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Work Productivity, Costs and Environmental Impacts of Two Thinning Methods in Italian Beech High Forests

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Abstract: In the Mediterranean area, the most common management of beech forests relies on the shelterwood system. However, more effort has been put into developing alternative silvicultural treatments to enhance the forests' capacity to provide the higher ecosystem services. The crop-tree management system seems to perform well, particularly under the economic point of view. Moreover, it can provide higher quality timber from thinning interventions which are carried out before the end of the rotation period. However, very few articles have been found in the literature dealing with evaluation of the economic and environmental performance of the alternative thinning method based on crop-tree management (AT) in comparison to the traditional thinning from below typical of the shelterwood system (TT). Therefore, three study areas in Italy were selected to assess working productivity, costs and GHG emissions associated with the two methods. In the study areas with the application of mechanized extraction systems, AT showed higher work productivity and lower costs than TT, whereas GHG emissions reduction by AT was observed only in one of the three study areas. There was not significant improvement related to AT application when using animals for extraction operations. AT was more economically sustainable for thinning interventions in beech high forests, but the reduction of GHG emissions was not as effective as in TT. Crop-tree management proved to be a suitable option to be applied in beech forest stands, although further studies should focus on the overall rotation cycle and include the evaluation of impacts on productivity of a higher presence of saplings expected after crop-tree intervention.

Keywords: work performance; harvesting costs; winching; GHG emissions; thinning

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1. Introduction

Beech (*Fagus sylvatica* L.) is the most widespread broadleaf species in Europe and it plays a key role in the European forest sector [1], covering more than 11 million hectares throughout Europe [2]. Beech grows in different climatic and edaphic conditions, it can be found in the Atlantic, Continental and Mediterranean zones and it can tolerate moderately dry to periodically wet soils [2]. In central Europe, beech grows generally in lowland stands, while in the Mediterranean context, it is a typical mountain species [3].

For these kinds of forests, the standard management applied is high forest and following the Continuous Cover Forestry (CCF) criteria, the shelterwood system is the most common treatment adopted for European beech forests, mostly in the Mediterranean area [2,4–6]. In the framework of the shelterwood system, thinning interventions are crucial for the proper development of the stand [7]. Thinning is beneficial for the quality of standing trees, species mixture, tree mechanical stability and biodiversity [8–10]. Usually, beech high forests in the Mediterranean area are managed by applying a uniform shelterwood system with a long rotation period (>90–100 years), a regeneration period of

20–30 years, and the repeated application of thinning from below starting at the age of about 20–30 years [11].

However, cost-effectiveness of the typical thinning from below interventions is not always assured [12]. This is due to rising labor costs and to the fact that the majority of the assortments produced from this kind of intervention do not have value as sawlogs but only as firewood, lacking a market of pulpwood and wood chips.

Furthermore, European silviculture has recently faced a shift towards new models such as ecological forestry [13]. The objective is to assure higher multifunctionality of forests providing higher ecosystem services compared to traditional systems [14,15]. There is, therefore, the need to craft beech silviculture according to these issues, and a possible solution could be the development of alternative thinning methods which are based on the concept of crop-tree management [16–19]. This alternative method is based on the concept of selecting a limited number of target trees (a number comparable to the final density at the beginning of the regeneration period), which are the most promising individuals in the stand, concerning both economic value and ability to produce seeds [20,21], and localizing the intervention around these target trees by removing the direct canopy competitors [14].

Similar approaches were demonstrated to be effective in providing timber of high quality [14,22] but a complete evaluation of the benefit of this alternative thinning method from an economic and environmental point of view, applying a time motion study and calculating the related pollutant emissions, in European beech high forests has yet to be done. Considering the high importance of these ecosystems in Europe, the application of the Sustainable Forest Operations (SFOs) approach is necessary, which means to carry out forest operations ensuring cost-effectiveness without compromising the environment and allowing for safe working conditions for the operators, in these cases the precision forest harvesting could be an important tool [23–25]. According to the SFOs approach, it is necessary to acquire specific scientific data supported by field analysis. Therefore, this study was developed with the aim of carrying out an evaluation of work productivity, costs and GHG emissions of logging interventions carried out with the alternative thinning method (AT) in comparison to the traditional one (TT) in three different study areas in Italy.

The application of time motion studies to analyze productivity and costs of forest operations are indeed fundamental for the determination of the economic feasibility of forestry interventions [26,27]. Although often representing case studies, evaluations of productivity and costs of forest operations are the base for evaluating the economic sustainability of various forest interventions carried out applying different silvicultural treatments and harvesting methods [28]. Furthermore, studies dealing with pollutant emissions represent a valuable tool for the evaluation of environmental impacts related to forest operations [29].

