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Potential of a Light Combined Harvester/Forwarder to Reduce Wildfire Risk in Mediterranean Forests: Comparison with Current Work System

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Abstract: In the last decades the impact of wildfires on forest ecosystem and human assets has steadily increased. Forest operations can help to reduce the spread rate and intensity of wildfires by limiting the biomass available for combustion. Fuel removal is mainly done with preventive silviculture works which, in the Mediterranean basin, typically feature a negative economic balance. The introduction of small-sized forest machines may enhance efficiency and safety of such operations. The study compares the performance of the common motor-manual work system with an innovative machine performing both harvesting and forwarding of biomass. The study took place in a post-fire regenerated *Pinus halepensis* Mill. area with high fuel accumulation. Three plots were selected to represent the main development stages of this type of forest, respectively with a density of about 1700, 5000 and 9600 trees·ha^{-1}. The machine showed a clear advantage over the manual system with the lower and intermediate trees density, where the capacity to valorize the biomass reduced the overall balance per hectare respectively to 19% and 50% of the alternative. This allows to cover the whole operation with the local public subsidy, unlike the manual system. With the higher density, the overall balance is unfavorable for both work systems and different solutions should be tested.

Keywords: mechanization; thinning; wildfire; preventive silviculture; cost analysis; forest operations; light machinery; manual work

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1. Introduction

Wildfires are a complex phenomenon with a global impact on ecosystems [1]. According to Garcia-Llamas et al. [2] fire severity is influenced mainly by three factors: topography, weather and availability of fuel (intended as composition and distribution of the vegetation). The latter factor, regarded as the main driver of fire behavior [3], is the only one that can be modified in order to reduce the damages caused by wildfire events. In fact, fuel can be effectively manipulated in the forest, influencing the probability of fire ignition and the fire intensity [4]. Several fuel management techniques can be used for this purpose, separately or with an integrated approach. The most common and effective are prescribed burning, controlled grazing and mechanical treatments: mastication and thinning [5]. By reducing

the basal area, the latter reduces the damage severity in case of wildfire [6] but provides also additional services such as controlling species selection, removing fuel ladders, and optimizing canopy density [7]. Furthermore, proper thinning enhances tree growth and health as well as stand structure, contributing to increasing the value of the forest stands, hence promoting its active management [8]. However, thinning can only be profitable when the value of the harvested timber is higher than the operation costs [9], an unlikely occurrence in preventive silviculture in Mediterranean forests which typically feature low standing volume (compared to other EU areas) and low mechanization level [10]. These factors contributed to a general abandonment of silvicultural traditions, dramatically increasing the fire hazard due to biomass accumulation. This is the case, for example, of the Mediterranean landscape of the Iberian Peninsula, where large areas of shrublands and pine forests (mainly *Pinus pinaster* and *Pinus halepensis*) are highly prone to fire, also due to landscape uniformity and ladder fuels which facilitate crown fires [11,12], representing an actual management emergency. In these conditions, forest works for wildfire prevention are non-productive operations with negative economic balance requiring public subsidies to be widely applied. Hence, However, huge investments are required to secure the largest area possible or at least the most strategic and critical zones over the landscape. A trend further worsened by the expansion of wildland-urban interfaces (WUI) [13], which triggers the public and private urge to reduce fuel loads and prevent ignitions in human-dominated landscapes [14,15]. For instance, the European Union invests more than € 3.2 billion every year in fire suppression to limit the socioeconomic impacts of wildfires [16,17]. Besides securing public and private funding for preventive silviculture, it is essential to optimize its deployment, leading to larger areas treated with the same resources. Presently, forest fuel reduction is mainly carried on by manual work (chainsaw and brushcutters) for felling, processing and bush cleaning, relying on farm tractors equipped with winch for wood extraction [18], when this task is accomplished. This system is adaptable to any type of terrain and vegetation. Additionally, allows an agile relocation over a landscape of forest and agricultural parcels, often fragmented in a plethora of small sized ownership. Yet, manual work systems typically provide low productivity and higher costs per hectare when compared to alternative mechanized solutions [19,20]. For the specific application of forest thinning a wide range of professional forest machinery is available. Yet, the application of wildfire preventive silviculture has specific needs:

- Minimal investment and operative costs due to the non-profitable nature of the operations
- Capacity to modify density and structure of forest stands while causing a minimal ground cover reduction (an increased access to light would promote grass and understory regrowth, rapidly boosting wildfire risk)
- Increase the accessibility into the forest stand, enabling fast and safe intervention of firefighting teams
- Work system effective in forest stands with high density and low diameter trees.

These requirements are quite similar to those posed in industrial first thinning operations where harvesters and forwarders represent the most competitive alternative [21]. In fact this type of equipment features a low capital, transportation and overhead costs, high degree of maneuverability, minimal access requirements and flexibility to deal with different tree sizes [22]. Even if apparently suitable for the purpose of fuel reduction, to predict the economic feasibility of a mechanized operation such as thinning, it is important to precisely estimate its productivity [23]. This is the scope of most studies in the frame of productive silviculture [24,25], while no research is available on the application of forest machinery in wildfire preventive silviculture. In this case, the goal is to design effective fuel treatment strategies returning resilient landscapes, fire-adapted communities, and effective ecosystem response to wildfire [26] In this frame, besides the cost reduction and effective

surface fuels removal it is also relevant to minimize damages to the remaining vegetation with the twofold purpose to enhance the value of the stand and maintain the health of the trees, as their eventual decline could influence fire behavior and burn severity [27]. Considering the above, the present research aims at comparing the cost, productivity, and the impacts of a highly mechanized system based on light forest machinery with the current preventive silviculture treatments in the Mediterranean forests. In order to maximize the scope of the research, the comparison of the two systems was conducted on conifer dominated stands with different level of development. This allows to gather information relevant for future applications of the outputs at a territorial level (e.g., providing cost maps based on the stand characteristics).

