expected stand structure, and site-specific constraints (e.g., presence of protected endemic species).

Current operational practices were also documented, with an emphasis on understanding:

- Benefits: Why the current system is used.
- Constraints: Why it cannot be easily changed.
- Limitations: What should be improved from a future-oriented perspective.

This information forms the basis for evaluating potential improvements in operational efficiency, stakeholder engagement, and the economic viability of fire prevention treatments through a more robust and sustainable value chain.

4.2.1 Living Lab Sardinia

The site selected for the Sardinia Living Lab has already been extensively described in Deliverable D2.2 (Busquets et al, 2024). The primary strategic treatment identified for this area is the maintenance and restoration of wildfire prevention infrastructure, specifically firebreaks and fuelbreaks.

These infrastructures are strategically placed in zones with a high risk of wildfire and/or limited accessibility in case of emergency. Typically, they consist of a central access route (viability) flanked by buffer zones on either side, with a total recommended minimum width of 30 meters. Originally designed as firebreaks, completely cleared of vegetation, these areas have evolved into fuelbreaks or shaded fuelbreaks, which maintain a broader width but retain a sparse cover of vegetation to reduce ecological impact while still serving their preventive function.

The role of these infrastructures is twofold: to facilitate the rapid access and operation of firefighting crews, and to mitigate fire intensity by creating a strategic discontinuity in fuel load. This “breach” becomes a key location for concentrating suppression efforts during wildfire events.

Silvicultural Requirements

The main objective was to convert an existing firebreak into a shaded fuelbreak extending 30 meters from the roadside. The fuelbreak was designed to show a gradual increase in vegetation density from the roadside inward, targeting approximately 70% ground cover. This density would help protect the soil from erosion, suppress regrowth, and preserve the site's aesthetic value. Protected endemic species (e.g., *Chamaerops humilis* L.) were to be preserved during operations.

Due to restrictions linked to the site's protected status and public perception, no visible ground disturbance was permitted. This limited the use of heavy machinery and ruled out whole-tree extraction, as dragging branches could scar the sandy soil creating visible marks on the ground, which the general public would perceive as a damage to the forest. To reduce wildfire risk, all residues were to be removed and piled at the roadside. On-site mulching was only considered under minimal machinery transit conditions.

Value Recovery

Timber recovery options were limited due to market constraints:

- Pine logs could be processed into high-quality wood chips from debranched stems. Sawmilling was excluded due to poor log form and the absence of local facilities.
- Pine branches, crowns, and shrubs had no viable market within 150 km and were mulched and left at the roadside.

Work System Selection

Given these constraints, CNR-IBE researchers selected a solution with the following features:

- Lightweight, mobile, and affordable equipment, ideally compatible with second-hand machines to reduce costs.
- Multi-functional machinery, capable of supporting all required tasks while enhancing—not substituting—manual work.
- Accessible and user-friendly technology suitable for aging crews.

The final choice was a mini-winch (Figure 15) mounted on the boom of a 4-ton micro-excavator. While winches are common in forestry, boom-mounted micro versions are relatively new and have mainly seen use in niche applications in Scandinavia and Iberia.

Figure 15: Excavator equipped with mini-winch in Sardinian Fuelbreak management.

This work system, hereafter referred to as the innovative method, was compared with the traditional system currently used by FORESTAS, the agency responsible for managing Sardinia's fuelbreak networks. The traditional method involves tree and shrub felling using chainsaws, followed by extraction using a tractor equipped with a winch.

The economic results of the comparison are summarized in Table 8, which details the intervention costs. The data clearly show that the innovative method consistently offers cost advantages over the traditional one. When looking at the cost per individual tree, the innovative system proves more efficient: €6.92 per tree versus €7.62 per tree with the traditional method. This outcome reinforces the benefit brought by the innovative approach, especially in contexts where tree density is higher.

Since the intervention was a deconiferization, the uneven distribution affected the comparability of results. Nonetheless, when normalized on a per-tree basis, the innovative method still demonstrates a clear advantage.

Overall, the innovative system showed remarkable cost savings, reducing total fuelbreak management costs by 35% in Porto Ferro, and by 13% in Monte Grighine, despite the site-specific challenges. These findings confirm the potential of the innovative system to enhance the economic efficiency and scalability of wildfire prevention operations across Sardinia.

Table 8: Economic results of the comparison between the two work methods.

	Porto Ferro		Monte Grighine	
System	Traditional	Innovative	Traditional	Innovative
Shrub removal cost (€·ha^{-1})	238	192	1649	1202
Wood extraction cost (€·ha^{-1})	973	400	389	581
Stacking cost (€·ha^{-1})	502	534	1137	1010
Total Cost (€·ha^{-1})	1714	1126	3174	2792
Difference (%)	100	-35	100	-13

4.2.2 Living Lab Catalonia

This study was conducted in a naturally regenerated Aleppo pine (Pinus halepensis) forest located in Viladecavalls, Catalonia (Spain), which had regenerated after a wildfire. The site selected for the Catalonian Living Lab has already been extensively described in Deliverable D2.2. The forest includes sporadic holm oak (Quercus ilex) in the understory and exhibits a high accumulation of fuel loads. The vegetation cover is heterogeneous, with varying plant densities across the area.

Sample plots were selected to represent different stages of tree development and stand structure. Plot 1 presented a dense stand of tall, slender pines with a heavy presence of climbing plants, making it nearly impenetrable by foot. The terrain ranged from moderately steep (up to 25%) to nearly flat. Plot 2 had smaller trees than Plot 1, fewer climbing plants, but with obstacles such as rocks. The slope was moderately steep. Plot 3 was a very dense stand of short, thin trees, free of climbing plants but still difficult to access due to the sheer number of pines. Terrain was moderately steep.

Traditional work System

The current preventive silviculture practices in the area rely on motor-manual felling, supported by agricultural tractors equipped with winches for timber extraction. A few weeks prior to the testing of the innovative machine system, a local company carried out forest operations on the same plots which had been previously divided in two homogeneous subplots to be treated with the innovative and the traditional system, respectively. A team of five operators was involved in clearing the first 20 meters from the main roads and forest tracks. Only large logs were extracted; smaller material (<8 cm diameter) and branches were roughly crosscut and left on the ground to reduce operational costs, although this left a significant amount of coarse biomass in the forest. The value of the extracted timber was barely sufficient to cover hauling and transportation, and as such, the biomass contribution was not factored into the overall economic balance. Table 9 presents the costs associated with manual operations as reported by the company. A detailed description of the performance of the innovative system is reported in deliverable 2.2.

Table 9: Cost of manual operations for the same test plots. Source: BOSCAT.

Plot	1	2	3
Managed Area (ha)	0.9	1.2	1.48
Cost (€)	-3600	-3600	-6525
Cost per Area (€·ha^{-1})	>4000	3000	4409
Subsidy (€·ha^{-1})	2000	2000	3000
Total loss (€·ha^{-1})	−2000	−1000	−1409

When the same subsidy (€2,000/ha) was applied to manual operations across all plots, the financial feasibility was not achieved in any of the cases:

In Plot 1, manual operation costs exceeded 200% of the subsidy, primarily due to the difficulty in felling tall trees with entangled crowns.

In Plot 2, where trees were smaller and easier to manage, costs were still around 150% of the subsidy.

In Plot 3, costs were comparable to those of mechanized operations, but still about 150% of the subsidy, rendering the intervention financially unfeasible.

Innovative work system

For this study, the Malwa 560C Combi (Malwa Forest AB, Skene, Sweden. Figure 16) was selected as the most suitable machine. This lightweight, "combo" forest machine can be quickly converted in the field from harvester to forwarder mode, and vice versa, making it especially well-suited for small-scale early thinning operations in compact harvesting units (Ackerman et al. 2021). In harvesting mode, the machine was equipped with a Log Max 928A harvesting head (weighing 412 kg) and fitted with stabilizing ballasts to ensure balance during felling. When switched to forwarder mode, the machine utilized a standard timber grapple mounted on the crane, and stakes were added to the load bed for efficient roundwood loading and transport.

Figure 16: Malwa 560C harvesting mode (left) and forwarder mode (right).

Table 10 presents the machine cost values used for the economic analysis of the innovative system. The cost per Productive Machine Hour, including delays shorter than 15 min (PMH_{15}), was calculated at €89.60, which led to different costs per area depending on each plot. The biomass value at the roadside was estimated based on the local market, at a rate of €30 per cubic meter.

Table 10: Economic balance of the innovative system

Plot	1	2	3
Costing per Productive Machine Hours (€·PMH15^{-1})	89.60		
Area treated (ha)	0.21	0.28	0.17
Unitary cost (€·m^{-3})	44.67	54.52	183.58
Cost per Area (€·ha^{-1})	2257	3336	4951
Biomass value at the road site (€·m^{-3})	30.00		
Biomass value at the road site (€·ha^{-1})	1516	1836	809
Economic Balance (€·m^{-3})	−14.67	−24.52	−153.58
Economic Balance (€·ha^{-1})	−741	−1501	−4142

The costs recorded for Plot 1 are comparable to those reported by Bigot et al. (2012) for small-diameter trees (around 0.06 m^3/tree), with a range of €40–45/m^3 under optimal conditions using compact harvesters. However, these are still higher than costs reported in other studies involving similar equipment and larger trees (Codd et al. 2008).