The experimental design was developed so as to test two research hypotheses. The first hypothesis is that AT shows higher work productivity and lower harvesting costs than TT. The second hypothesis is that AT is also able to reduce GHG emissions in comparison to TT. By increasing the retrieved timber amount and being localized in a less scattered way, a decrease in the time needed is indeed expected, mostly for bunching and extraction operations, considering that the extracted timber amount and bunching/extraction distance are among the most important influencing factors for work productivity and related harvesting costs [27,30,31]. As well as increased work productivity, for the same machinery, it can lead to reduced pollutant emissions, as a consequence of the lower time needed for the operations [32].

2. Materials and Methods

2.1. Study Areas

The study was carried out in three different study areas located within Italian territory, each study area had an overall surface of about 30 ha. One half of the area was harvested by the traditional thinning method, i.e., shelterwood system. The other half was harvested according to the alternative thinning method, i.e., crop-tree management. The two thinning methods were implemented by using the same machinery within each study area.

The first area was located in the Pian Cansiglio forest (Veneto, Italy, 46°03′ N, 12°23′ E), located at 1100–1200 m a.s.l. and characterized by gentle slope (0–20%), low roughness (I class, obstacles present on less than 1/3 of the surface) with calcareous bedrock.

The second study area was in the Chiarano forest (Abruzzo, Italy, 41°51′ N, 13°57′ E) at an altitude of 1700–1800 m a.s.l. with high slope (40–50%) and high roughness (III class, obstacles present on more than 2/3 of the surface) with calcareous bedrock.

The third study area was located in the Mongiana forest (Calabria, Italy, 38°30′ N, 16°14′ E) at 740–1100 m a.s.l. The stand showed moderate slope (20–40%) and limited roughness (I class) with granitic bedrock.

The main dendrometric characteristics of the three study areas before logging interventions are reported in Table 1, while the geographic locations are shown in Figure 1.

Table 1. Dendrometric characteristics of the three investigated stands before logging intervention.

Parameter	Pian Cansiglio	Chiarano	Mongiana
Age (yr)	100	70	75
Stand density (N ha^{-1})	320	1825	510
dbh (cm)	40	18	30
Basal area (m^2 ha^{-1})	40.19	46.42	36.03
Average height (m)	27.00	14.00	22.71
Average tree volume (m^3)	2.040	0.210	0.740
Average tree biomass (Mg FM)	1.46	0.16	0.58
Average tree biomass (Mg DM)	1.22	0.15	0.52
Standing volume (m^3 ha^{-1})	652.80	340.27	376.32
Standing biomass (Mg ha^{-1} FM)	470.03	265.41	293.53
Standing biomass (Mg ha^{-1} DM)	391.60	238.19	263.42

dbh: diameter at breast height; FM: fresh matter; DM: dry matter.

2.2. Investigated Thinning Methods

Traditional thinning based on the shelterwood system (TT) consisted of a typical thinning from below carried out on the total surface of the forest sub-compartment, removing dominated trees and damaged co-dominant ones. In this way, the canopy cover is practically not interrupted, and the moment of natural regeneration is postponed to the starting of the regeneration period.

Alternative thinning based on crop-tree management (AT) consisted of the selection, prior to logging, of 40–80 target trees (depending on the stand age and density, higher in younger and denser stands). Intervention was carried out only around the target trees by removing the direct canopy competitors of these trees. In this way, canopy cover is partially altered, allowing light to reach the soil. Natural regeneration is promoted from the seeds of the target trees. As a result, the stand assumes a more complex structure as compared to the monoplane one, which is typical of even-aged high forests managed by the shelterwood system.

Data on the characteristics of AT and TT in the three study areas are given in Table 2. It is important to notice how in all the study areas there were no differences in average skidding distance between the two investigated thinning methods.