2. Materials and Methods

2.1. Study Area

The study has been conducted in November 2023 in Catalonia (Northern Spain) (Figure 1, 41.54705 N, 1.93381 E), on three *Pinus halepensis* Mill. stands (Table 1) with dominated layer composed by sporadic oak (*Quercus ilex* L.) and a dense layer of climbing plants such as Smilax (*Smilax aspera* L.). The plots were selected as representative of the different stages of development of pine forests naturally regenerated after wildfire. Featuring a high density of trees, accumulation of dead and live biomass and fuel continuity from ground to crown these conifer stands represent a widespread management emergency in the Mediterranean basin [28].

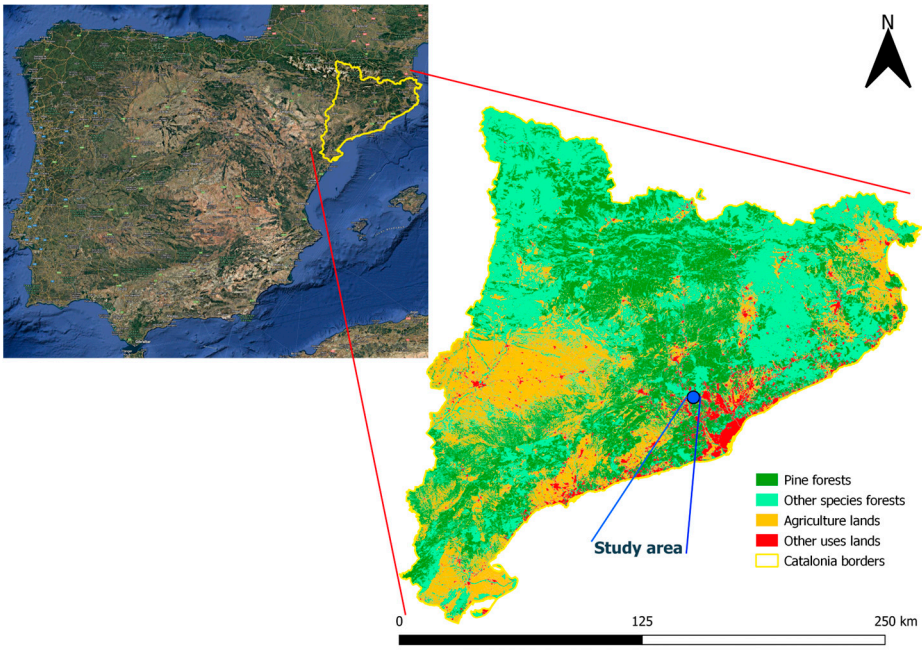


Figure 1. Map of Catalonia, divided by land use, including pine forests. Source: Mapa Forestal Español.

Table 1. Inventory data for the three plots tested in the study.

Plot	1	2	3
Density (trees ha^{-1})	1700	4980	9620
Mean DBH (cm)	16.9	10.2	5.9
Basal Area (m^2 ha^{-1})	42.7	47.0	30.7
Mean height (m)	7.16	6.17	4.32
Mean square diameter (cm)	17.9	11.0	6.4
Mean stem volume (m^3 $tree^{-1}$)	0.059	0.033	0.007
Mean ground cover ($m^2 \cdot tree^{-1}$)	5.892	2.049	1.039

The forest characteristics were assessed by means of three randomly selected circular areas (10 m radius) in each plot. Within these, the DBH and the height of all enclosed trees were recorded. The main characteristics and differences among the plots are synthetized below and in Table 1:

- Plot 1: Dense stand of tall and slender trees with a large quantity of climbing plants. Almost impenetrable by walking. Moderately steep to almost flat (23% average slope).
- Plot 2: Intermediate stand with smaller trees than plot 1 and lower density of climbing plants. Moderately steep (25% average slope).
- Plot 3: Very high density of thin and low trees, no presence of climbing plants but almost impenetrable by walking. Moderately steep (25.5% average slope).

2.2. Harvesting System

For the study a light forest machine Malwa 560C Combi (Malwa Forest AB, Skene, Sweden. Figure 2, Table 2) was selected as the most appropriate solution. The machine has a "combo" design and can be quickly converted in the forest from harvester to forwarder (and vice versa). This makes it particularly suitable for small-scale early thinning operations in smaller harvesting compartments [29]. In harvesting mode, the machine installed a Log Max 928A header (412 kg of mass) along with stabilizing ballasts. In forwarder mode, a common timber grapple was attached to the crane and stakes were installed for roundwood loading/unloading.



(**a**) (**b**)

Figure 2. (**a**) Malwa 560C harvesting mode; (**b**) and forwarder mode.

Table 2. Specifications of the Malwa 560C used in the study. Source Malwa Forest AB.

Factor	Specification
Weight (kg)	4900 (forwarder)–5400 (harvester)
Length (m)	6.3
Width (m)	1.94 (with 500 mm tyres)
Height (m)	2.85
Ground clearance (mm)	400
Payload (kg)	5500
Engine power (kW)	55
Crane length (m)	6.1
Processor head cutting capacity (mm)	20 mm (min) 420 mm (max)

2.3. Trial Design

Prior to the tests, trees to be left (future trees) were marked in all plots for easier identification. In common practice, the selection is performed directly by the operator; but in this case, in spite of being a highly experienced machine operator (over 10 years),

the driver was facing Mediterranean forests and their silviculture for the first time. Thus, manual marking was considered necessary.