It is important to note that manual clearing operations, especially in Plot 1, accounted for over 20% of the total productive machine hours (PMH_{15}), significantly affecting cost efficiency. Without these extensive clearing tasks, the estimated total costs per hectare would have been reduced to €1,735, €3,030, and €4,239 for Plots 1, 2, and 3, respectively.

As expected, tree size and stand density caused significant variation in both performance and cost across the plots:

In Plot 1, the economic balance was close to zero, meaning no financial loss. Here, public subsidies of €2,000/ha fully covered operational costs, which only represented 37% of the subsidy amount (Figure 17).

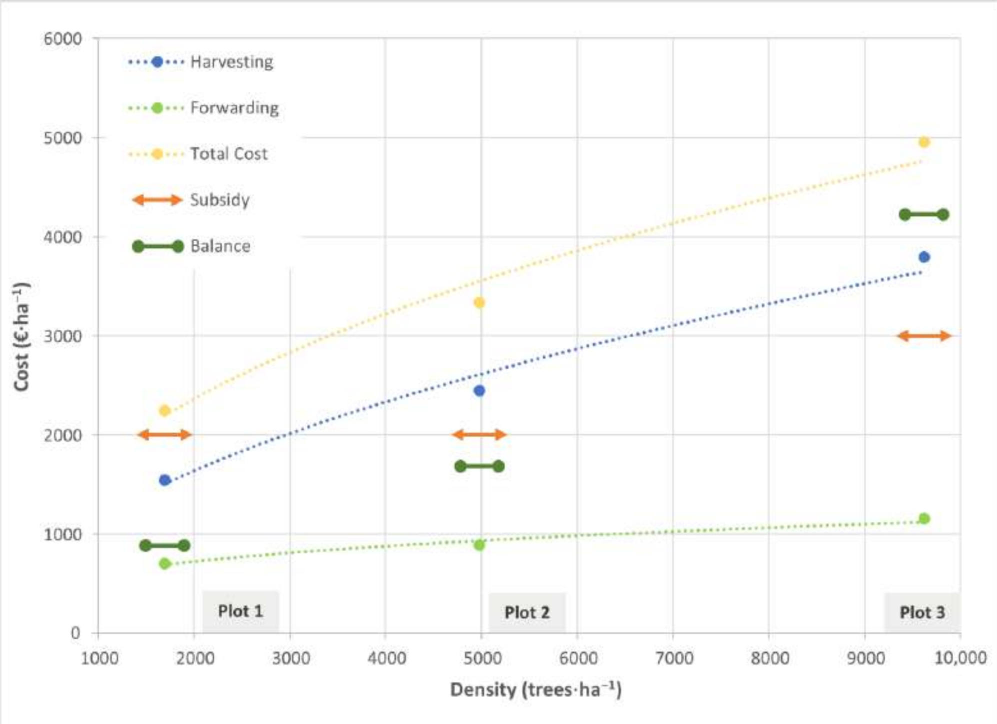


Figure 17: Sensitiveness analysis of costs as function of tree density. The green mark represents the economic balance for each plot, including the positive value of the biomass: being negative it is still a cost. The orange mark indicates the public subsidy granted according to the specific characteristics of each plot, despite being an income it is shown among the costs to visualize the share of costs covered by subsidies and the remaining costs as a difference. Green, blue and yellow dotted lines represent the trend of forwarding, harvesting and total operational costs respectively.

In Plot 2, although the biomass value per hectare was higher, overall productivity was lower, and costs were roughly double those of Plot 1. Still, the total cost was within 75% of the available subsidy, making the intervention economically viable under the current support scheme.

In contrast, Plot 3 showed both higher total costs and a negative balance, exceeding the financial support available. In this case, the cost of forwarding alone surpassed the value of the harvested biomass, making this phase of the operation economically unsustainable.

Comparison between the two systems

As can be seen in Table 11, the innovative work system has a lower cost per area compared to the traditional method in all three plots. When subsidies are taken into account, the innovative method results in a positive value for plots 1 and 2, while the traditional method remains negative in all three plots. The percentage increase compared to the traditional method is very high for plots 1 and 2 (163% and 150%), and it remains advantageous in plot 3 (19%). Although the innovative system does not lead to an absolute positive balance, as in plot 3 where there is still a loss, it is interesting to note that companies responsible for preventive forestry operations against wildfires can manage areas with a negative balance if they are offset by those with a positive balance.

Table 11: Comparison between the two work systems.

	Plot 1		Plot 2		Plot 3	
System	Traditional	Innovative	Traditional	Innovative	Traditional	Innovative
Cost per area* (€·ha-1)	>4000	741	3000	1501	4409	4142
Subsidy (€·ha-1)	2000	2000	2000	2000	3000	3000
Difference between cost and subsidy (€·ha-1)	-2000	+1259	-1000	+499	-1409	-1142
Improvement over the traditional method (%)	0	163	0	150	0	19

*Considering the biomass value.

Harvesting productivity

As shown by the scatter plots (Figure 18, Figure 19, Figure 20), there is a strong correlation between harvesting productivity (measured in m^3 per PMH_{15}) and stem volume (m^3) across all three plots. This suggests that stem volume is a reliable predictor of the system's productivity. Notably, Plot 1, which featured the lowest tree density, achieved significantly higher productivity per hectare compared to the denser plots. However, this plot also exhibited greater variability, likely due to the heterogeneous structure of the stand.

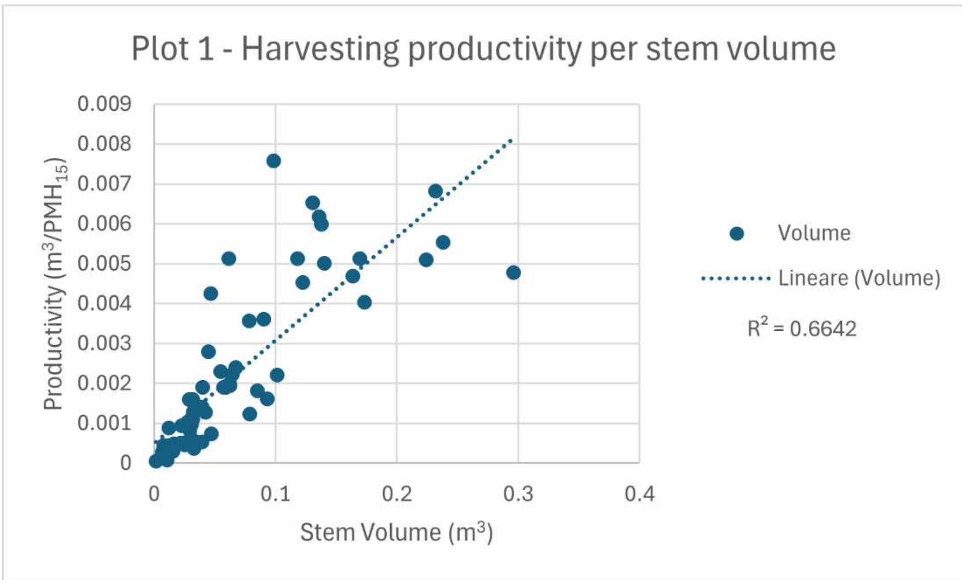


Figure 18: Harvesting productivity (felling and processing) per stem volume in Plot 1.

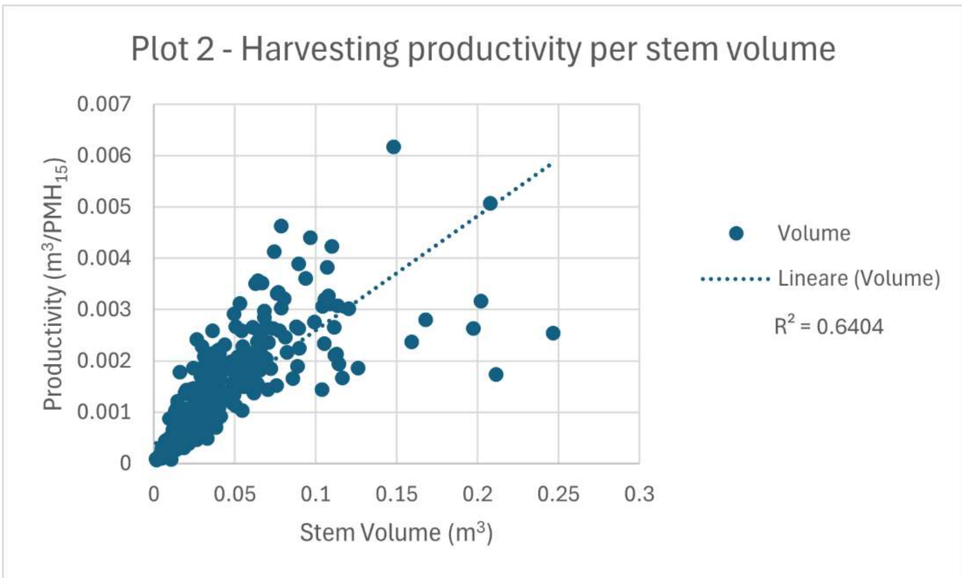


Figure 19:Harvesting productivity (felling and processing) per stem volume in Plot 2.

