,5
% <i>Fagus sylvatica</i>	70	70	95	93

Table III- Moss-dominated facies of Beech Forest (*covering rate ≥ 50 %)

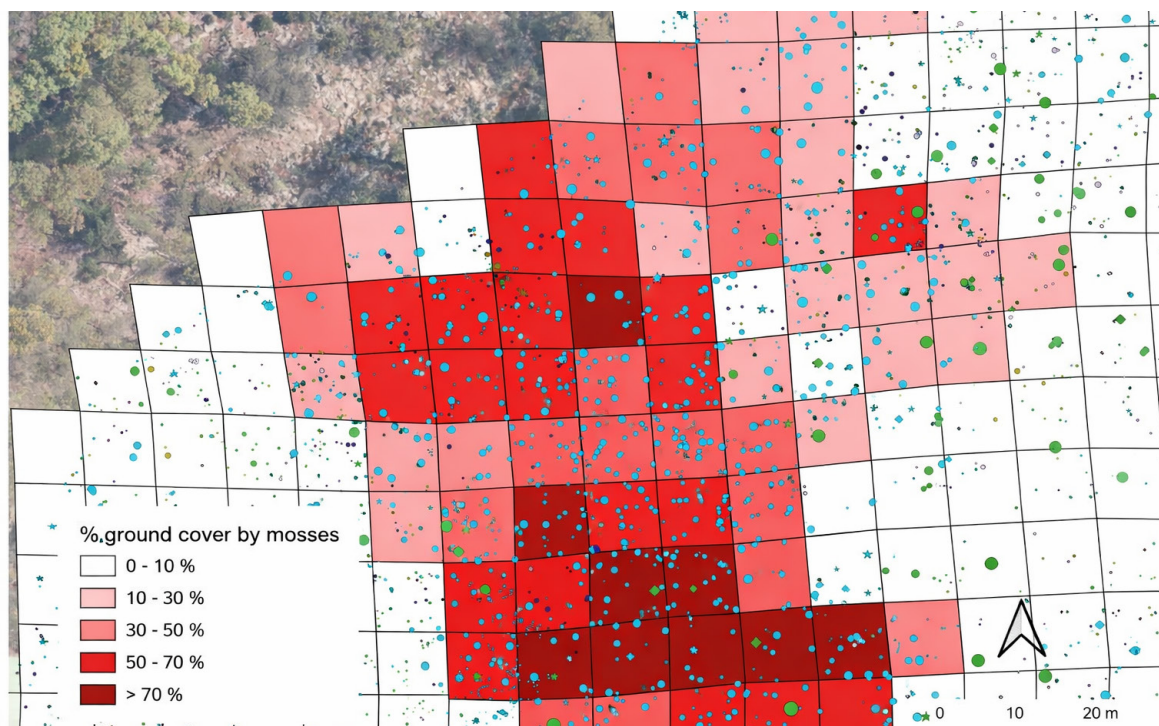


Fig.4.- Structure of the forest stand in the moss-dominated facies.

Among the various types that make up the beech forest, the “mossy beech forest” develops under a canopy cover of approximately 70 to 80 %. Thanks to the dense tree layer and surface runoff, a very humid microclimate is maintained in the understory, favoring the growth of bryophytes (PUIG, J.-N., 1979). Across the entire studied stand, bryophytes

account for 11 % of ground cover. The relationship between moss cover and stand structure makes it possible to assess the distribution and characteristics of the “mossy beech forest” type within the limits of the Strict Nature Reserve. Areas with high moss ground cover (more than 50 %) are underrepresented in the overall forest stand. However, bryophytes do form a more extensive and localized carpet in the northern half of the Reserve. Areas with heavy moss coverage (greater than or equal to 50 %) are those where *Fagus sylvatica* predominates at 95 % (Table III). The remaining 5 % consists of the following three species: *Ilex aquifolium*, *Quercus pubescens*, and *Sorbus aria*. Tree density and basal area are particularly high, with 1,300 stems per hectare and a basal area of 41.7 m² per hectare, respectively compared to the entire integral reserve (945 stems per hectare and 32,5m² per hectare).