While harvesting, the operator was requested to open limited corridors, as narrow as possible, and fell trees up to the maximum reach of the crane. The same corridors were used later for timber hauling. Logs were piled at roadside for following transportation to the end user.

2.4. Data Collection

The time study data was recorded using an Action Cam (GoPro 9 Hero) worn on the head by the machine operator to ensure maximum visibility of all actions. Time recording was carried out in all stages of the operations. These cycles are divided into elements which define the individual work procedure steps [30].

The study has been conducted using productive machine hours (PMH_{15}), delays shorter than 15 min, unitary cost (€·m^{-3}), and economic balance (€·m^{-3}).

Videos were post-processed with dedicated software (DaVinci Resolve) to distribute time data among all the work phases. Data of felled trees and processed logs (number, dimensions and volume) was extracted from the StanForD 2010 files generated by the bucking computer. In order to maximize the accuracy of the data collected, the encoders of the processor head had been calibrated prior to the beginning of the operations. The position of the machine throughout the operations and the location of felled trees/stacks was assessed with the onboard GPS (StanForD data) and with an additional GPS receiver (Garmin GPSmap 60CSx) installed into the cabin, which continuously measured GNSS position every 3 s.

Fuel consumption was measured at the end of the workday by weighing the fuel canister before and after refueling the machine.

Finally, a post-harvest assessment of stand damages was done according to the methodology of Picchio et al. [31] which considers wound surface area (WSA), wound position (WP), and severity on the remaining trees.

2.5. Harvester Work Procedure

In the harvester mode the operator felled, processed, and delimbed stems in front of the machine, driving over the slash while advancing. Logs were staked on either side of the machine trail. The requested assortment was high-quality (delimbed) biomass roundwood 2.5 m long and with a small end diameter (SED) under-bark (ub) ranging from 2.0–30.0 cm. All unmerchantable trees were cut into smaller pieces and discarded in the harvesting corridor. The harvesting work cycle has been divided into the work elements described in Table 3.

2.6. Conversion from Forwarder to Harvester

During the conversion from harvester to forwarder, the operator dismounts the processor and mounts the grapple onto the crane of the machine to remove the ballasts and install the stakes delimiting the loading area directly in the forest. This operation is unique to double-purpose Combi machine allowing a single machine and a single operator to perform both harvesting and forwarding. The average conversion time was 18 min.

2.7. Forwarder Work Procedure

Once converted to forwarder, the same operator hauled the roundwood from the corridors. The machine drove into the corridor cab-first up to the first pile of assortments, loaded until the bunk reached capacity, or the machine reached the end of the corridor and traveled out of the forest to the roadside landing for unloading.

The forwarding work cycle has been divided into the work elements described in Table 3.

Table 3. The work elements with their description.

	Work Element	Description
Harvesting	Felling	From moving the crane to the tree felled. It includes crane movement, sawing and machine repositioning to cut.
	Processing	From felled tree to all logs processed and delimbed.
	Movements between blocks	Machine movements among different plots.
	Movements between trees	Machine movements with the aim of cutting trees inside a plot.
	Cleaning felled trees	Grabbing trees naturally fallen for processing. It ends when the machine starts processing.
	Cleaning	Cutting shrubs, climbing plants, or other vegetation.
	Conversion	Switch harvester and forwarder components (or vice-versa)
Forwarding	Loading	Loading the logs.
	Unloading	Unloading the logs.
	Moving empty	Moving the unloaded machine from the wood piles to the plot.
	Moving loaded	Moving the loaded machine from the plot to the wood piles.
	Moving between logs	Moving the machine between different loading stands
	Delay < 15	Delays shorter than 15 min.
	Delay > 15	Delays longer than 15 min.

2.8. Cost Analysis

According to Szewczyk ([32]) hourly machinery operating costs were calculated only for a productive work time. The data adopted for the calculation of machinery operational cost are presented in Tables 4 and 5. Other overhead cost, such as company management cost or the cost of transporting machines between harvesting areas were not considered when calculating the cost (Formula (1)):

$$\text{Co: Operating cost } (€\cdot PMH_{15}{}^{-1}) = \text{Cint} + \text{Cd} + \text{Cins} + \text{Cfl} + \text{Cr} + \text{Cv} + \text{Ctt} + \text{Cw} \quad (1)$$

where:

$$\text{Cint : Interest cost } (€\cdot PMH_{15}{}^{-1}) = \frac{\frac{Purchase\ Cost\ (€)}{2}\cdot p}{H(PMH)}$$

$$\text{Cd : Depreciation cost } (€\cdot PMH_{15}{}^{-1}) = \frac{Purchase\ Cost\ (€)}{H(PMH)}$$

$$\text{Cins : Insurance cost } (€\cdot PMH_{15}{}^{-1}) = \frac{Insurance\ Cost\ (€/year)}{J\cdot\left(\frac{PMH}{year}\right)}$$

$$\text{Cfl : Fuel and lubricant cost } (€\cdot PMH_{15}{}^{-1}) = \left(\frac{Liters}{PMH}\cdot\frac{€}{Liters}\right)\cdot 1.25$$

$$\text{Cr : Repair cost } (€\cdot PMH_{15}{}^{-1}) = \frac{Purchase\ Cost\ (€)\cdot r}{H\cdot 100}$$

Cv: variable costs related to the use of the machine. The variable cost was calculated as 500 € per year per annual utilization.