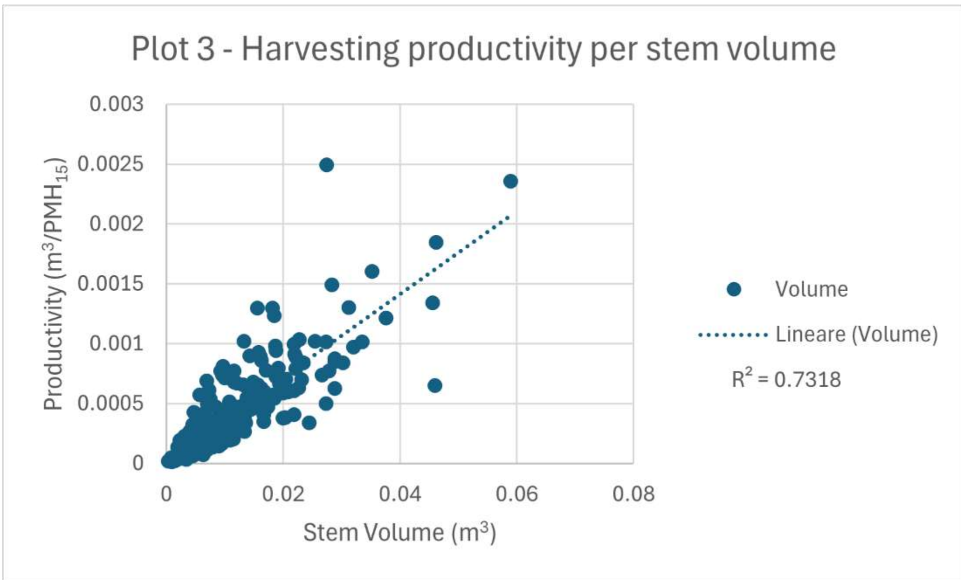


Figure 20: Harvesting productivity (felling and processing) per stem volume in Plot 3.

The average harvesting productivity values were:

- 2.93 m³·PMH15−1 for Plot 1,
- 2.24 m³·PMH15−1 for Plot 2, and
- 0.64 m³·PMH15−1 for Plot 3.

Currently, there are no directly comparable studies using similar lightweight equipment in wildfire prevention operations. The closest available references are from thinning trials in plantation forests, which are generally more homogeneous and present more favorable working conditions. In those cases, reported productivity reaches up to 4.5 m³·PMH15−1 (Mederski, 2006; Moskalik et al. 2017; Mederski et al. 2018), nearly double the highest value observed in this study. The discrepancy is largely attributable to the challenging post-fire vegetation encountered here, characterized by high stem density, the presence of climbing plants, and the need for selective and cautious tree removal. These operations are primarily aimed at wildfire prevention - rather than timber production - and must ensure that understory fuel is effectively controlled without triggering regrowth through excessive disturbance.

The average forwarding productivity values were:

- 6.43 m³·PMH15$^{−1}$ for Plot 1,
- 6.17 m³·PMH15$^{−1}$ for Plot 2, and
- 2.09 m³·PMH15$^{−1}$ for Plot 3.

As for the Malwa 560 C forwarder, its productivity is understandably lower than that of larger, industrial-class forwarders (Lazdiņš et al. 2016, Eriksson et al. 2014, Williams et al. 2016). However, its performance is in line with that of other compact and lightweight equipment (Ackerman et al. 2021, Spinelli and Magagnotti, 2010) and is consistent with the machine's design for small-scale, sensitive, or fragmented forest operations.

4.2.3 Living Lab Tuscany

Monticiano. The study was carried out in Monticiano (SI), Italy, within a dense forest dominated by maritime pine (*Pinus pinaster* Aiton). The understory vegetation was primarily composed of strawberry tree (*Arbutus unedo*) and tree heath (*Erica arborea*). Key characteristics of the forest stand are summarized in Table .

Table 12: Inventory of the Monticiano stand.

Species	*Pinus pinaster Aiton*
Density (trees·ha^{-1})	1974
Mean DBH (cm)	17
Basal Area (m^2·ha^{-1})	44.80
Mean height (m)	12.3
Surface treated (m^2)	7235

Silvicultural requirements

The silvicultural objective was to establish a 50-meter-wide fuelbreak along a forest road by removing all coniferous biomass while preserving the most vigorous broadleaved trees, aiming to maintain a density of 60 broadleaved trees per hectare. Shrubs and branches were to be mulched on site to further reduce wildfire risk. Research supports this mixed-forest management approach, emphasizing the retention of broadleaved species in fire-prone areas to reduce wildfire severity and enhance ecosystem resilience. In particular, Kent et al. have demonstrated that mechanical fuel treatments, including biomass removal and mulching, can significantly mitigate wildfire intensity and improve ecological outcomes (Yocom Kent et al. 2015).

Value Recovery

The local market offers limited demand for pine-based products, with biomass being the only accepted output. In most preventive silvicultural interventions, coarse woody material is typically left on the ground, and only larger-diameter logs are occasionally extracted. This is largely due to the high extraction costs using current systems, which are not offset by the low market value of the material, combined with the relatively low wildfire risk posed by the remaining stems. As a result, the typical product of such interventions consists of small-diameter logs, suitable only for biomass use. The market value for this material in the region is approximately €10 per cubic meter.

Technical and Social Requirements

This type of forest management is intended not only to reduce wildfire risk but also to ensure safe access for firefighting crews. Although these operations are often publicly funded, they are sometimes avoided or delayed by landowners who are concerned about diminishing the visual or ecological value of their forests. Striking a balance between fire prevention and landowner interests is therefore essential. In Tuscany, forest ownership is highly fragmented, especially in peri-urban zones areas that also face the highest wildfire risk. This fragmentation calls for a highly mobile, cost-effective work system. A versatile, multifunctional solution capable of handling multiple tasks (e.g., felling, extraction, mulching) is particularly valuable in this context.

Figure 21: The lightweight, multifunctional tracked harvester chosen for the fuelbreak management in Tuscany, equipped with the processor (left) and the mulcher (right).

Work System Selection

The study evaluated the performance of the Konrad KDH, a lightweight, multifunctional tracked harvester designed for felling, extraction, and mulching in Mediterranean forests prone to wildfire. The goal was to compare the cost-effectiveness and productivity of this system with traditional methods, which largely rely on manual labor. The chosen machine (Figure 21) was an innovative self-leveling harvester equipped to perform three key functions: felling trees, extracting them using a shovel-logging approach, and mulching shrubs and branches. Its compact design enhances maneuverability and reduces relocation costs. In harvesting mode, the machine is fitted with a Woody 40 processor, which can fell, delimb, and process stems. The processor head can also act as a grapple for hauling, making it a truly flexible and efficient tool for preventive silviculture.

Traditional work system

The work system described above was compared with the current operational approach used by the Unione dei Comuni Val di Merse, the authority responsible for wildfire prevention in the area. At present, the organization deploys a team of 4 workers, including two skilled operators. One operates two excavators equipped with a grapple for log extraction and a mulcher for shrubs and branches, while another drives a tractor-mounted mulcher. The remaining two workers handle tree felling using chainsaws.

Economic balance and comparison between the two systems

The cost analysis was based solely on the labor time required to open one hectare of fuelbreak. As shown in Table 13, the mechanized system using the harvester resulted in a 36% lower cost compared to the traditional method. When factoring in the revenue from biomass, the economic balance of the traditional system drops to 50% of that of the harvester-only approach. This substantial advantage is mainly due to the efficiency of having a single operator perform all tasks, which in the traditional system requires a team and three different machines, significantly driving up hourly costs.

Moreover, transport and relocation costs are considerably lower for the harvester, thanks to its compact size and ease of mobility. Another important advantage of the harvester is its ability to carry out felling operations in virtually any weather condition, whereas chainsaw operators are often hindered by adverse weather, reducing their working time and efficiency.

Table 13: Economic results of the comparison between the two work methods in Tuscany.

Innovative system	
Cost per PMH15 (€·PMH_{15}^{-1})	96.36
Costs Harvesting (€·ha^{-1})	2781
Cost Mulching (€·ha^{-1})	1307
Total Costs (€·ha^{-1})	4087
Value biomass (€·ha^{-1})	1768
Economic balance (€·ha^{-1})	-2319
Traditional system	
Cost Harvesting (€·ha^{-1})	3229
Cost Mulching (€·ha^{-1})	3177
Total Costs (€·ha^{-1})	6406
Value biomass (€·ha^{-1})	1768
Economic balance (€·ha^{-1})	-4638
Difference (%)	**50%**

Study and Demo Execution

As integration of D.2.2, this study evaluated the use of lightweight machinery for fuelbreak management in Mediterranean forests, comparing an innovative mechanized approach with traditional, labor-intensive methods. The primary objective was to create an effective fuelbreak by reducing combustible biomass and improving accessibility for firefighting crews. The use of a compact harvester capable of felling, hauling, and mulching offered greater operational flexibility and minimized relocation costs, an ideal solution for areas with small, fragmented forest ownership.

The results showed that mechanization could reduce the cost of preventive silvicultural treatments by up to 50% compared to conventional manual systems. The harvester achieved a mean productivity of 12.02 m^3 per productive machine hour (PMH_{15}) in felling and processing operations, which outperforms figures commonly cited in literature. For comparison, studies on thinning in forest plantations, typically under more favorable working conditions, report average productivities below the value reported. This difference is largely attributed to the characteristics of the fuelbreak intervention, which required the complete removal of conifers, allowing for more efficient operations.

However, despite these advantages, the economic sustainability of mechanized thinning remains influenced by the low market value of extracted wood, which limits potential revenue.

Figure 22: public demonstration of the work system.