Dead wood on the forest floor

Dead wood is known to be an important structural element of forests that influences many ecosystem functions and constitutes an essential resource for organisms living in wood (Stokland *et al.* 2012). This component has received special attention in this context of unmanaged forest dynamics, in light of its importance for biodiversity and its multiple vital functions for the ecosystem. A total of 9,254 pieces of dead wood were recorded between 1999 and 2019 in the study area (3,706 within the strict reserve and 5,548 along the riparian zone). Within the strict reserve, the dynamics of dead wood on the ground are not influenced by the river’s hydrology, unlike those in the riparian zone where major floods can rearrange or even sweep away wood downstream, making individual tracking of pieces virtually impossible. Monitoring within the reserve, however, allows researchers to study dead wood dynamics without being subject to this uncertainty. A first exhaustive inventory was conducted in 2002, followed by a second in 2014 (Table IV). A third inventory is currently underway.

	2002			2014			Including pieces recorded in 2002 and relocated in 2014.		
	nb	m ³	m ³ /ha	nb	m ³	m ³ /ha	nb	m ³	m ³ /ha
<i>Fagus sylvatica</i>	1778	88,5	9,4	1699	87,7	9,3	806	41,9	4,5
<i>Quercus pubescens</i>	783	115,6	12,3	741	123	13,1	583	103,1	11,0
Others	88	3,5	0,4	65	2,2	0,2	60	2	0,2
Total	2649	207,6	22,1	2505	212,9	22,6	1449	147	15,6

Table IV.- Dead wood on the ground (number of pieces and volume)

For the fully protected area, the 2002 and 2014 surveys show similar values in terms of both number of items and volume. In 2014, 54 % of the wood pieces were relocated: 75 % for pieces belonging to *Quercus pubescens* and 45 % for those from *Fagus sylvatica*. The volume

calculations were based on the diameters at the base and top of each piece as well as on their lengths.

Complex pieces were broken down into as many tapering sections as needed in order to apply the volume of a truncated cone to the calculation (known data: r_1 , radius at the top; r_2 , radius at the base; H , height)

To gain insights into the duration and progression of the complex processes involved in dead wood decomposition, a four stage (from 1 to 4) (Garrigue J *et al.* 2000) was used to classify the decay stage.