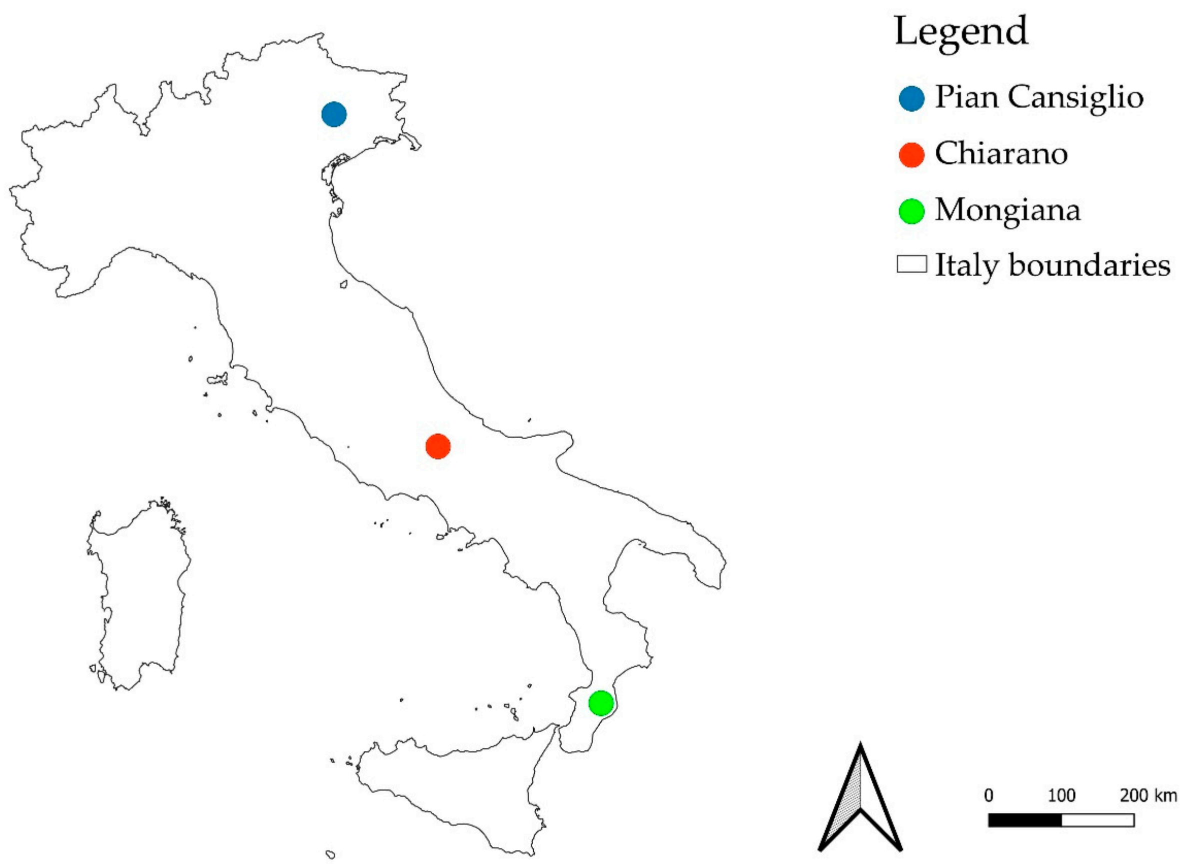

Figure 1. Geographic location of the study areas.

Table 2. Data of AT and TT in the three study areas.

Parameter	Pian Cansiglio		Chiarano		Mongiana	
	AT	TT	AT	TT	AT	TT
Target trees (N ha^{-1})	40	-	80	-	50	-
Felled trees (N ha^{-1})	150	110	200	210	152	99
Felled trees dbh (cm)	38	36	17	15	31	35
Average felled tree volume (m^3)	1.22	1.13	0.49	0.36	0.60	0.62
Average felled tree biomass (Mg FM)	0.95	0.88	0.38	0.28	0.47	0.49
Average felled tree biomass (Mg DM)	0.85	0.79	0.34	0.25	0.42	0.44
Felled volume (m^3 ha^{-1})	183.00	124.00	98.00	76.00	91.00	61.78
Felled volume (%)	28	19	29	22	19	16
Felled biomass (Mg ha^{-1} FM)	142.53	96.76	76.34	59.39	70.98	48.18
Felled biomass (Mg ha^{-1} DM)	127.91	86.84	68.51	53.30	63.70	43.24
Average extraction distance (m)	280	255	200	231	251	245

dbh: diameter at breast height; FM: fresh matter; DM: dry matter.

2.3. Applied Harvesting Systems

In the Pian Cansiglio and Mongiana study areas, for both AT and TT, the applied wood system was Tree Length System (TLS), a chainsaw was applied for felling and delimbing trees with a 4 kW chainsaw and one operator. Bunching and extraction operations were performed by two operators by a forestry-fitted 70 kW farm tractor equipped with a 60 kN winch. Bucking was carried out at the landing site.

In the Chiarano area, for both AT and TT, intervention was carried out by Short Wood System (SWS), one operator with a chainsaw performed felling, delimbing and bucking at the stump. Mules were used to carry out extraction.

2.4. Work Productivity and Costs Evaluation

Work productivity of felling and processing operations were performed by identifying and marking 100 trees with spray for each treatment, measuring their dbh and height and estimating their volume according to the local dendrometric tables. The working cycles analyzed for the work productivity evaluation consisted of a single tree, i.e., the time to fell and process each of the 100 marked trees was recorded separately.

The same procedure was applied for bunching and extraction operations and the number of identified trees per each treatment was 600. In this case, however, the analyzed working cycle was one load of the extraction mean (about 180–200 kg of short wood for mules and about 3–6 tree-length logs for forestry-fitted farm tractor).

The time to carry out each working cycle was measured and recorded with a handheld chronometer with an accuracy of 1/100 min, separating work time from delay time [33]. After calculating working times and the volume of the trees in each working cycle, net work productivity was derived in m^3 PMH^{-1} (productive machine hour, which does not include delay) and gross productivity measured in m^3 SMH^{-1} (scheduled machine hour, considering delay). It is important to underline that the analysis finished at the landing site, not accounting for the time needed for logs' loading and transport.