A public demonstration (Figure 22) of the system was organized, attracting technicians from local public authorities, as well as high school and university students. The event generated significant interest, especially regarding the versatility of the machine, which performed three key functions:

1. As a harvester, it felled, processed, and delimbed trees.
2. With the multifunctional head processor, it transported the timber to the roadside.
3. As a mulcher, it shredded shrubs and branches, facilitating access for firefighters and creating a vegetation-free buffer between the road and the forest, critical for safe firefighting operations during wildfires.

Date of public demonstration	25th October 2024
Number of attendances	31

4.3 Conclusions

The testing applied demonstrate that lightweight, multifunctional machinery, such as the Malwa 560C or the Konrad KDH, can offer a viable and cost-effective alternative to traditional manual systems for wildfire prevention in Mediterranean forests. In Catalonia the harvesting productivity was closely linked to stem volume, confirming that stand characteristics significantly influence operational efficiency. In particular, lower-density plots like Plot 1 allowed for higher productivity per hectare, albeit with increased variability due to the uneven stand structure. Although productivity values were lower than those reported in thinning trials of plantation forests, this is expected given the complexity of post-fire environments, the presence of climbing vegetation, and the ecological care required in fuelbreak management. The goal of reducing wildfire risk, rather than maximizing wood production, naturally leads to a more cautious and less aggressive harvesting approach.

Furthermore, while the Malwa 560C does not match the output of larger machines in pure forwarding performance, it proves well-suited to fragmented and steep terrain, where mobility, low environmental impact, and versatility are key advantages.

The ability of a single operator to perform multiple functions (felling, processing, forwarding, and mulching) offers substantial savings in labor and transport costs, helping offset the limitations in per-hour productivity, as highlighted in the study in Tuscany. Notably, findings also indicated that mechanized operations have the potential to cut the costs of preventive silvicultural treatments by as much as 45% when compared with conventional manual methods.

Overall, these studies reinforce the strategic role of adaptable mechanized solutions in modern forest management for fire prevention. By aligning operational practices with ecological goals and economic constraints, such systems represent a promising direction for future silvicultural treatments, especially in regions with fragmented ownership and high wildfire risk.

4.4 References

Ackerman, S.A.; McDermid, H.; Ackerman, P.; Terblanche, M. The Effectiveness of a Small-Scale Combination Harvester/Forwarder in Industrial Plantation First Thinning Operations. Int. J. For. Eng. 2021, 33, 56–65.

Bigot, M.; Ruch, P.; Cacot, E.; Bouvet, A.; Ulrich, E.; Pischedda, D. Test of Mechanized Logging Systems in First Thinnings of Oak and Beech Stands. In Proceedings of the FORMEC 2012: Forest Engineering-Concern, Knowledge and Accountability in Today's Environment, Dubrovnik, Croatie, 8–12 October 2012.

Codd, J.; Nieuwenhuis, M. A Feasibility Study on the Performance of a Harwarder in the Thinning of Small Scale Forests in Ireland. Ir. For. 2008, 65. Available online: https://journal.societyofirishforesters.ie/index.php/forestry/article/view/10008 (accessed on 8 April 2025).

Yocom Kent, L.L.; Shive, K.L.; Strom, B.A.; Sieg, C.H.; Hunter, M.E.; Stevens-Rumann, C.S.; Fulé, P.Z. Interactions of Fuel Treatments, Wildfire Severity, and Carbon Dynamics in Dry Conifer Forests. For Ecol Manage 2015, 349, 66–72.

Mederski, P.S. A Comparison of Harvesting Productivity and Costs in Thinning Operations with and without Midfield. For. Ecol. Manag. 2006, 224, 286–296.

Moskalik, T.; Borz, A.; Dvořák, J.; Ferencik, M.; Glushkov, S.; Muiste, P.; Lazdiņš, A.; Styranivsky, O. Timber Harvesting Methods in Eastern European Countries: A Review. J. Theory Appl. For. Eng. 2017, 38, 231–241

Mederski, P.S.; Venanzi, R.; Bembenek, M.; Karaszewski, Z.; Rosińska, M.; Pilarek, Z.; Luchenti, I.; Surus, M. Designing Thinning Operations in 2nd Age Class Pine Stands-Economic and Environmental Implications. Forests 2018, 9, 335.

Lazdiņš, A.; Kaleja, S.; Daugaviete, M.; Zimelis, A. Productivity of Vimek 404 T5 Harvester and Vimek 610 Forwarder in Early Thinning. Agron. Res. 2016, 14, 475.

Eriksson, M.; Lindroos, O. Productivity of Harvesters and Forwarders in CTL Operations in Northern Sweden Based on Large Follow-up Datasets. Int. J. For. Eng. 2014, 25, 179–200.

Williams, C.; Ackerman, P. Cost-Productivity Analysis of South African Pine Sawtimber Mechanised Cut-to-Length Harvesting. South. For. A J. For. Sci. 2016, 78, 267–274.

Spinelli, R.; Magagnotti, N. Performance and Cost of a New Mini-Forwarder for Use in Thinning Operations. J. For. Res. 2010, 15, 358–364.

5 Enhancing fire-resilience in value chains: concepts, methods, strategies

5.1 Rationale and Objective

Climate change and biotic risks generate an increased uncertainty on the availability and characteristics of wood world-wide, causing unforeseen and profound disruptions along forest-based supply chains. Droughts, winds, leading to infestations and wildfires, can result in large amounts of salvage logging that must be processed quickly to avoid decay. At the same time, operational capacity may be temporarily reduced. Environmental impacts must be carefully mitigated. Resilience has become a key focus in forest research and management, driven by the need to develop solutions to address increasing uncertainty and unpredictability. However, resilience is still a difficult concept to define, and although numerous approaches can be found in the literature, there is no common agreement on its definition and application in forestry and forest sector. Hence, the objetives of this study undertaken by CoLAB ForestWISE are as follows :

1) Develop a holistic conceptual framework for forest-value chain resilience, informed by socio-ecological and value chain literature, to guide the practical implementation of resilience enhancement strategies by forest planners
2) Develop a methodology to enhance resilience of forest-based value chains towards wildfires. The methodology uses a systems perspective to model the value chain and mathematical programming to optimize its configuration—capacity and stock levels—to account for the likely effects of wildfires, including increased wood availability and operational restrictions.
3) Test the proposed methodology in a case study in Portugal (FIRE-RES Living Lab Vale do Sousa).

5.2 Conceptual framework: towards a resilience definition and its operational application in forestry and forest sector

The conceptual framework resultant from the literature review, and presented in the IUFRO 2024 world congress[1], define five main dimensions to characterize resilience of a system:

What is? Following the socio-ecological perspective, resilience is defined as the capacity (of a system) to deal with a disturbance caused by an (natural) hazard. It implies: *i)* Prevent (i.e. avoid disturbance, reduce impacts) *; ii)* Respond during hazard *; iii)* Recover to previous state (or evolve to next stable state)

[1] Marques AF, Gomes R, Fjeld D, Ronnqvist M, Póvoa A, Amorim P. Towards an innovative digital architecture for more resilient forest-based supply chains. IUFRO 2024. *Stockholm, 24/06/2024.*

Of what? forest systems, including trees, soil and forest ecosystem (ecological dimension); value chains (economical dimension); communities (social dimension). An holistic and integrated approach should take all into account.

To what? Drought, wind and other climate-change effects that can cause infestations and wildfires, depending on the regions:

How to measure it? with resilience metrics/indicators that measure how much resilience a system has. Depending on the context, can quantity ecological, economic, or social aspects of resilience, and have emerged from fields like ecology and economics. A multitude of quantitative methods can be applied to quantity resilience indicator, including, statistics, mathematic programming, simulation. Measuring resilience aims to detect change over time, hence the reference stage for the indicator must be established and compared with a future stage when the disturbance occur and/or a certain enhancement solution is implemented (Figure 23).

Some researchers differentiate measurement, which is quantitative, and resilience assessment, which employs qualitative, process-oriented approaches to understand system dynamics and identify the relevant indicators according to the perspectives of the stakeholders involved in the case studies.

How to enhance it? With resilience strategies that are management actions that can be implemented by the planners (in the system) to better prevent, and/or respond, and/or recover from a disturbance. These can also be referred in the literature as resilience predictors, in opposition to with co-drivers, which also influence resilience but are largely unmanageable (Lloret 2024).

Figure 23 Examples of resilience strategies taken from the literature

5.2.1 Aproach for resilience value chains anchored in a system's perspective

According to Porter (1985) a value chain "is a series of activities that create value at each step, with the total value being the sum of all contributions throughout the company." Forest-based value chains, specifically, involve the sequential transformation of wood and other forest resources into various products and services, from sourcing to consumer delivery and end-of-life management. Main activities include: Forest harvesting, storage and logistics, primary transformation (e.g. roundwood to wood-boards), secondary transformation (e.g. wood-boards to furniture), sales (e.g. D'Amours et al., 2017). The system-based representation models these activities, including the capacity and stock levels required to transform initial feedstock inputs into final products. This model informs supply chain planning, which aims to balance wood availability from harvesting sites with consumption at transformation centers along the value chains, while defining the optimal operational capacity and stocks that minimizes costs and material value loss.