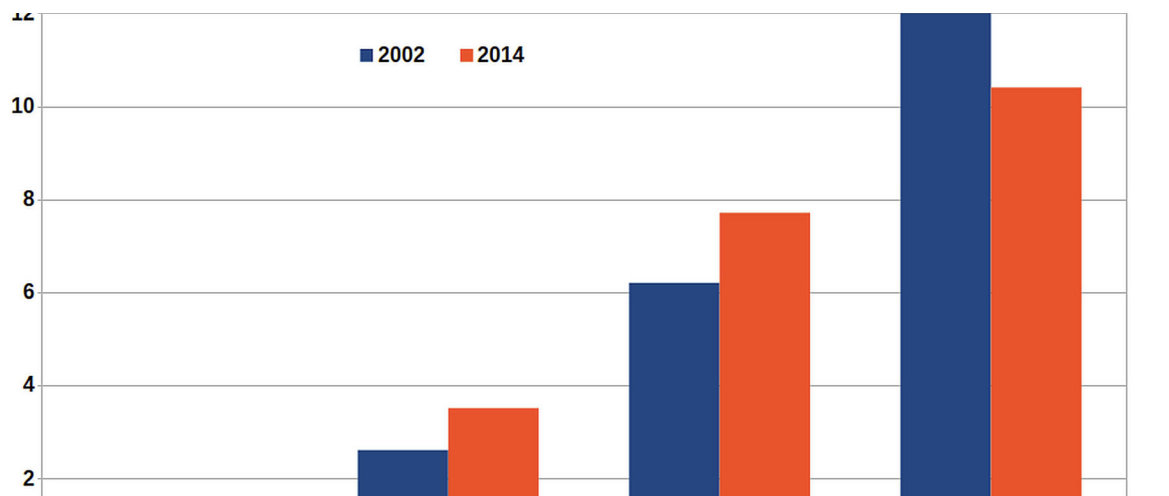
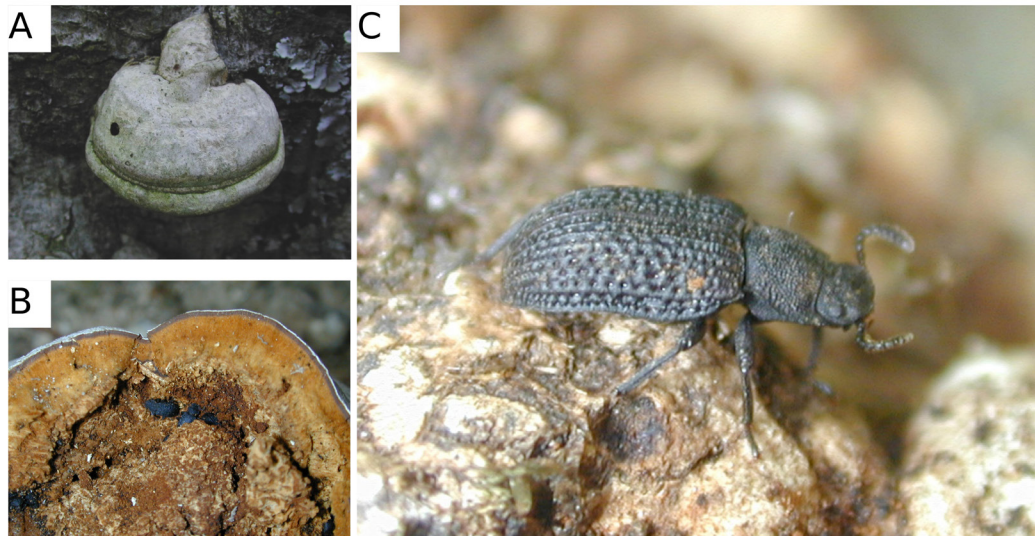


Fig. 5 - Volume distribution in m³/ha across the four decay classes (1 – unaltered, 2 – decay affecting less than one-third of the piece, 3 – decay affecting more than one-third but less than two-thirds, 4 – decay affecting more than two-thirds).

Dead wood accumulates in decay classes 3 and 4 (Fig. 5). The persistence of very large pieces of dead pubescent oak (*Quercus pubescens*) explains the significant representation of stage 4. In contrast, for beech (*Fagus sylvatica*), the distribution follows a bell-shaped curve, with stage 3 being the most represented.

Tree-Related Microhabitats

A tree-related microhabitat (TreM) is a morphological feature on a tree utilized by species that are sometimes highly specialized, at least during a part of their life cycle. Recent studies have enhanced the understanding of their ecological role in biodiversity (e.g. Larrieu L *et al.* 2014, Asbeck *et al.* 2021, Paillet *et al.* 2018). A hierarchical typology of TreMs has been proposed (Larrieu *et al.* 2018), comprising seven forms based on morphological properties relevant to biodiversity: cavities in a broad sense, trunk wounds and exposed wood, dead wood in the canopy, growth anomalies, fungal and slime mold fruiting bodies, epiphytic, epixylic, or parasitic structures, and exudates. These seven forms are now subdivided into 17 groups and 52 types (Bütler R *et al.* 2024)



Example of Tree-related microhabitat: a sporophore of *Fomes fomentarius* (a, b) hosting the Tenebrionid beetle *Bolitophagus reticulatus* (c)