Statistically significant differences between the working times between the two thinning methods were investigated via unpaired sample *t*-test, after testing data for normality and homoscedasticity, respectively, with Shapiro–Wilk and Levene's tests.

Machine costs were calculated according to the Harmonized European Costing Model developed within EU COST Action FP0902 [34]. The model allowed for the calculation of fixed costs (costs associated only to owning the machinery) and variable costs (related to the machinery usage). Interviews and a literature search were applied to obtain the input data for the model. In detail, local forest contractors were previously interviewed to collect information on purchasing costs, service life and annual usage (Table 3). For the calculation of other parameters, such as interests, insurance, personnel costs and overhead profit, authors referred to recent publications on similar topics in the same study context [35,36]. Fuel consumption was estimated through the refilling method while oil consumption was estimated as a function of engine power [37].

Table 3. Cost calculations for the machines applied in the investigated thinning methods. SMH refers to scheduled machine hour, including delays.

Cost Component	Unit	Chainsaw	Tractor for Winch	Forest Winch	Ten Mules
Investment price	EUR	1000.00	59,071.00	6000.00	21,600.00
Salvage value	EUR	0.00	17,448.64	1131.78	0.00
Service life	yr	4	10	10	15
Annual use	PMH	500	1000	1000	1000
Operator wage	EUR SMH^{-1}	16.00	16.00	16.00	16.00
Interest	%	4	8	8	8
Depreciation	EUR yr^{-1}	250.00	4162.24	486.82	1440.00
Interest	EUR yr^{-1}	20.00	3060.79	285.27	432.00
Insurance	EUR yr^{-1}	2.50	147.78	15.00	54.00
Maintenance	EUR yr^{-1}	200.00	4730.00	480.00	1000.00
Fuel and lubricant (fodder for mules)	EUR yr^{-1}	1660.00	6200.00	0.00	9360.00
Personnel	EUR yr^{-1}	8000.00	16,000.00	16,000.00	16,000.00
Overhead and profit	%	20	20	20	20
Overhead and profit	EUR yr^{-1}	2026.15	6863.73	3453.82	5657.20
Total	EUR yr^{-1}	12,156.90	41,180.00	20,720.00	33,943.20
Total	EUR SMH^{-1}	24.31	41.18	20.72	33.94

2.5. GHG Emissions

The system boundaries consisted of felling, processing, bunching and extraction operations, the applied functional unit was 1 m^3 of wood extracted.

Regarding mechanized operations, pollutant emissions are related to fuel consumption. In detail, emissions were calculated concerning emissions related to fuel combustion and emissions linked to fuel production and transport [38].

Pollutant emissions related to fuel combustion were calculated taking into account fuel calorific value, emission factors related to engine power and the efficiency of combustion process.

CO_2 emissions were calculated with the methodology proposed by Athanassiadis (2000) [39], while for other pollutants (CO, NOx, PM) the equations and emission factors proposed by Klvac et al. (2012) [40] were applied. Equation (1) was used for the calculation of emissions related to fuel combustion (EFC).

$$EFC = Fc \cdot Ef \cdot Cv \cdot Te \quad (1)$$

where Fc represents fuel consumption expressed as L m^{-3} of wood, Ef is the emission factor related to the power of the engine (g MJ^{-1}), Cv is the calorific value of the fuel (MJ L^{-1}) and Te the percentage thermal efficiency.

Emissions related to fuel production and supply chain (EFP) were estimated following the methodology proposed by Klvac et al. (2012) [40] and applying an emission factor of 0.0862 for HC as suggested by Athanassiadis (2000) [39] according to Equation (2).

$$EFP = Fc \cdot Ef \cdot Cv \quad (2)$$

Furthermore, emissions related to oil consumption were considered and calculated as the sum of emissions generated by oil production (EOP—g m^{-3} of wood) [41] and emissions related to the reprocessing of waste oils for combustion (EOR—g m^{-3} of wood) [42].

EOP and EOR were calculated according to Equations (3) and (4).

$$EOP = Oc \cdot Ef \quad (3)$$

$$EOR = Oc \cdot Ef \quad (4)$$

where Oc is the oil consumption measured in L m^{-3} and Ef the emission factor (g L^{-1}).

To estimate the emissions related to the operations carried out by animals, reference was made to the methodology proposed in 2013 by the Italian Council for Research In Agriculture [43] regarding emissions related to enteric fermentation and animal manure handling. CO_2 emissions related to animal respiration were estimated from literature data considering 3.8 kg CO_2 yr^{-1} per kg of animal weight [44].

The methodology proposed by [43] represents a simple assessment of emissions based on fixed coefficients. Regarding methane emissions as a consequence of enteric fermentation for each mule, a value of 10 kg yr^{-1} of CH_4 was considered. An amount of 0.84 kg yr^{-1} of CH_4 for each mule was further considered as emissions related to animal manure. Indeed, during manure storage and management a certain amount of methane can be emitted because of methanogenic bacteria activity. Regarding N_2O emission, 0.02 kg N_2 N_2O per kg of excreted N was applied. N_2O emissions from animal manure are related to nitrification and denitrification processes and were calculated considering as a reference the prairie/paddock system, which is the one which describes the situation which is the most similar to what happens during forest operations by mules. In this system, manure produced from animals was not collected but left to natural degradation without any form of management [43].