Ctt: The tyres and tracks cost ($€\cdot PMH_{15}{}^{-1}$) were only calculated from interest and depreciation of the purchase value of them, adopting the data presented in Table 5. Cw: The wages cost was collected from TragsaGroup, Spanish State-owned holding company for machines operators for a total of 30.11 $€\cdot PMH_{15}{}^{-1}$ [33]. Into Cw is considering all insurance costs and taxes paid by the company.

Table 4. Data adopted for machinery cost calculation.

Parameters	Value
Annual utilization (J) (PMH) (8 h working shifts)	1200
Technology obsolescence (N) (years)	10
Expected useful life (H) (PMH)	12,000
Interest rate (p) (%)	5
Repair cost ratio (r) (%)	70
Agricultural fuel cost (€·l) *	1.1
Lubricant cost (€)	25% of fuel cost

* Common diesel with a lower taxation for farm activities. Preventive silviculture works are locally allowed to use this fuel as additional incentive.

Table 5. Data adopted for tires and tracks cost calculation.

Parameters	Tyres	Tracks
Annual utilization (J) (PMH) (8 h working shifts)	1200	900
Expected useful life (H) (PMH)	4800	9000
Interest rate (p) (%)	5	5

The machine costs were compared with the traditional fire prevention system used in these areas, consisting of a team of operators with chainsaws, tractors, winches, and manual tools.

The overall balance per hectare of the operation was calculated as follows (Formula (2)):

$$\text{Balance } (€\cdot ha^{-1}) = \text{Operating cost } (€\cdot PMH_{15}{}^{-1}) \cdot \text{Operation time } (PMH_{15}\cdot ha^{-1}) - \text{biomass value} \quad (2)$$

The unique assortment produced was high quality biomass (delimbed logs), with a value at roadside of 30 €·t^{-1}.

2.9. Statistical Analysis

Statistical analysis, including descriptive statistics, box-plot visualization, factor analysis, correlation analysis, regression modeling, and analysis of variance (ANOVA) was conducted using R Studio [34]. A boxplot was created to visually compare the distribution of Productivity across the Plot groups. The box-plot presented highlights the productivity differences (m^2 per second) across the three plots, indicating variability in median values, interquartile ranges, and the presence of outliers.

An analysis of variance (ANOVA) was performed to test for differences in productivity among the plot groups. This was done by fitting a linear model with productivity as the response variable and Plot as the predictor.

To validate the assumptions of the ANOVA, several diagnostic tests and graphical analyses were performed. The Shapiro-Wilk test was applied to each Plot group to assess normality. Additionally, the residuals of the linear model were extracted using the residuals function and tested for normality using the Shapiro-Wilk test. The homogeneity of variances was assessed using Bartlett's test. Diagnostic plots for the linear model were generated to visually inspect the residuals and other model assumptions.

Finally, a post-hoc Tukey Honest Significant Differences (HSD) test was conducted on the ANOVA model to identify specific differences between the Plot groups. This test was performed after fitting an ANOVA model with productivity as the response variable and plot as the predictor.

3. Results

3.1. Time Element Distribution

Figure 3 summarizes the time study results for each plot for the "Harvester work procedure". For the "Forwarder work procedure" (Figure 4), the highest time was spent on loading the logs, followed by unloading, with little time for trips due to short forwarding distances, averaging 75 m. In plot 1, cleaning stands out as the most significant work element, accounting for 23.23%. In plot 2, processing and felling are the primary work elements, making up 22% and 19% of the total work time, respectively.

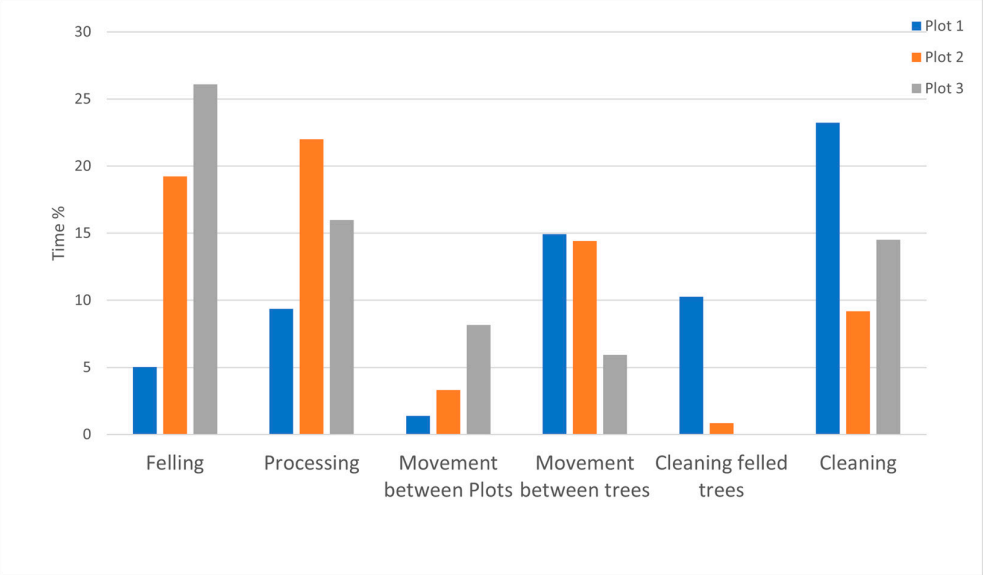


Figure 3. Distribution of work elements for each plot by percentage of time for the harvester work procedure. NOTE total operative time (100%) is the sum of harvesting and forwarding (whose figures are reported in Table 4).