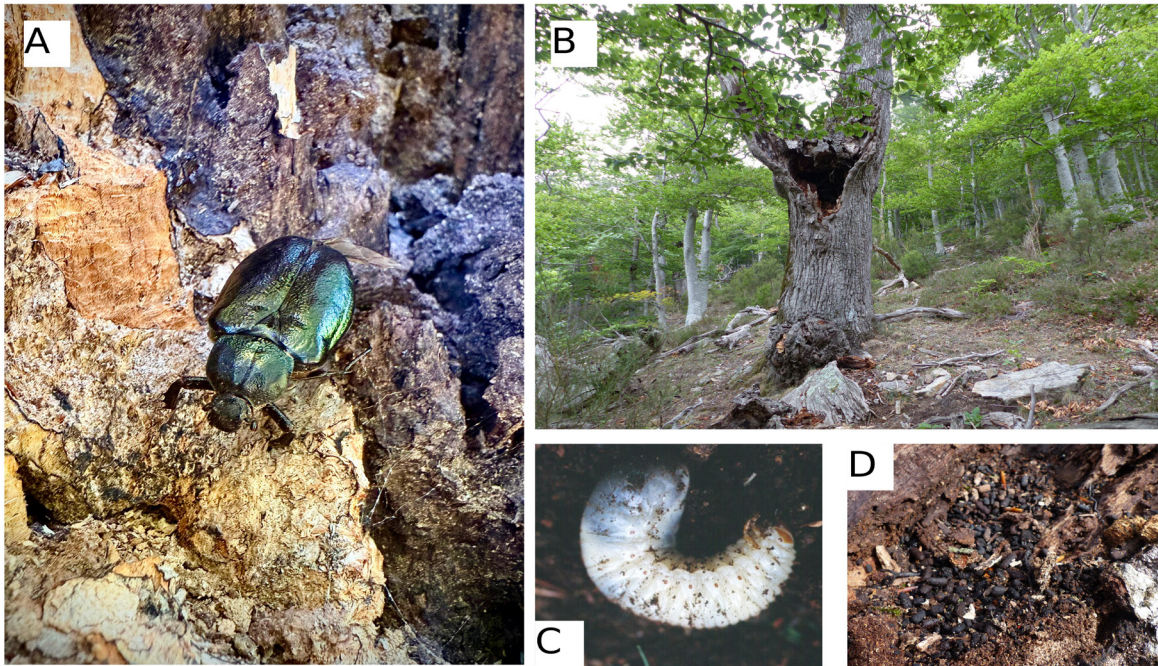
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The full inventory of the strict nature reserve and the riparian woodland includes the recording of fungal sporophores (presence/absence and species identification when possible through macroscopic examination), as well as epiphytes (presence/absence), such as ivy (*Hedera helix*) and the lichen *Lobaria pulmonaria*. Special attention was paid to cavities and red heartwood decay (cubical brown rot), in order to better characterize habitats favorable to the hermit beetle (*Osmoderma eremita*) and the small stag beetle (*Aesalus scarabaeoides*).

Example of wood mould cavities.

Four types of cavities were considered: basal cavities, branch cavities, trunk cavities, and dendrotelms (naturally occurring tree cavities, more or less open, capable of holding rainwater). Accessible trunk cavities were examined to detect signs of *Osmoderma eremita* (individuals, larvae or adults, frass and/or macro-remains). This species, present in the Massane forest, develops exclusively in large cavities that take decades to form.

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Osmoderma eremita (adult beetle) (a)– photo: Diane Sorel; cavity inhabited in an old oak tree (b), with larva (c) and frass (d) – photo: RNN Massane

607 cavities were located within the strict nature reserve (9.4 ha), including 254 trunk cavities. Of these, 99 contained mould. Signs of presence were found in 23 of these potentially suitable cavities (including 4 with confirmed occupation). Along the riparian forest strip (18.4 ha), 168 trunk cavities were identified. Only 5 showed clear evidence of occupation. In the Massane forest, conditions favorable to the establishment of the species are rare. Trunk rot-holes with mould and confirmed occupation are poorly represented. This was highlighted thanks to the effort to be thorough, which led to the systematic inspection of cavities.