Data from the various GHG emissions (CO_2, CH_4 and N_2O) were further converted into equivalent carbon dioxide (kg CO_{2eq}) through the application of characterization factors which convert the mass of these substances into the mass of CO_2 which would have an equivalent potential of climate warming [45].

3. Results

3.1. Work Productivity and Costs Analysis

Data of work productivity concerning felling and processing operations showed how the alternative system did not cause significant changes in work productivity apart from the Pian Cansiglio study area, where a significant reduction of time for felling operation was achieved (Table 4). It is interesting to note how delay time did not differ between AT and TT in all the study areas.

Table 4. Work productivity of felling and processing in the three study areas for both the traditional (TT) and alternative (AT) thinning methods. Differences were considered statistically significant in the case of $p < 0.05$.

	Pian Cansiglio			Chiarano			Mongiana		
	AT	TT	*p* Value	AT	TT	*p* Value	AT	TT	*p* Value
Average felling time (min cycle^{-1})	1.8	1.7	**<0.05**	1.1	1.1	>0.05	1.4	1.3	>0.05
Average processing time (min cycle^{-1})	2.5	2.6	>0.05	5.8	4.0	**<0.05**	2.0	2.1	>0.05
Avoidable delay time (%)	18.6	18.2	>0.05	15.1	14.3	>0.05	12.6	11.3	>0.05
Unavoidable delay time (%)	3.5	3.4	>0.05	10.5	11.4	>0.05	4.5	4.1	>0.05
m^3 PMH^{-1}	18.700	17.400		3.740	3.600		8.200	8.600	
m^3 SMH^{-1}	14.500	13.600		2.300	2.220		7.059	7.440	

The alternative thinning method caused instead more substantial changes regarding bunching and extraction operations. In fact, a significant reduction in working time was achieved in the study areas with mechanized extraction (Pian Cansiglio and Mongiana). In particular, for both areas, AT caused a reduced time for both bunching and extraction, as well as a significant reduction of avoidable delay time. However, in the Chiarano study area, where mules were used for extraction operations, the improvement in work productivity was not as significant as in the other study areas (Table 5).

Table 5. Work productivity of bunching and extraction in the three study areas for both the traditional (TT) and alternative (AT) thinning methods. Differences were considered statistically significant in the case of $p < 0.05$.

	Pian Cansiglio			Chiarano			Mongiana		
	AT	TT	*p* Value	AT	TT	*p* Value	AT	TT	*p* Value
Average bunching time (min cycle^{-1})	1.8	2.7	**<0.05**	-	-		1.7	2.6	**<0.05**
Average extraction time (min cycle^{-1})	3.4	5.7	**<0.05**	46.1	53.8	>0.05	4.5	6.1	**<0.05**
Avoidable delay time (%)	4.0	6.9	**<0.05**	5.1	6.8	>0.05	5.1	7.9	**<0.05**
Unavoidable delay time (%)	10.4	2.9	**<0.05**	7.3	12.3	**<0.05**	7.3	2.2	**<0.05**
m^3 PMH^{-1}	5.600	3.400		1.460	1.310		6.075	4.040	
m^3 SMH^{-1}	4.800	3.100		1.220	1.175		5.400	3.175	

The variation in work productivity, mostly for bunching and extraction, caused by AT also led to a reduction of harvesting costs. Cost reduction was particularly evident in the Pian Cansiglio and the Mongiana areas, where the improved work productivity in mechanized extraction led to a reduction of costs related to these two operations. On the other hand, felling/processing costs remained comparable between TT and AT in the three study areas. Costs for extraction by animals in the Chiarano area did not change between the two methods (Figure 2).