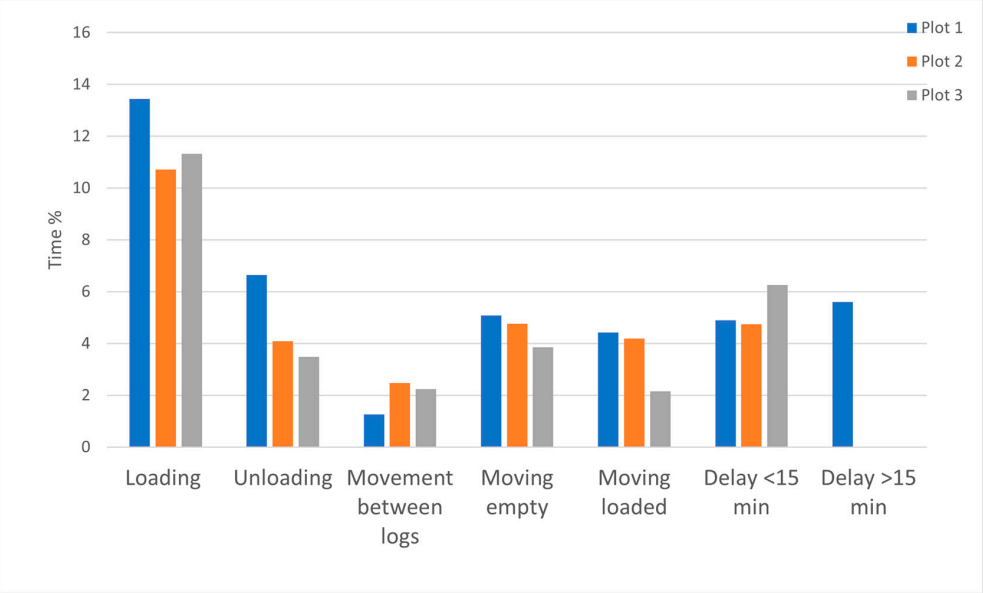


Figure 4. Distribution of work elements for each plot by percentage of time for the forwarder work procedure. NOTE total operative time (100%) is the sum of harvesting (whose figures are reported in Table 3) and forwarding.

Plot 3 had the highest density of stems with the smallest diameters among the treated areas, as a result, felling was the most relevant time element by far (26%). In forwarding,

similar to the previous plots, loading is the phase of work where there is the most productive time, despite having higher forwarding distances, about 110 m.

3.2. Productivity of Thinning Operation

Harvest productivity rapidly dropped with higher tree density levels. Box-Plot in Figure 5 reports the productivity of the harvester considering the average area occupied by a single tree (or ground cover) and the time needed to fell and process it.

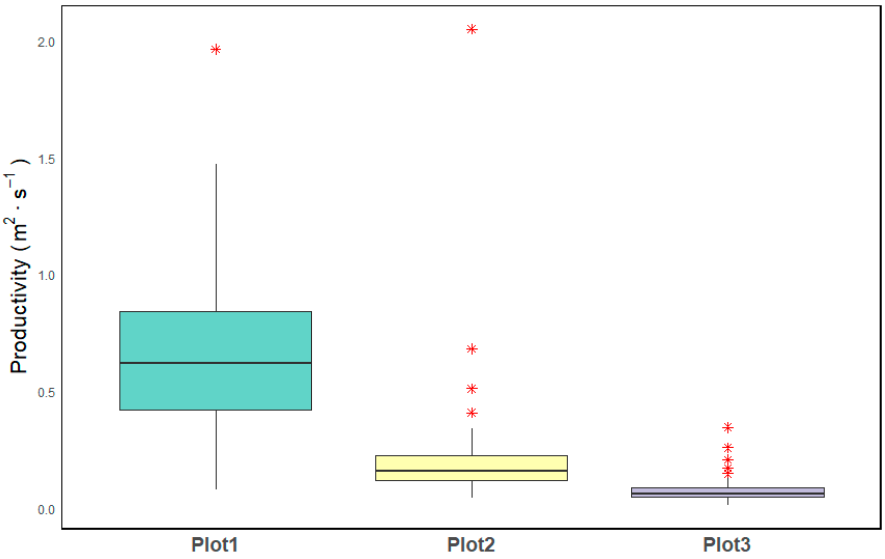


Figure 5. Productivity of harvesting considering the average area occupied by a single tree.

According to the analysis of variance (ANOVA) productivity is significantly different among the different plots ($F = 485.11$, $p < 2.2 \times 10^{-16}$). A Post-hoc analysis with Tukey Honest Significant Differences (HSD) test was used to confirm the differences between the plots. The results showed that all pairwise comparisons were statistically significant ($p < 0.05$).

3.3. Cost Analysis and Economic Balance

With a fuel consumption of 6.16 L per PMH_{15} the overall running cost of the machine is 89.60 € per PMH_{15} (Table 6). Plot 1 has an average cost per hectare of 2257 €, divided into harvesting (1543 €) and forwarding (714 €), Plot 2 of 3336 € (harvesting 2447 € and forwarding 889 €) and Plot 3 of 4951 € (harvesting 3794 € and forwarding 1156 €).

Table 6. Harvested volume, productivity and economic balance.