Example of brown rot

Brown rot of wood is rarely observed and is also the result of a highly random process. It is caused by the presence of a fungus that mainly decomposes cellulose, causing the tree to fragment through perpendicular breaks in the wood grain. “However, it is the brown rot of oak - or even better, that of alder or wild cherry - that is preferred by *Aesalus* when various tree species are present in a given site. The sites are cool, located in small valleys or on north- or west-facing slopes, within the colline belt for its southernmost records.” (Brustel H 1999). The small Lucanid beetle *Aesalus scarabaeoides*, present in the Massane forest, develops in this habitat, particularly in dead wood from *Alnus glutinosa*. During a comprehensive survey in 2005 of dead wood lying on the ground along the riparian forest (18.4 ha), 1,621 pieces were recorded, representing a total volume of 675 m³. Only 29 pieces, with an estimated volume of 8 m³,

distributed across 3 locations, showed “brown rot” suitable for the beetle.



The small Lucanid *Aesalus scarabaeoides* adult (a); its larva (b); an Elaterid *Ampedus quercicola* (c), commonly found among the species associated with brown rot

Tree mortality

	Number of trees (mortality) with DBH \geq 1 cm	Number of trees showing new damage such as crown dieback, branch mortality
2004	165	1250
2005	128	1022
2006	123	1456
2007	210	884
2008	102	195
2009	59	55
2010	159	302
2011	81	182
2012	159	52
2013	110	164
2014	84	357
2015	58	519
2016	112	765
2017	64	953
2018	122	445
2019	44	419
2020	123	489
2021	41	232
2022	172	735

Table V - Annual report of observations on *Fagus sylvatica* in the integral reserve.

Over the period 2004-2022 (Fig. 6), the average mortality rate for *Fagus Sylvatica* is 1.9 %. This takes into account 5,956 living individuals (DBH \geq 1 cm) as of December 31, 2003. As of December 31, 2012, following dendrometric surveys carried out that year, the number of individuals in the category is 4,871. The year 2007 shows the highest rate at 3.7 % (Table V).

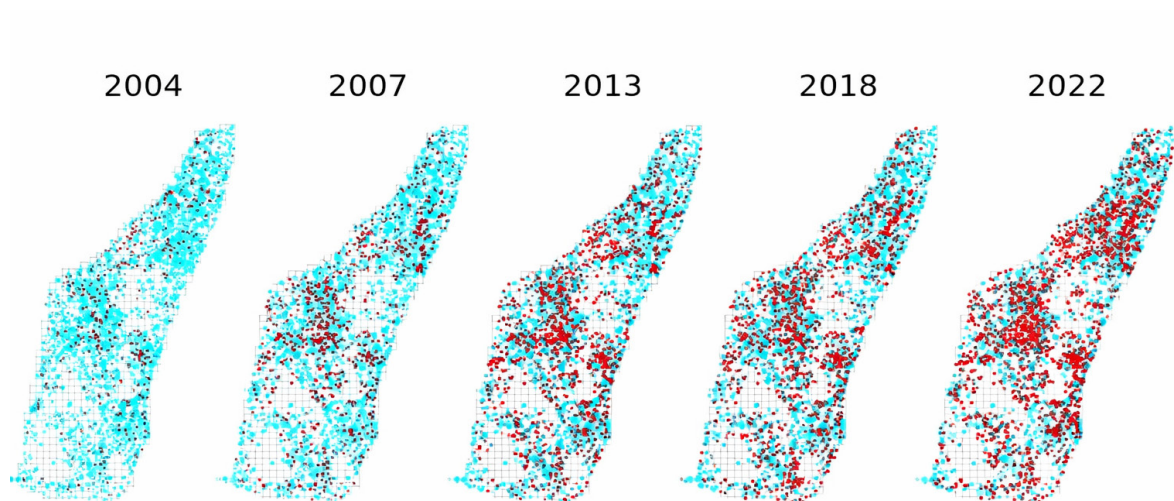


Fig.6 - Cumulative mortality of European beech (*Fagus sylvatica*) over an 18-year period (live trees in blue, dead trees in red)

A Phenological Anomaly in *Fagus sylvatica*: Autumn budburst observed in late October 2023

During a field visit on October 22, 2023, we observed that the buds of several *Fagus sylvatica* individuals, which had just entered dormancy at the end of summer, had resumed metabolic activity and growth. This previously undocumented phenological phenomenon in the Massane Reserve suggests a dysregulated metabolic response to extreme climatic stressors. This autumnal budburst, likely triggered by severe hydric and thermal stress during the spring and summer of 2023, had not been previously documented in the Massane reserve. Out of the 4,173 *Fagus sylvatica* trees in the integral reserve (Fig. 7), 361 standing individuals measuring at least 1.3 meters in height exhibited this phenological anomaly, representing 8.6 % of the population.