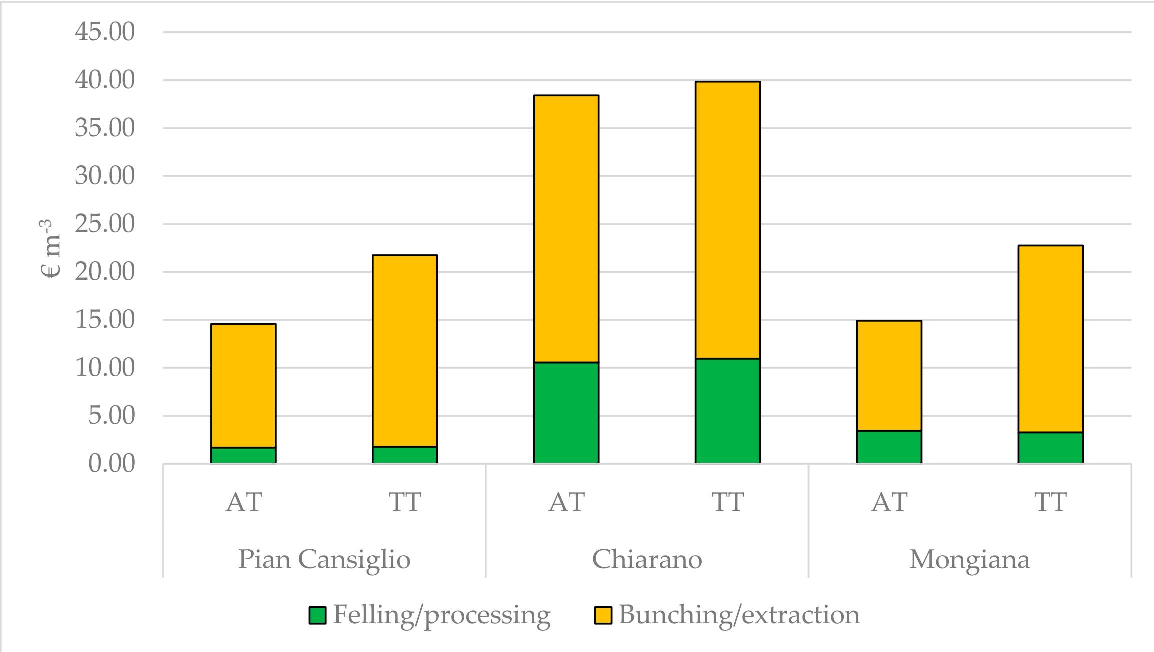

Figure 2. Harvesting costs subdivided into felling/processing and bunching/extraction for the two investigated thinning methods (traditional shelterwood TT and alternative crop tree management AT) in the three study areas.

3.2. GHG Emission Analysis

Pollutant emission analysis for the Pian Cansiglio study area revealed how CO_2 represented the larger amount of the total emissions in both AT and TT, accounting for about 95% of emitted pollutants. Emissions related to fuel combustion (EFC) accounted for the majority of total emissions, while both EFP and the emissions related to oil consumption (EOP and EOR) contributed much less. It is worth mentioning that, regarding all the investigated pollutants, AT was less polluting than TT, leading to a 4% reduction of total emissions (Table 6).

Table 6. Pollutant emissions for Pian Cansiglio study area.

		CO_2 g m^{-3}	**CO g m^{-3}**	**HC g m^{-3}**	**NO_X g m^{-3}**	**PM g m^{-3}**
TT	EFC	8343.40	100.00	3.40	147.40	20.70
	EFP	545.30	0.60	6.70	3.20	0.00
	Tot. EF	8885.80	100.60	10.10	150.60	20.70
	EOP	9.00	0.00	0.10	0.10	0.00
	EOR	2.10	0.00	0.00	0.00	0.00
	Tot. EO	11.10	0.00	0.10	0.10	0.00
	TOT	8896.90	100.60	10.10	150.60	20.70
		CO_2 g m^{-3}	**CO g m^{-3}**	**HC g m^{-3}**	**NO_X g m^{-3}**	**PM g m^{-3}**
AT	EFC	8013.50	94.80	3.30	138.60	19.00
	EFP	523.70	0.60	6.50	3.00	0.00
	Tot. EF	8534.50	95.40	9.80	141.60	19.00
	EOP	8.70	0.00	0.10	0.10	0.00
	EOR	2.00	0.00	0.00	0.00	0.00
	Tot. EO	10.70	0.00	0.10	0.10	0.00
	TOT	**8545.20**	**95.40**	**9.80**	**141.60**	**19.00**

A similar trend was confirmed also for the Chiarano study area (Table 7), where lower emissions were found related to AT in comparison to TT. CO_2 and EFC accounted for the majority of overall emissions. In contrast, some emissions were also related to the use of animals, although the overall GHG emissions resulted to be substantially lower than in the other study areas where extraction operation was mechanized.

Table 7. Pollutant emissions for Chiarano study area.

		CO_2 g m^{-3}	CO g m^{-3}	HC g m^{-3}	NO_X g m^{-3}	PM g m^{-3}
TT	EFC	1953.40	18.20	0.70	31.90	4.20
	EFP	127.70	0.10	1.30	0.70	0.00
	Tot. EF	2080.40	18.30	2.00	32.60	4.20
	EOP	2.10	0.00	0.00	0.00	0.00
	EOR	0.50	0.00	0.00	0.00	0.00
	Tot. EO	2.60	0.00	0.00	0.00	0.00
	Animals	1089.30	0.00	7.50	0.70	0.00
	TOT	3172.30	18.30	9.50	33.30	4.20
		CO_2 g m^{-3}	**CO g m^{-3}**	**HC g m^{-3}**	**NO_X g m^{-3}**	**PM g m^{-3}**
AT	EFC	1960.40	18.30	0.60	31.50	4.10
	EFP	128.10	0.10	1.20	0.70	0.00
	Tot. EF	2087.90	18.40	1.80	32.20	4.10
	EOP	2.10	0.00	0.00	0.00	0.00
	EOR	0.50	0.00	0.00	0.00	0.00
	Tot. EO	2.60	0.00	0.00	0.00	0.00
	Animals	1049.60	0.00	7.20	0.70	0.00
	TOT	**3122.20**	**18.40**	**8.90**	**32.80**	**4.10**

Interestingly, in the Mongiana study area the obtained results showed a different trend. The AT-related emissions resulted to be higher (cumulatively 3.7% higher) than TT. CO_2 and EFC resulted also in this case as the major contributor to overall emissions (Table 8).