Including uncertainty in these supply chain representations, implies understanding that wood availability is subject to seasonal restrictions and fluctuations (quantity & quality), intensified by climate-driven hazards e.g. wildfires. Following an event, such as wildfire, two primary consequences may arise: Supply Disturbances, which reduce the availability (and eventually quality) of feedstock, and Operational Disturbances, which directly impair a system's internal processes or infrastructure, leading to a reduction in processing capacity or efficiency. Wildfires create a 'supply disturbance' by generating large volumes of salvage logging that require rapid processing to prevent decay. Also, operational capacity may be temporarily reduced, causing an 'operational disturbance'. In the long term, frequent fire regimes can induce market changes, leading to a 'demand disturbance' that impacts upstream activities in the value chain.

5.2.2 Proposed methodology to enhance resilience of forest-based value chains towards wildfires

This research employs a methodological approach centered on value chain optimization to identify optimal configurations and performance levels under various scenarios of fire occurrence and the implementation of resilience strategies. These scenarios, generated by preparing specific input datasets for the optimization model, enable a comparative analysis that informs how resilient a value chain is, the effectiveness of the resilience strategies and guides practical managerial insights for forest planners. Similar to Weskamp et al. 2019 (see figure 2).

VALUE CHAIN OPTIMIZATION MODEL: The proposed methodology builds on a mathematical programming model that optimizes value chain configuration by establishing the optimal wood flows, from forests to transformation centers along the value chain, minimizing transportation costs while meeting demand or assuring the mobiliation of all harvested wood.

These mathematical programming models are commonly used to help reduce transportation costs, which can account for up to 30% of wood procurement expenses and significantly impact value chain efficiency (Audy et al. 2014). Once wood flows are established, the capacity needed to conduct operations that generate wood inflows and outflows becomes predictable, enabling effective resource allocation and stock management. FlowOpt: Decision Support Tool for Strategic and Tactical Transportation Planning in Forestry (Flisberg 2006), is one of the most used tools world-wide, and was used as a reference in this study. It allows transportation planning in a complex setting: e.g. with several alternative transportation modes (truck, and train), possibility to use terminals to intermediate stocking, combine several wood assortments, possibility of backhauling. It relies in a Linear Programming model and includes user friendly interfaces to visualize the model solutions over a map. The main variables are: x_ija $= amount\ of\ assortment\ a\ transported\ from\ location\ i\ to\ j$. The set of locations include all supply points (forest sites and terminals), demand points (terminals and transformation centers). A penalty variable can be used to penalize unfulfilled demand at transformation centers.

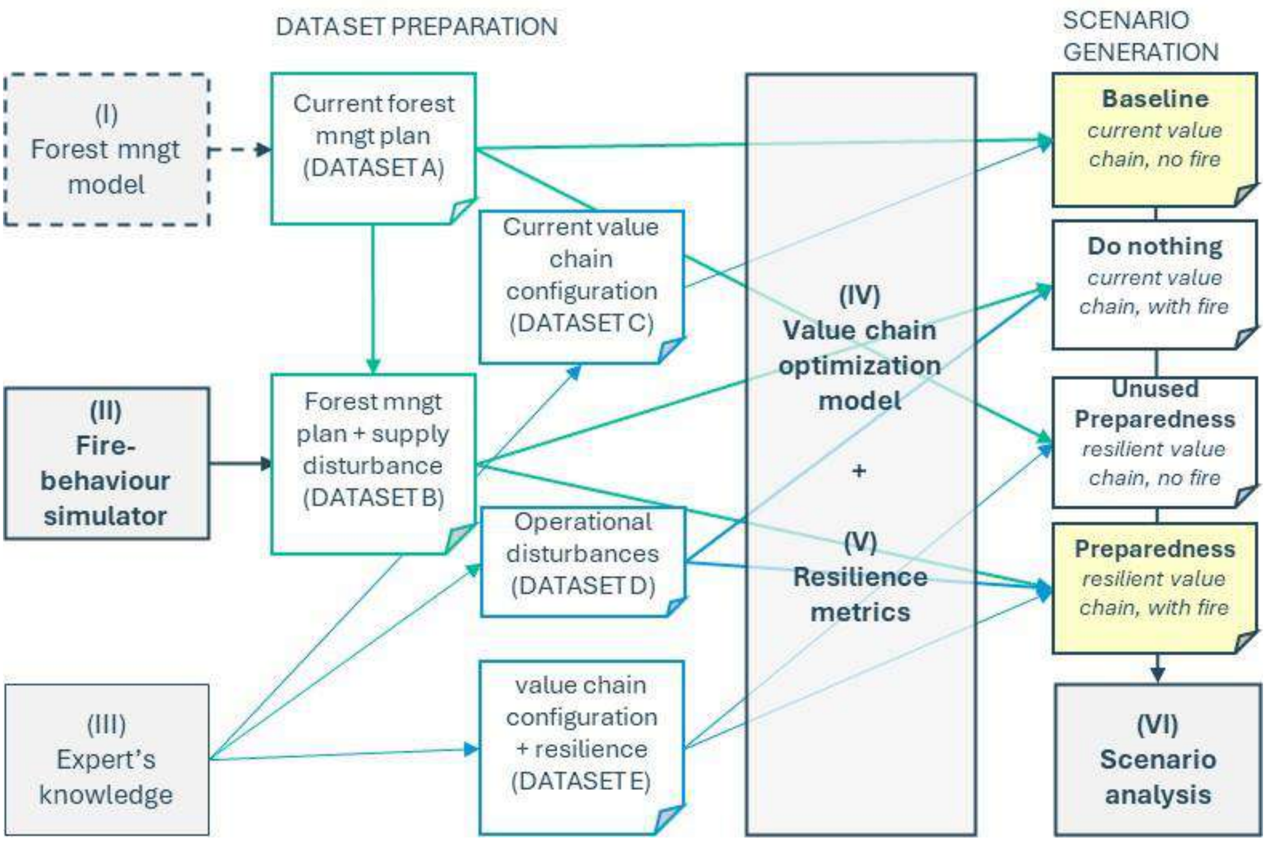


Figure 24 Proposed methodological approach

MODEL INPUT DATA: Datasets A to E are used in a series of scenarios (figure 24).

Current Forest Management Plan (Dataset A): comprises a list of all management units scheduled for harvesting in the next year, along with their area (ha) and expected standing volume (m3/ha). It represents the next-year output of a longer-term strategic forest planning model for the entire forest area, designed to schedule harvesting over a long planning horizon (decades), maximizing the forest's net present value.

Forest mngt plan + supply disturbance (DATASET B): comprises dataset A and adds the MUs projected to burn with high severity and, therefore, subject to salvage logging, regardless of its rotation age. Burn probability for each MU was estimated with a wildfire risk probability model calibrated for Eucalyptus globulus stands Botequim et al.(2013), using slope, aspect, stand age, height, stand density and distance to roads as predictors, combined with regional fuel type and climatic exposure. MUs with a simulated probability of burn ≥ 0.15 % were classified as affected ("1") in Dataset B1, representing a plausible disturbance under extreme weather conditions and supporting the testing of resilience strategies in the value-chain model. The complementary Dataset B1real integrates the observed fire events of 2024 and 2025 from the mapped perimeters

Current value chain configuration (DATASET C): comprises the transformation centers and intermediate stockyards along the value chain, including their location, demand, stock levels, and operational capacity. It also includes data on local harvesting and transportation contractors, which collectively define the harvesting and transportation capacity. This information is collected locally through interviews with key stakeholders, as well as from literature and expert knowledge.

Operational disturbances (Dataset D): builds on datasets C or E and updates operational capacity of the value chain agents to capture limitations imposed by the fire, such as forced shutdowns and delays. The information is based on expert knowledge and historical wildfire data in the region.

Value chain configuration + resilience (DATASET E): combines information on transformation centers and stockyards (DATASET C) with modifications resulting from the implementation of proposed resilience strategies. Examples include intermediate stockyards and/or expanded capacity and stocks implemented to manage potential wood flow surpluses after a fire. Adequate value chain resilience strategies are derived from literature and validated with local experts.

RESILIENCE METRICS: The comparison among different scenarios provides a valuable framework for assessing the resilience of the value chain, offering insights into its ability to respond to the consequences of fires. For example, a baseline scenario, configured to manage the planned harvest volume under normal conditions, can be contrasted with fire-affected scenarios and predict resulting supply and operational disturbances.

The following resilience metrics can be used to compare the post-fire situation against the baseline scenario (referred to as DoNothing) and to quantify the value chain's lack of response to the fire's consequences:

Supply Surplus: Indicates the amount of raw materials available beyond the planned harvest, corresponding to salvage logging.

Capacity Shortfall: Measures the amount of raw materials that cannot be processed due to reduced operational capacity.

Operational Impairment: Quantifies the decline in maximum processing efficiency or capacity resulting from damage or resource constraints.

Additional resilience metrics can be employed to evaluate the extra capacity and costs associated with a fire-prone value chain operating under conditions where no fire occurs ("unused preparedness" scenario):

Preventive Capacity surplus: reflects the amount of operational resources included in the fire-prone value chain that will remain unused if no fire occurs.

The interplay between these metrics, applied to each value chain operation is further reflected in global metrics such as Unused Raw Material Availability and Unsatisfied Demand. For example, high operational impairment can lead to increased unused raw materials, while a significant supply deficit results in greater unmet demand. Analyzing these interdependencies across various scenarios helps identify the primary bottlenecks limiting system resilience and guides targeted interventions to enhance robustness and adaptability in the face of fire-related disruptions.