Based on prior observations of branch mortality attributed to cavitation, our analysis did not

reveal a higher proportion of trees displaying visible signs of decline. Approximately 50 % of the beech trees in the integral reserve have shown such symptoms (branch mortality and/or crown dieback), and this proportion is consistent among the individuals that experienced the autumnal budburst in 2023. No specific category emerged on the basis of dendrometric criteria. However, these individuals are clearly spatially clustered and are concentrated within just 18 % of the reserve’s area, specifically in 184 out of the 1,035 10x10 meter plots. 77 % of the individuals concerned are concentrated in areas with heavy rock cover and/or *Calluna vulgaris*, which grows at La Massane on the poorest, rockiest soils, and most exposed to sunlight, and which are not known to be the most favorable for the development of beech forests, indicating a probable influence of edaphic and topographic microconditions.

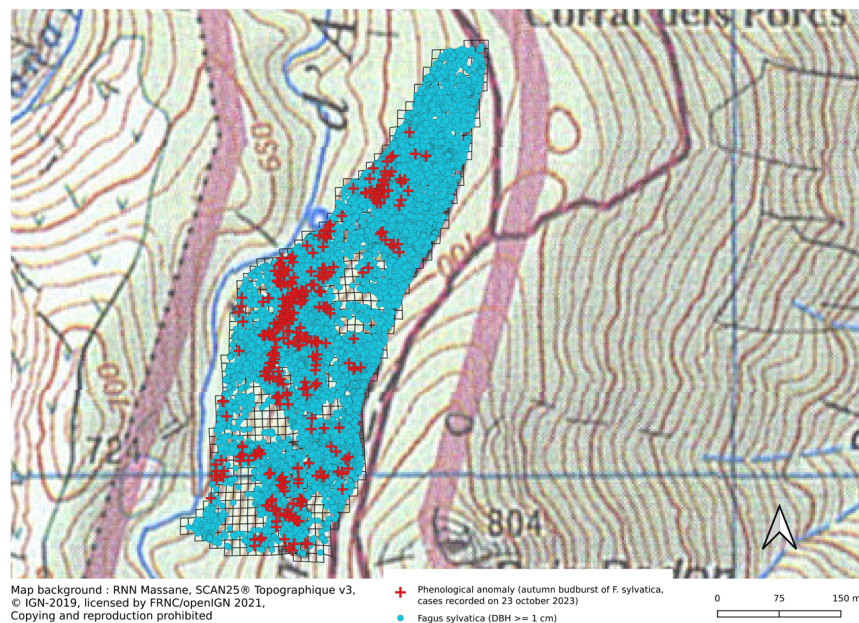


Fig.7- Observation of autumn budburst, a phenological anomaly in autumn 2023 on *Fagus sylvatica* within the strict nature reserve.

DISCUSSION

Conducting a comprehensive mapping over 28.8 hectares—representing 15 % of the Massane Nature Reserve’s forested area—proved to be a substantial undertaking, with time investment being the most significant factor. Transect mapping is much easier and quicker to implement. The time savings are much greater. This method is more suitable for linear study areas such as riparian forests. However, it is much less suitable for integral reserves due to difficulties related to the condition of the terrain and its steeper nature. The implementation of quadrats enriched the database by enabling measurements of ground cover percentages (mosses, rocks,

grasses, etc.) and shrub densities.

Advancements in geolocation tools, the use of GIS tablets, and improved protocols have optimized recent campaigns. The initial methodological effort has been rewarded by the depth and richness of the obtained results.