Plot	1	2	3
Productive Machine Hour (PMH_{15})	5:09:52	10:21:06	9:36:52
Productivity harvesting ($m^3 \cdot PMH_{15}^{-1}$)	2.93	2.24	0.64
Productivity forwarding ($m^3 \cdot PMH_{15}^{-1}$)	6.43	6.17	2.09
Extracted volume ($m^3 \cdot ha^{-1}$)	49.3	60.75	27.6
Total productivity ($ha \cdot PMH_{15}^{-1}$)	0.041	0.027	0.018
Costing per Productive Machine Hours (€$\cdot PMH_{15}^{-1}$)		89.60	
Area treated (ha)	0.21	0.28	0.17
Unitary cost (€$\cdot m^{-3}$)	44.67	54.52	183.58
Cost per Area (€$\cdot ha^{-1}$)	2257.24	3336.36	4950.89
Biomass value at the road site (€$\cdot m^{-3}$)		30.00	
Biomass value at the road site (€$\cdot ha^{-1}$)	1516.10	1835.72	809.05
Economic Balance (€$\cdot m^{-3}$)	−14.67	−24.52	−153.58
Economic Balance (€$\cdot ha^{-1}$)	−741.14	−1500.65	−4141.83

As expected, even when the value of the recovered biomass is considered, the operation resulted in a negative economic balance in all plots (Table 6). For this purpose, the local public authorities provide different types of subsidies for preventive silviculture. In Catalonia, the subsidy is granted depending on the characteristics of each forest stand (mainly vegetation type and accessibility).

3.4. Comparison with the Traditional Method

The current work system deployed in the region for preventive silviculture is carried out with motor-manual felling supported by a farm tractor for winching timber. A few weeks before the tests with the machine, the local company BOSCAT carried out forest operations on different sections of the same forest plots described above. A team of 5 operators were involved in the operations. In detail, the work implied cleaning all vegetation in the first 20 m from the main roads and tracks. Only larger logs were hauled while smaller logs (<8 cm diameter) and branches are roughly crosscut and left on the ground to reduce overall operational costs (but leaving abundant coarse biomass in the forest). The value of the timber extracted is considered just sufficient to cover the cost of hauling and transportation, thus the biomass contribution is not included in the overall economic balance. Table 7 reports the costs of manual operations as reported by the company.

Table 7. 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

3.5. Silvicultural Result of the Operations

The main goal of the operation was to reduce wildfire risk by decreasing the fuel load and modifying its spatial distribution. Basal area (BA) is one of the main indicators for this purpose. The mechanical operation brought to a homogeneous −23/−24% BA reduction in the three plots (Table 8). Coarse biomass (stems up to 2 cm in small diameter) has been completely removed, while slash and tops were concentrated on the harvesting corridor and repeatedly trampled on by the machine, compacting it on the ground.

Table 8. Variation in dendrometry parameters after thinning.

Plot	1	2	3
Trees removed per hectare (total n.)	829	1807	3706
Resulting final density (trees·ha^{-1})	849	3112	6055
Variation in density (%)	−50	−38	−37
Mean DBH (cm)	21.8	11	6.53
Variation in DBH (%)	+29	+7.8	+11
Basal Area (m^2 ha^{-1})	32.54	35.57	23.63
Variation in Basal Area (%)	−24	−24	−23
Mean height (m)	8.73	5.96	4.52
Variation in mean height (%)	+22	−3	+5

Damage to the remaining stand is summarized in Table 9. In the mechanized treatment, 71 trees per hectare (13.5 cm of mean DBH) were damaged, with a total of 80 wounds per hectare due to the occurrence of multiple damages in several trees. In the traditional

system, the damage was more extensive, with 181 trees per hectare affected (17.8 cm mean DBH) and 258 wounds per hectare.

Table 9. Damages analysis between mechanized and traditional harvesting systems.

		Mechanized		Traditional	
Damaged trees per ha		71		181	
Total Wounds per ha		80		258	
Damage factor		% of wounds	N° wounds per hectare	% of wounds	N° wounds per hectare
Wound severity	Bark squeezed	52.9	41	67.2	174
	Bark removed	31.4	24	11.9	31
	Wood damage	15.7	12	20.9	54
Wound Surface Area	WSA1	30.2	24	24.4	66
	WSA2	35.8	29	43.3	112
	WSA3	26.4	21	26.9	69
	WSA4	7.5	6	4.5	12
Wound Position	WP1	1.9	2	0	0
	WP2	30.2	24	1.5	4
	WP3	45.3	36	32.8	85
	WP4	22.6	18	65.7	170

Mechanized harvesting causes fewer bark squeeze wounds (52.9% vs. 67.2%) but removes more bark (31.4% vs. 11.9%) than traditional methods. While mechanized harvesting results in less wood damage (15.7% vs. 20.9%), traditional chainsaw use inflicts deeper wounds, reducing wood quality. In terms of wound surface area (WSA), mechanized harvesting produces more small wounds (30.2%), suggesting a more controlled process, while traditional methods create more moderate wounds (43.3%), likely due to chainsaw cutting. Both methods cause similar rates of large wounds. For wound position (WP), mechanized harvesting slightly affects superficial roots (1.9%) and significantly damages the stump area (30.2% vs. 1.5%). Both methods heavily impact the lower trunk, though mechanized harvesting does so more frequently (45.3%).