SCENARIO GENERATION AND ANALYSIS:

Baseline scenario: This scenario optimizes the value chain configuration for the expected wood volume based on the current forest management plan, using DATASETS A and C as inputs for the optimization model.

Do nothing: This scenario assumes the baseline's optimal value chain configuration with operational disturbances and predicts its performance and resilience metrics if a fire occurs, using DATASETS B, C and D as inputs for the optimization model.

Preparedness: This scenario optimizes the value chain configuration with resilience strategies, that deal with the surplus of salvaged logging (supply disturbance) and operational disturbances resulting from the fire, using DATASETS B, D, and E.

Unused preparedness: This scenario assumes the optimal value chain configuration of the preparedness scenario and predicts its performance and resilience metrics without fire occurrence, using DATASETS A, and E.

5.2.3 Case study: Vale do Sousa (FIRE-RES Living Lab)

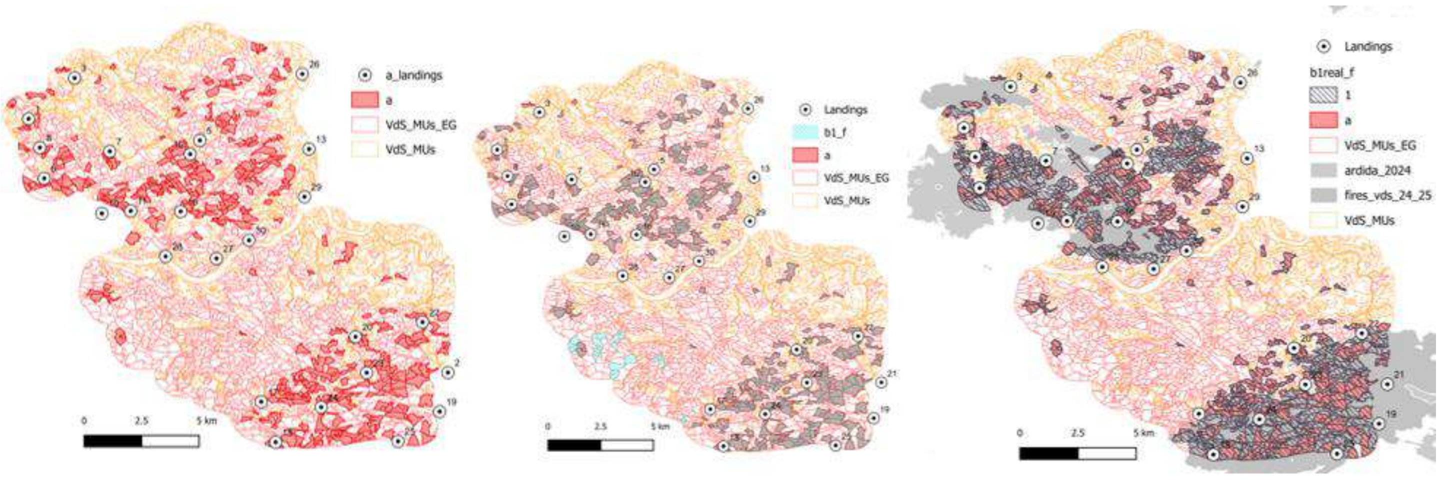
Located in Northwest Portugal, the Vale do Sousa region spans 28,942 hectares, comprising 3205 Management Units (MUs) within a rural area characterized by a Mediterranean climate with Atlantic influence. Ownership is highly fragmented among 360 forest owners, supported by the AFVS Forest Owner Association, which manages the ZIF (Zonality for Integrated Forest Management) Entre Douro e Sousa and Paiva. This ZIF is dominated by Eucalyptus globulus plantations, making up over 55% of the managed area and serving as the primary feedstock for the pulp industry, with smaller patches of Pinus pinaster, native oaks, and riparian species. The landscape is notably vulnerable to wildfires, with approximately 46% of the ZIF area having burned in the last seven years, indicating a recurrent fire regime. Significant fire events occurred in September 2024 and August 2025, consuming around 7,200 hectares of forest (roughly 25% of the total area) and impacting 743 management units within the Vale do Sousa landscape.

5.2.3.1 Data collection for the case study

Current Forest Management Plan (Dataset A): The 351 Management Units (MUs) of Eucalyptus globulus (EG) to be harvested in 2025 only considering Eucalyptus globulus (EG), extend over3628 ha, have between 10 to 12 yrs, and sum almost 253 thousand m3 (first year of the strategic schedule). These correspond to the first year of the forest strategic model applied in the region for a 40-year planning period, aiming to maximize the net present value (NPV) of forest production. Forest yield and growth were computed with the GLOBULUS model (Tomé et al., 2006; Barreiro et al.,2016), which integrates site index, stand density, and rotation length to estimate annual increment and expected harvest volumes for each MU.

Forest mngt plan + supply disturbance [DATASET B] - B1 (fire simulation): According to fire simulation, only 58 MUs of EG have a probability equal or higher than 0.15% of being burnt. Of these, 33 are at the end of the rotation was were selected for harvesting. The other 25 are younger stands or reserved for protection purposes, whose harvest needs to be harvested to avoid decay. The total volume planned for harvest, including both unburned and burned wood, matches that in DATASET A. However, their applications differ: experts agree that burnt wood is generally unsuitable for sawmilling. A small portion, estimated at 40%, may still be suitable for pulpwood, with the main use being bioenergy. Total volume to be harvested: is approximately 284 thousand m^3, representing an increase of over 4.3% compared to the initial harvest plan, of which about 33 thousand m3 are salvage logging. Harvested areas grew by 7%. Pulpwood volume decreased only 1.4%, totaling 201 thousand m^3, with 17% in MUs with Ddom >15 cm and the remaining in Ddom class]10,15]. Sawlogs volume obtained only in the fraction of the planned harvested areas not burned, decreased by 8%, totaling 11 thousand m^3.

Forest mngt plan + supply disturbance [DATASET B - B1real] areas brunt in the fires of 2024 and 2025: The area was affected by wildfires in September 2024 and August 2025. The burnt area is known, allowing for the identification of affected MUs and comparison with fire simulation results. A total of 743 MUs were affected by fire, of which 128have less than 80% of the area affected, and 615 show greater impact. The 80 % threshold is applied to classify a MU as burnt (=1); below that, the MU is only partially affected. This distinction allows a realistic estimation of salvage logging needs and prevents over-counting of lightly scorched stands. This threshold is based on expert opinions, indicating that if only a small proportion of trees are burned, the whole stand doesn't need harvesting. Total volume to be harvested is approximately 568 thousand m³, representing an increase of over 108% compared to the initial harvest plan, of which about 451 thousand m3 are salvage logging. Harvested areas grew by 99.5%. Fire occurrence had a much greater impact than the predicted with the fire simulation. Distribution of volume per classes of wood use: Very high increase in biomass for bioenergy (more 482%), totaling 324 thousand m³, with 23% in Ddom ≤10 cm, 69% in]10,15], and 8% in Ddom >15 cm.Pulpwood volume decreased by 15.4%, totaling 236 thousand m³, with 15% in MUs with Ddom >15 cm and the remaining in Ddom class]10,15]. Sawlogs volume obtained only in the fraction of the planned harvested areas not burned, decreased by 32.5%, totaling 8 thousand m³. Distribution of volume by age classes: shows that most of the harvest is in the 8 to 10-year age class. As expected, the harvest plan (A) only includes MUs older than 10 years. The wildfire probability model (B1) also indicates older stands, but fire occurrence can affect all age classes (B1real) (figure 25).



Dataset A		-> monthly
N. MUs	351	~29
N. landings	25	~2
Total Harvested volume (m³)	272229.1	22685.8
sawlogs:	11957.5	996.5
pulwood:	204565.5	17047.1
biomass:	55706.1	4642.2

Dataset B1		-> monthly
N. Mus	376	~31
N. landings	25	~2
Total Harvested volume (m³)	283997.0	23666.4
sawlogs:	11000.0	916.7
pulwood:	201633.8	16802.8
biomass:	71363.2	5946.9

Dataset B1real		-> montlhy
N. Mus	752	63
N. landings	25	~2
Total Harvested volume (m³)	568289.6	47357.5
sawlogs:	8075.7	673.0
pulwood:	236030.4	19669.2
biomass:	324183.6	27015.3

Figure 25 Geographical representation of the datasets used in this study

Current value chain configuration [DATASET C]: 14 transformation centres and 6 intermediate stockyards were identified in a survey conducted through consultation with industry experts in the region. The location and characteristics of the material received were identified (Fig. 3), but for confidentiality reasons, only fictitious names and approximate locations were used. Sawlogs (logs with larger dimensions) go to 1 sawmill. Pulpwood (logs with smaller dimensions), and forest residues (branches, leaves, etc), go to 5 pulp mils with co-generation, or to 7 regional biomass centrals, or 1 pellet factory. In rare cases, pulpwood may be chipped at the roadside and transported to the same destinations. Sawlogs and pulpwood can be delivered to 2 intermediate log stockyards, where they may be left to dry before being transported to transformation centres. There are 4 woodchips and logs stockyards, associated to the pulp and paper mils. Due to the lack of information from the survey, indirect methods were used to estimate the storage capacity, demand and price. Regional harvesting and transportation capacity data were unavailable due to limited information on service providers. Instead, capacity was estimated based on the total volume to be explored and industry expert consultations, assuming no shortage of service providers in or near the region. Financial information is sensitive and not disclosed by the agents; therefore, it had to be estimated based on assumptions defined in collaboration with experts and supported by a review of the relevant literature.