Initially, geographic data lacked precision due to inadequate equipment and GPS limitations for valley-bottom surveys. Technological progress has since achieved near-metric accuracy, though it remains insufficient for tracking individual seedlings and saplings, which can be densely populated in certain areas. The development of digital tools and the use of GlobeXplorer tablets have greatly facilitated database navigation and field operations. Since their introduction in 2020, the time required for spring and autumn dieback surveys has been halved—from 24 agent-days for both campaigns to just 12. These surveys allow for correlation between observations and weather station data, enabling assessment of climatic disturbances' effects on forest stands. The 2004-2022 observation period for tree decline was marked by the unprecedented combination of drought and heatwave in 2003. The delayed effects were significant in 2007, with a mortality rate of 3.7% (average annual rate of 1.9 % over the study period). Visible symptoms of damage were evident and numerous from 2004 onwards (branch mortality or crown decline), with more than 20% of trees affected (Magdalou *et al.* 2005). In the context of the prolonged drought affecting our region in recent years, the observed tree deaths and signs of decline are often the result of a major physiological dysfunction triggered by severe water stress: cavitation, which leads to embolism in the sap-conducting vessels. This phenomenon, caused by the formation of air bubbles in the xylem vessels, breaks the water column and disrupts sap transport, which can ultimately result in tree death. Cavitation typically occurs during extreme drought episodes and can be fatal to plants when it reaches critical levels (Delzon & Cochard 2014).

These records of mortality or symptoms that can be attributed to water or heat stress provide valuable information to forest managers, who often lack reference data, and highlight the importance of long-term monitoring to measure the consequences of exceptional climatic events: mortality and recovery of individuals weakened by the intensity and duration of climatic episodes (short to medium term), species composition and stand structure (long term), etc.

The phenological anomaly observed in certain individuals in October 2023 raises questions about the resilience of beech forests in the face of increasingly frequent temperature and water fluctuations, and about the potential emergence of new decline syndromes. It also highlights the importance of systematic phenological monitoring, which should be incorporated into future campaigns.

The interval between dendrometric surveys is set at 12 years, requiring significant investment. Diameter measurements at breast height (DBH) are systematically taken for standing trees over 1.3 meters tall, while only heights are recorded for smaller trees to monitor recruitment. In 2012, updating the integral reserve required 45 field days. Data processing yields valuable insights into growth, stand structure evolution, particularly regeneration dynamics, and the development of dendromicrohabitats.

However, this interval is insufficient for monitoring dead wood on the forest floor. Clearly, the time gap between two inventories is far too long for studying the flow dynamics, given the faster decomposition rate of *Fagus sylvatica* compared to the persistence of *Quercus* wood. Numerous *Fagus* pieces may have appeared and completely decomposed in the meantime. In temperate European forests where the decomposition of different species has been studied (Kahl *et al.* 1997), *Fagus sylvatica* exhibits very high decomposition rates among angiosperms, in contrast to species with distinct heartwood such as *Quercus* spp. It is clear that the rate of degradation of certain species, such as the main species, *F. sylvatica*, compared to *Q. pubescens*, only provides information on the state of stocks at a given moment in time and not on the dynamics of flows. The time interval between two dead wood surveys must therefore be reduced. A five-year inventory cycle is therefore recommended to better capture the dynamics. The method used to measure and characterize the four stages of decomposition of dead wood on the ground does, of course, have its limitations. The implementation of the PSDRF (Protocol for Dendrometric Monitoring of Forest Reserves) in the integral reserve (Daudel P 2021) has yielded results that are fairly close to those obtained by the local sampling protocol for living or dead standing trees. The 2021 PSDRF survey campaign revealed significant discrepancies with the local sampling protocol, with a ratio of 1 to 3 for the estimation of dead wood volumes on the ground. In the future, it will be necessary to pay particular attention to this essential component of the forest ecosystem in order to fully understand the origins of this discrepancy. Adjustments must therefore be made in order to best understand the dynamics and structure of this component and take full advantage of the opportunity offered by this context of free evolution to study dead wood, which is insufficiently taken into account in forest inventories.