4. Discussion

4.1. Time Element Distribution

The share of the work elements is different in the three plots, and it appears highly influenced by the characteristics of the standing trees. In plot 1, cleaning is by far the most relevant work element (23.23%). This is due to the characteristics of the stand, featuring a high share of climbing plants (Figure 6). Furthermore, in this plot it was also necessary to clean naturally fallen trees, which were abundantly present, and it required more time than felling standing plants for the same product.

In Plot 2, processing and felling are the main work elements, respectively with 22% and 19% of total work time. This is due to the density of trees and the difficulty of placing them in the proper position for processing once felled: the specific requirements of the thinning made quite laborious to avoid damages to the remaining trees. Forwarding distances were slightly larger than in the previous plot, around 85 m, but loading time was still the most relevant work element, accounting for 10.72% of the productive times.

Due to the complexity of the work and the short forwarding distances, harvesting required double the time compared to forwarding in plots 1 and 2. The same operation needed thrice the time of forwarding in plot 3 due to the trees' size and the minimal

roundwood production. Overall, the time analysis highlights that in the tested working conditions the machine dedicates most of the time to harvesting.



Figure 6. Plot 1. In the foreground: the area treated with the traditional method, with abundant coarse biomass left on the ground. In the background: the machine approaching the untreated area: note the high density of climbing plants.

The observation that harvesting operations can consume significantly more time than forwarding, especially under complex working conditions and varying tree sizes, aligns with the findings of other studies. Pajkoš et al. [35] compared conventional cut-to-length (CTL) and integrated harvesting methods finding that the integrated method required 33% more time for harvesting operations, while forwarding time was reduced by 16%. Furthermore, research on time consumption [36] in mechanized CTL systems indicates that harvesting time is influenced by stand conditions, operator skills, and equipment characteristics, which can lead to variations in time allocation between harvesting and forwarding. Finally, an analysis of forwarder productivity in a Pinus radiata plantation [37] demonstrated that time consumption for forwarding is affected by factors such as slope and terrain, which can also impact the relative time spent on harvesting versus forwarding.

4.2. Productivity of Thinning Operations

The lower density of Plot1 (leading to higher area per tree) provides a much higher productivity per hectare than the other density levels (Table 6). It should also be noted that the variability is also much higher.

Productivity per unit area of harvesters and forwarders is not commonly addressed in bibliography. Thus, to compare the performance of the tested solution with previous studies, also productivity per cubic meter was calculated (Table 6). For the harvesting stage, the authors could not find studies with comparable machinery in wildfire preventive forestry. The close references are trials in thinning of forest plantations, a much more favorable work condition, where the productivity reported is almost doubled: 4.5 $m^3 \cdot PMH_{15}{}^{-1}$ [9,38,39]. The difference can be mainly explained by the characteristics of the post-fire vegetation with high density of trees and climbing plants, and the fire prevention goal of the operations (with secondary production purposes), which require cautious removal of trees to avoid understory fuels regrowth.

Regarding the forwarder productivity of the Malwa 560 C (Table 6), it is lower than larger forwarders [21,40,41], but consistent with smaller equipment: Ackerman et al. [29], with the same machine model operating in eucalyptus plantations reported similar productivity rates (5.03 $m^3 \cdot PMH_{15}{}^{-1}$). While Spinelli and Magagnotti [25] reported a productivity between 3.1–3.8 $m^3 \cdot PMH_{15}{}^{-1}$ with a different light forwarder in plantation thinning.

4.3. Cost Analysis and Economic Balance

The costs of Plot 1 are close to those reported by Bigot et al. [42] for small trees (about 0.06 $m^3 \cdot tree^{-1}$), where the total range was 40–45 $€ \cdot m^{-3}$ at the best (with a very compact harvester) but are higher than other studies conducted with similar machines and larger trees [43].

It is worth noting that without the cumbersome cleaning operations, which especially in the first plot affected more than 20% of the total PMH^{15}, the total costs per hectare would have been reduced to 1735 €, 3030 € and 4239 € respectively in Plot 1, 2 and 3.

Consistently, different tree size and density led to high variations of performance and costs among plots. Plot 1 resulted in balance closer to 0 (corresponding to no losses). In this case, the local public subsidies (2000 $€ \cdot ha^{-1}$) fully cover the balance (operation costs—biomass value), which represent just 37% of the financial support (Figure 7). For Plot 2, in spite of the higher biomass value per hectare, the overall cost is double the cost compared to Plot 1 due to the lower productivity. Still, the overall balance is favorable compared to the subsidy granted, given the type of vegetation to be treated, but it is still 75% of the subsidy and thus fully covered. Finally, in Plot 3 both the total cost and the overall balance are higher than the financial support available, making the operation economically unviable. It is worth underlying that in this case the cost of forwarding is higher than the value of biomass, making this additional operation economically unviable.