Operational disturbances [DATASET D]: Out of the 47 value Chain agents, 18 were partially affected by fire, corresponding to a 50% activity reduction during the fire month and the following two, including 1 pulp mill, 1 biomass plants, 4 stockyards, 9 harvesting companies, and 1 transport operator, all located in or near burned areas. 6 agents were fully affected (no activity for 3 months), including 2 stockyards, 2 bioenergy plants, 1 sawmill, 3 stockyards, and 1 harvesting company. Furthermore, according to the experts mandatory fire risk legislation prohibited forest operations 1.5 days per week over the three summer months, impacting all harvesting service providers. This reduction of wood inflow will impact indirectly in the transportation needed, although no transportation company was directly affected by the fires. Consequently, total storage capacity at the stockyards was reduced by 17%, at sawmills by 25%, at biomass plants by 16%, and at pulp mills by 2.5%. Harvesting operational capacity decreased at least 8%% due to legislation prohibitions, while transportation was not directly affected.

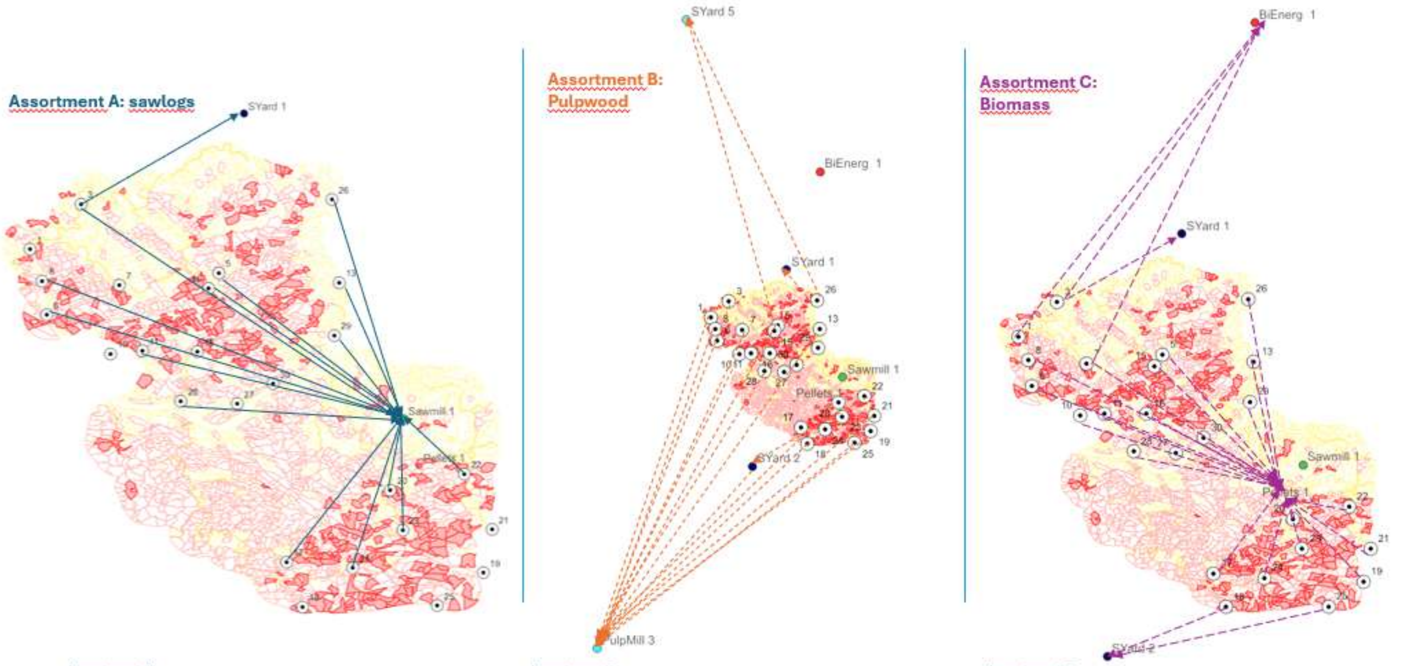
Value chain configuration + resilience [Dataset E]: The analysis of wood flows helped to identify bottlenecks related with insufficient operational capacity or stocks. Once, an resilience strategy is overcome these bottlenecks with specific adjustments, such as increasing the number of harvesting and/or transportation companies involved. Another possibility is to increase stockyards capacity or add new stockyards. Intermediate stockyards are considered an effective resilience measure in the literature. These can be temporarily opened and closed as needed, facilitating quick mobilization of wood from the burnt areas. Effective resilience strategies can be proposed after analysing the results first scenarios (Baseline and DoNothing).

5.2.3.2 Model development for the case study

A new model formulation was created, adapting the FlowOpt commonly used for planning harvesting, transportation and intermediate storage. The objective is minimizing all operational costs (harvesting, transportation & storage). Main decision variables relate with then harvesting occur at the management unit and the wood flows between the management units and the transformation centre or stockyards, and from the stockyards to the transformation centres. Auxiliary variables set the amount of demand unsatisfied and the number of harvesting and transportation companies needed. All decision variables are continuous, which helps to provide an optimal solution in shorter computational times. The model is applied during 1 year, corresponding to 4 trimesters. Fire occur typically in the 3rd trimester. Main constraints include: (I) Total Harvest: Each Management Unit must be fully harvested over all periods; (II) Harvest Continuity: If the harvest of a Management Unit begins in a period, it must continue in the following (or preceding) period until fully harvested; (III) Flow Balance (Management Units): The total amount of each assortment leaving a Management Unit in a period must equal the available volume harvested in that period; (IV) Flow Balance (Stockyards): The inventory at the end of each period is equal to the initial inventory (or previous period's inventory) plus what enters minus what leaves the stockyard; (V) Storage Capacity: The inventory at each stockyard cannot exceed the maximum capacity; (VI) Demand (with Penalty): The total amount of each assortment arriving at a transformation centre in a period, plus the slack, must equal the demand; (VII) and (VIII) Harvest and Transportation Capacity: The total amount produced and transported each period cannot exceed the maximum available capacity of the companies involved; Non-Negativity: All decision variables must be continuous non-negative. The computational model was implemented in Python and solved using the PuLP library with the CBC solver.

5.2.3.4. Results analysis and managerial insights

BASELINE: The optimization model for Vale do Sousa indicates that all 272 thousand m^3 of available wood are harvested across four periods, requiring 5 medium harvesting companies in each period for a total cost of €891 thousand. Log transportation costs €1.152 million, utilizing 3-4 companies per period, while biomass transport costs €162 thousand, requiring one company operating at full capacity in periods 3 and 4. Stockyards SY1, SY2 (for B), and SY5 (for B) reach full capacity by period 4, highlighting storage as a bottleneck. Despite this, some demands remain unsatisfied: the sawmill receives 61% of its demand, PM3 70%, and BC1 98%, while BC8's demand is fully met. Other transformation centers receive no supply. Overall, harvesting capacity is 5% underutilized, log transport 11%, biomass transport 12%, log storage 70%, and biomass storage 89%.



Assortment A:

Total flows (m³):	11957,6	
. forest to stockyard	18	(SY1)
. forest to transf. centre	11939,6	(SM1)
. stockyard to transf. centre	0,0	

Assortment B:

Total flows (m³):	214409,7	
. forest to stockyard	40374,0	(SY1, SY2, SY5)
. forest to transf. centre	164191,7	(PM3)
. stockyard to transf. centre	9844,0	(SY2->PM3)

Assortment C:

Total flows (m³):	55706,16	
. forest to stockyard	3528,6	(SY1, SY2)
. forest to transf. centre	52177,6	(BC1, BC8)
. stockyard to transf. centre	0,0	

Figure 26 Wood flows along the value chain according to the baseline scenario

RESILIENCE ASSESSMENT: DONOTHING SCENARIO (WITH B1): With fire simulation (B1), the total harvest volume is approximately 284,000 m^3, representing a 4.3% supply surplus over the baseline, primarily by shifting wood use towards biomass. This analysis utilized the baseline's maximum harvesting, transport, and storage capacities. Due to operational disturbances, harvesting capacity, initially 285,720 m^3/yr (five companies per period, averaging 14286 m^3/period), was reduced by 23.3% to 219,290 m^3/yr during fire season stops, resulting in a 22.8% shortfall where available raw materials cannot be harvested. Transport capacity, 242,872 m^3/yr for logs (3 companies in periods 1&2, 4 in periods 3&4, averaging 17348 m^3/period) and 15,840 m^3/yr for biomass (1 company per period), was assumed unaffected by fire. However, increased biomass flows led to an 11.2% transport capacity shortfall. Storage capacity (30,548 m^3 for logs, 3,529 m^3 for biomass across stockyards 1, 2, and 5) was reduced by 19% due to two stockyards closing for three months. Despite this operational impairment, the remaining storage capacity far exceeded usage, thus experiencing no capacity shortfall. The resilience assessment concludes that the baseline value chain configuration is not resilient to the consequences of the B1 fire simulation and foreseen operational disturbances, leading to a 22.8% unavailability of raw materials, which represents the primary bottleneck. Specifically, the lowest capacity shortfall is in harvesting, followed by biomass transport. Managerial insights thus indicate a critical need to increase both harvesting and biomass transport capacities to mitigate this unused availability, with no immediate necessity to alter storage capacity.