In the Massane forest, conditions favorable to the establishment of *Osmoderma eremita* are rare. Cavities in tree trunks that are known to be occupied are few and far between, and their presence has undoubtedly been highlighted by the desire for completeness in a comprehensive inventory. These comments also apply to *Aesalus scarabeoides*. These cavities and pieces of dead wood with brown rot are two examples of rare microhabitats that are difficult to approach in the context of simple plot sampling. The results obtained for these two groups clearly argue in favor of maintaining an exhaustive effort in the study of these elements, which are essential to forest biodiversity. Although time-consuming, this effort is essential for

properly identifying, characterizing, and monitoring these dendromicrohabitats.

These surveys have also highlighted the difficulty of making management recommendations for the conservation of these species in forest environments. In the case of *Osmoderma eremita*, for example, the preservation of many old trees is necessary because the formation of a wood mould cavity is not always the result of a tree's decline. The random nature of this process should therefore encourage forest managers to allow part of their stands to age naturally and to ensure their renewal.

Comparable studies have been conducted in recent decades in beech forests with little human disturbance in different regions of Europe. They used plot sampling techniques (Commarmot *et al.* 2013, Diaci *et al.* 2009) or complete dendrometric surveys above a threshold based on a minimum diameter (Vandekherkove *et al.* 2018). The local sampling protocol implemented at La Massane includes all trees with a height greater than or equal to 30 cm, and DBH is systematically measured when it is greater than or equal to 1 cm. The methodological choice made in 1999 was implemented again in 2012 and, despite its complexity, once more in 2024-2025 (inventory in progress) in order to study the evolution of stands using comparable data sets. Clearly, in the future, a methodological adjustment will be necessary in order to have data that is comparable with other sites and to facilitate its integration into European observation networks. Annual surveys of new cases of mortality or damage (branch mortality and/or crown dieback) feed into the database and provide valuable information on individual responses to different stresses. These data have, for example, proved particularly interesting and useful for studies characterizing the interaction between decline and genetic quality of regeneration (Oddou-Miratorio *et al.* 2021) as well as for analyses combining genomics and ecology, such as those carried out as part of the BEECHGENOME and FAGADAPT projects.

The implementation of this field sampling protocol requires a considerable investment of time and was made possible by the provision of a permanent team of two full-time equivalents at the nature reserve since 1999. The effort to be exhaustive provided a good guarantee of approaching as closely as possible the richness and complexity of this freely evolving forest ecosystem. The work was tedious at first, but the results obtained, the potential uses, and the development of numerous scientific collaborations around the availability of the database demonstrate the value of the approach undertaken 25 years ago.

CONCLUSION

This ongoing monitoring system, built on a cartographic database, forms the core and foundation of the forest observatory—unique in its kind due to the volume of data, measurements, and observations collected over nearly 25 years. It has enabled the creation of a detailed

assessment of stand structure, with precise location and characterization of numerous microhabitats, parasitic and/or saprophytic fungi, and, in particular, dead wood lying on the forest floor—an element often underrepresented in such inventories. This singular approach makes it possible to establish a highly accurate baseline of forest structure, to track its changes over time, and to better understand the effects of climate change on ecosystems. It serves as a solid foundation for both scientific research and conservation management.

Periodic dendrometric campaigns, as well as biannual monitoring of dieback and mortality events, provide valuable insights into individual tree growth, intra- and interspecific competition, regeneration, degradation, and climate change-related mechanisms (correlated with data from the weather station). The resulting database is an invaluable resource supporting a wide range of research efforts within numerous scientific collaborations.

Finally, while proven plot sampling methods undoubtedly provide a detailed picture of forest stand structure (specific distribution, density, stratification, basal area, etc.), the full inventory principle implemented at La Massane has enriched the forest observatory by taking into account changes in dead wood stocks on the ground, the evolution of the forest canopy, and the distribution of dead wood on the forest floor. etc.), the location and monitoring of Tree-related microhabitats that are under-represented but of great interest to heritage species of saproxylic beetles, and annual monitoring of dieback. This ongoing experiment, which requires a truly exhaustive effort, continues to reveal the richness and complexity of an old forest in free evolution.

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