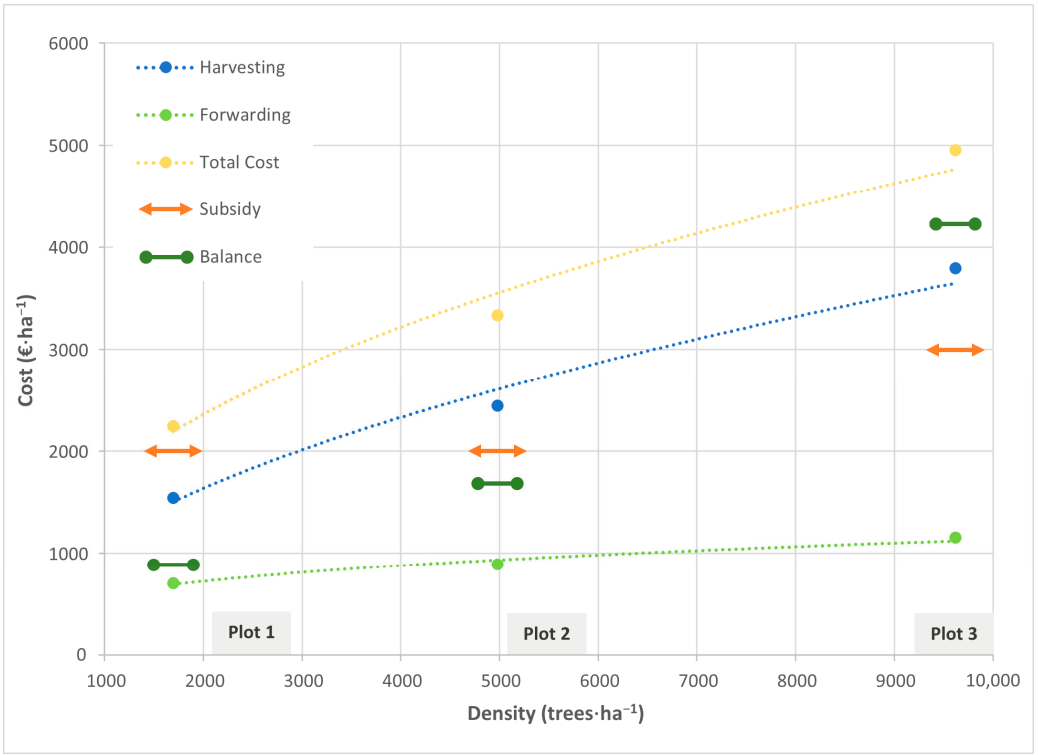


Figure 7. Sensitive analysis of costs as function of tree density. The green mark represents the economic balance (negative) for each plot. The orange mark indicates the public subsidy granted according to the specific characteristics of each plot. Green, blue and yellow dotted lines represent the trend of forwarding, harvesting and total operational costs respectively.

4.4. Comparison with the Traditional Method

Considering that in each plot, the subsidy granted was the same as previously described, the manual operation resulted financially unsustainable in all cases. In Plot 1, the cost of manual operations is over 200% of the granted subsidy. This is due to the difficulty to manually felling the high trees whose crowns tended to get entangled with the standing ones. In Plot 2, featuring smaller trees, this issue was less hindering, leading to an overall cost of 150% compared to the subsidy. In Plot 3 the economic balance is comparable to the mechanized system and about 150% of the granted subsidy (Table 7).

4.5. Silvicultural Result of the Operations

The narrow corridors and the layer of slash integrated into the ground constitute unfavorable conditions for the growth of the understory, reducing the risk of a quick post-treatment accumulation of high-combustible biomass. The presence of such structural impediments can contribute to a reduction in the accumulation of high-combustible biomass, as suggested by studies that emphasize the importance of understory management in forest ecosystems [44,45]. Additionally, if considered necessary, a mulcher could be easily driven along the harvesting corridors. Climbing plants had been removed by the side of the corridors, but just partially as the operation was carried on to facilitate access and visibility during felling and forwarding.

A reduction of manual operations was equal to the mechanical system, yet the silvicultural result is not fully comparable. In fact, this work system included a rough pruning of the remaining trees up to 1.5 m, removal of the climbing plants, release of all coarse biomass on the ground and mulching of needles and twigs.

The traditional system is significantly more damaging, likely due to manual felling, and tree pruning. The latter action is probably responsible of most damages and helps to explain the difference with the mechanized system where pruning was not carried on. Moreover, manual pruning can negatively impact tree health by reducing photosynthetic surfaces and triggering physiological stress responses [46].

Overall, mechanized harvesting ensures less damages to the remaining trees and with lower intensity, particularly on wood quality, indicating a sustainable approach to forest management that could become increasingly important in the face of climate change [47,48].

5. Conclusions

Wildfire is a growing threat for the forest environment and human society. Fuel removal by preventive silviculture is considered as one of the most effective solutions to reduce the occurrence and damage caused by forest fires. Yet, the economic balance of such operations is typically negative, relying on public or private investments for their execution.

The performance of the mechanized system was always higher than the traditional one and causing less damages to the remaining trees. As expected for a machine equipped with single-grip processor, the productivity is higher with larger trees and drops quickly when the average DBH drops due to the high density of stems. Just in this last case the subsidies currently available for preventive silviculture are insufficient to cover the fuel removal costs. The outcome of this study provides general cost thresholds in function of tree density. This may be used to optimize the public resources dedicated to securing strategic areas against wildfire and treat a larger area with the same available resources.

Further research should focus on the identification of suitable harvesting method for post-fire, high-density forests (>8000 trees·ha^{-1}). For instance, small harwarders equipped with accumulating grapple-shears could cope with the task of reducing overall costs and effectively remove the dangerous biomass accumulation. As for the current manual system,

surprisingly both extremes (large and small trees) reduce the operational efficiency making the costs largely unsustainable even with the support of subsidies.

In spite of being a professional forest equipment, the lightweight of the tested model and its capacity to perform both harvesting and forwarding tasks with a unique machine and operator makes this system very effective in the Mediterranean landscape. In this scenario preventive silviculture must be applied in a mosaic of small forest stands separated from each other: the relocation costs, which could severely impact a larger equipment, may be expected to have the same range of values of the manual system, where the relocation involves a team of workers and a farm tractor with attachable tools (winch and mulcher).

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