Table 8. Pollutant emissions for Mongiana study area.

		CO_2 g m^{-3}	CO g m^{-3}	HC g m^{-3}	NO_X g m^{-3}	PM g m^{-3}
TT	EFC	6430.60	149.90	5.10	220.90	31.00
	EFP	420.30	0.90	10.00	4.80	0.00
	Tot. EF	6848.60	150.80	15.10	225.70	31.00
	EOP	6.90	0.00	0.10	0.10	0.00
	EOR	1.60	0.00	0.00	0.00	0.00
	Tot. EO	8.60	0.00	0.10	0.10	0.00
	TOT	6857.20	150.80	15.10	225.70	31.00
		CO_2 g m^{-3}	**CO g m^{-3}**	**HC g m^{-3}**	**NO_X g m^{-3}**	**PM g m^{-3}**
AT	EFC	6666.30	159.70	5.60	233.50	32.00
	EFP	435.70	1.00	10.90	5.10	0.00
	Tot. EF	7099.70	160.70	16.50	238.50	32.00
	EOP	7.20	0.00	0.20	0.20	0.00
	EOR	1.70	0.00	0.00	0.00	0.00
	Tot. EO	8.90	0.00	0.20	0.20	0.00
	TOT	**7108.60**	**160.70**	**16.50**	**238.50**	**32.00**

The analysis of kg CO_{2eq} confirmed what shown from the data reported in Tables 6–8. While there was no difference between AT and TT in Chiarano, AT led to a slight reduction of emissions in Pian Cansiglio and to a slight increase in Mongiana (Figure 3).