RESILIENCE ASSESSMENT: PREPAREDNESS SCENARIO (WITH B1): The optimal value chain configuration for B1 supply data and operational disturbances was determined by running the flow model, incorporating necessary resilience strategies that increased harvesting and biomass transportation capacity. Namely, the number of companies in periods 1 and 2 was maintained at baseline levels but allowed to increase in subsequent periods to manage the supply surplus. Results show that all available raw materials are processed through optimized harvest, transportation, and storage activities. The optimal solution requires one additional harvesting company, two extra log transporters, and one more biomass transporter per period. This configuration leads to demand satisfaction levels exceeding baseline, further supported by the inclusion of two additional biomass centrals utilizing the biomass supply surplus. A slight increase in sawlog supply to SM1 and pulpwood to PM3 was also observed. Overall, this optimized solution results in an 18% increase in total costs compared to the baseline. Managerial insights highlight that harvesting remains the primary bottleneck due to its limited buffer capacity, whereas transportation operates with a larger buffer. Storage capacity is currently underutilized because these stockyards serve beyond the Vale do Sousa region, making additional stockyards irrelevant. However, increasing storage capacity at SY1 and SY2, which are reaching full capacity for pulpwood, could be beneficial.

RESILIENCE ASSESSMENT: PREPAREDNESS UNUSED (WITH B1): Comparing the B1 (fire simulated) value chain with baseline supply data using the new fire-resilient configuration reveals the capacity surplus that becomes available but remains unused if the initial, fire-free plan proceeds. This also allows for assessing increased operational costs and unmet demand. Results show that harvesting capacity is 283,577 m^3, with a 7.8% "preventive capacity" buffer for fire events. Log and biomass transportation capacities are 357,803 m^3 and 118,834 m^3 respectively, representing substantial surpluses of 39% and 53%, indicating significant overcapacity under baseline conditions. Storage capacities also far exceed requirements, providing additional resilience buffers. Overall, while this increased preventive capacity incurs an approximate 17.6% rise in operational costs compared to the baseline, it offers the potential to deliver over 6% more logs and 33% more biomass to transformation centers, drastically reducing unmet demand by more than 50%.

Similar analysis were conducted with the B1real dataset of observed fire. The "DoNothing" scenario, revealing a harvested volume of 568 thousand m^3, over 100% more than the baseline. However, harvesting capacity is severely impacted by operational disturbances, with a 23.3% reduction from baseline and a 61.4% shortfall against the required volume. Log transport capacity faces a 3% shortfall, while biomass transport has over 90% shortfall due to increased biomass volume. Storage capacity remains abundant despite potential shifts to transformation centers. This indicates the baseline value chain is highly unresilient to such fire events, with over 60% of raw materials unutilized, primarily due to bottlenecks in harvesting, followed by biomass and log transport.

The "Preparedness scenario" optimizes the value chain to manage observed fire supply and operational disturbances. Key findings indicate a substantial increase in operational requirements: the number of harvesting companies doubles from five to ten per period, and biomass transport companies increase from two to eleven. While log transport companies remain consistent, storage shifts from three to four stockyards (SY1, SY2, SY3, SY4), though SY2, SY3, and SY4 operate at low capacities (14% and 11% respectively), and SY1 is emptied by year-end. Biomass demand satisfaction significantly exceeds baseline, now including five biomass centrals (BC1, BC2, BC6, BC7, BC8). Conversely, SM1, PM3, and PM1 receive less supply than baseline, despite a slight increase in pulpwood availability. Managerial insights suggest that the supply surplus effectively doubles the harvest plan, necessitating twice the harvesting and nearly double the biomass transportation capacity. No storage restrictions imply that existing capacity, even with four stockyards, is sufficient, though considering larger harvesting companies (7,143 m^3/month vs. baseline's 4,762 m^3/month) is advisable.

The "Preparedness unused scenario" assesses the performance of the value chain set for B1real but in a no fire situation. Harvesting shows a preventive capacity of 571,440 m3 (double the baseline), suggesting a need for strategic early hiring of harvesting companies. Log and biomass transportation capacities exhibit significant surpluses of 17% and 92% respectively, highlighting a substantial preventive buffer, particularly for biomass transport, which should be considered in baseline planning. Existing storage capacity is sufficient for any salvage logging surplus. Overall, this solution allows for a 19% increase in log deliveries and a fivefold increase in biomass supply, though operational costs double.

5.3 Concluding remarks

This research highlights the critical need for a systems-based, quantitative approach to enhance forest value chain resilience. Through modeling and scenario analysis, vulnerabilities and bottlenecks are identified, enabling proactive evaluation of resilience strategies. A Portuguese case study demonstrates that increasing harvesting and transport capacity (including larger contractors) significantly reduces unused raw materials and unmet demand during wildfires. While these capacity enhancements, termed "preventive capacity," incur extra costs if fires don't occur, trade-off analyses are crucial for planners to balance this against risk profiles. Existing storage, if managed well, can absorb supply surpluses. Proactive planning—involving capacity expansion, resource pre-positioning, and flexible logistics—is essential for fire-prone regions. These findings provide evidence-based strategies for managers and policymakers, advocating for a paradigm shift towards systems-oriented resilience planning to protect forest resources and ensure socio-economic stability against climate threats.

5.4 References

Quinlan AE, Berbés-Blázquez M, Haider LJ, Peterson GD. 2016. Measuring and assessing resilience: broadening understanding through multiple disciplinary perspectives. J Appl Ecol. 2016;53:677–87. DOI: 10.1111/1365-2664.12550

Nikinmaa, L., Lindner, M., Cantarello, E. et al. 2020. Reviewing the Use of Resilience Concepts in Forest Sciences. Curr Forestry Rep 6, 61–80. DOI: 10.1007/s40725-020-00110-x

Pimm, S. L. 1984. The complexity and stability of ecosystems. Nature 307, 321–326. DOI: 10.1038/307321a0

Holling CS. 1973. Resilience and stability of ecological systems. Annu Rev Ecol Syst. 1973;4:1–23. https://pure.iiasa.ac.at/id/eprint/26/1/RP-73-003.pdf

Cantarello, E., Jacobsen, J.B., Lloret, F. et al. 2024. Shaping and enhancing resilient forests for a resilient society. Ambio 53, 1095–1108. DOI: 10.1007/s13280-024-02006-7

Walker B, Holling CS, Carpenter SR, Kinzig A. 2004. Resilience, adaptability and transformability in social – ecological systems. Ecol Soc. 2004;9:5 Available from: http://www.ecologyandsociety.org/ vol9/iss2/art5/

Gomes R. 2024. The role of flexibility in forest-to-bioenergy supply chain risk management. PHD Thesis in Industrial Management and Engineering.
https://sigarra.up.pt/feup/pt/teses.tese?P_ALUNO_ID=130556&p_processo=27873

Pires Ribeiro J, Barbosa-Povoa A, 2018. Supply Chain Resilience: Definitions and quantitative modelling approaches – A literature review, Computers & Industrial Engineering, 115. Pages 109-122. DOI: 10.1016/j.cie.2017.11.006.

Lloret, F., Hurtado, P., Espelta, J.M. et al. 2024. ORF, an operational framework to measure resilience in social–ecological systems: the forest case study. Sustain Sci 19, 1579–1593. DOI: 10.1007/s11625-024-01518-1

Garcia-Jacome S, Jankovský M et al. 2025. Forest value chain resilience from a local perspective in five European countries: analysis of predictors and co-drivers. Frontiers in Forests and Global Change. Vol 7. DOI:10.3389/ffgc.2024.1461932

Weskamp C, et al. 2019. A two-stage stochastic programming approach for identifying optimal postponement strategies in supply chains with uncertain demand, Omega, 83, Pages 123-138, DOI: 10.1016/j.omega.2018.02.008.

Audy JF, Epstein R, Marques AF, Rönnqvist M, Weintraub A. 2014. Chapter 9. Transportation and routing. In: Borges J.G., Diaz-Balteiro L., McDill M., Rodriguez L.C. (Eds.). The management of Industrial Plantations. Theoretical foundations and applications. Springer Verlag. ISBN: 978-94-017-8898-4.

Forsberg M, Frisk M, Rönnqvist M. 2005. FlowOpt – a decision support tool for strategic and tactical transportation planning in forestry, Internat. Journal of Forest Eng., V 16 (2), pp.101-114: DOI: 10.1080/14942119.2005.10702519

Botequim, B., Garcia-Gonzalo, J., Marques, S., Ricardo, A., Borges, J.G., Tomé, M., & Oliveira, M.M. 2013.Developing wildfire risk probability models for Eucalyptus globulus stands in Portugal. iForest – Biogeosciences and Forestry, 6, 217–227.DOI: 10.3832/ifor0824-006

Tomé, M., Barreiro, S., Faias, S., & Tomé, J. 2006. GLOBULUS 3.0: A regional model for the estimation of Eucalyptus globulus stand productivity in Portugal. Silva Lusitana, 14(1), 65–90. ~

Barreiro, S., Tomé, M., Tomé, J., & Soares, P. 2016.Improving individual tree-based modelling of Eucalyptus globulus growth in Portugal.Forest Systems, 25(2), DOI: 10.5424/fs/2016252-08926

FIRE-RES