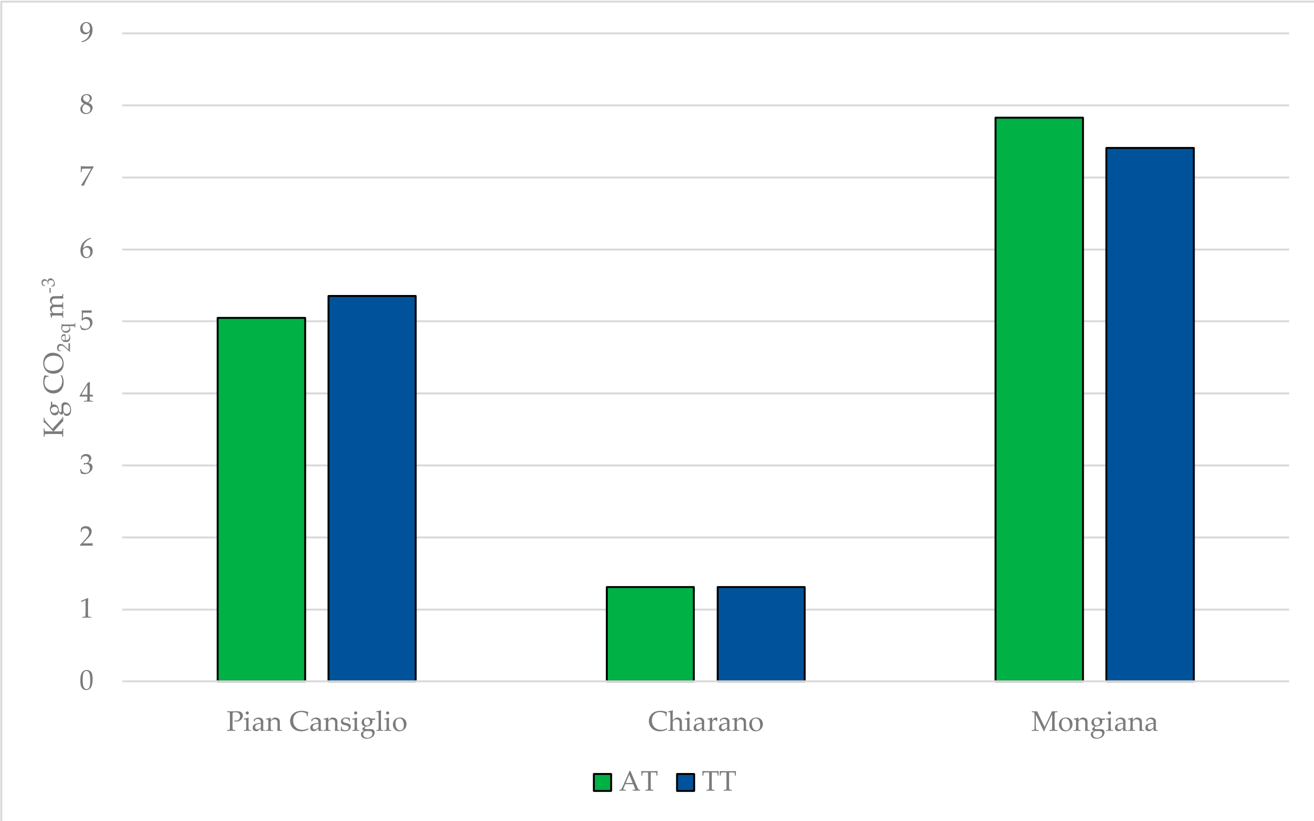

Figure 3. Analysis of kg CO_{2eq} per cubic meter of harvested wood.

4. Discussion

Comparing data on work productivity with similar studies carried out in hardwood high forests in different parts of the world, it is possible to notice how the values obtained in this study are very consistent with those in the literature.

Magagnotti and Spinelli (2011) reported a productivity of 1.9–3.0 m^3 PMH ^{1} for animal extraction in beech high forests, while a higher value of 4.0 m^3 PMH^{-1} was reported for extraction operations carried out by short wood system with a farm tractor equipped with frontal and rear loaders [46]. Obtained values are also in line with the range 3.2–5.0 m^3 PMH^{-1} reported by Vusić et al. (2013) for winching with a small-scale skidder in a mixed hardwood stand in Croatia [47] and even higher than the 2.836 m^3 SMH^{-1} for winching extraction in a poplar plantation in Central Italy performed with a tractor and a winch of similar dimensions as the ones applied in the Pian Cansiglio and Mongiana study areas [48].

The values of pollutant emissions are also consistent with similar studies in current literature. Indeed, for the yards in which extraction was performed in a mechanized way (Pian Cansiglio and Mongiana), the emission range of about 5–8 kg CO_{2eq} m^{-3} of harvested wood is in line with 7–9 kg CO_{2eq} m^{-3} shown by Vusić et al. (2013) [47] and 4.82–5.83 reported by Klein et al. (2016) for beech high forests harvested in Germany [49]. Obtained values are also in line with those reported by Haavikko et al. (2022) when analyzing thinning interventions in forest yards with a higher level of mechanization [50].

Focusing instead on the analysis of the effectiveness of the alternative thinning method based on crop-tree management (AT) in relation to economic and environmental aspects, the obtained results only partially confirmed the research hypotheses behind the experimental design. Although a substantial improvement in work productivity was achieved with the alternative thinning method AT, a reduction of pollutant emissions was not obtained.

The application of crop-tree management confirmed, therefore, its high suitability in the framework of improving cost-effectiveness of forest operations. Indeed, apart from providing higher quality timber [14,22], increased working productivity led to reduced harvesting costs. This was valid for the two study areas in which mechanized extraction operation was performed with a forestry-fitted farm tractor equipped with winch. In the Chiarano area, where animals were applied for extraction, there was no significant reduction in extraction costs.

This demonstrated how the design of the alternative thinning method is highly suitable to increase work productivity in winching operations, thanks to the fact that trees to be harvested are concentrated in a limited space around the target trees. Furthermore, crop tree management resulted in more stems per ha felled, providing more room to maneuver for the tractor and also reduced average costs due to gaining economies of scale—the more stems harvested, the more per unit costs will decrease. While there is the need to bring the mean of extraction close to the logs, such as in this case by the use of mules, the beneficial effects of crop-tree management in terms of improved working productivity are less evident.

Focusing instead on the analysis of pollutant emissions, the AT method led to better environmental performance than the traditional thinning method in the Pian Cansiglio area. However, there was an opposite trend in the Mongiana area, where despite higher working productivity in extraction operation, GHG emissions were about 5% higher in AT than in TT. This could be explained by the lower work productivity which was achieved in felling and processing operations in AT in comparison to TT in the Mongiana area. It was also due to the fact that this was the only area in which the average tree size was higher in TT than in AT, thus affecting the amount of extracted timber in the single working cycle.

Regarding costs and pollutant emission analysis in the study area where animals were used for timber extraction, it is shown how this harvesting system, as expected, produced lower emissions than the mechanized extraction approach. This is related to the absence of fuel emissions from machinery, which are only partially counterbalanced by the emissions related to animal physiological processes such as enteric fermentation and respiration. On the other hand, extraction costs were higher with negative consequences concerning the economic pillar of sustainability. Commonly, in the typical steep terrains with high roughness of the Mediterranean forestry, animal extraction is the only solution available. This is related to the scarce application of aerial extraction, which could be a suitable solution also in the framework of small-scale forestry [51,52].

It is worth highlighting that this study focused on only one harvesting entry in the rotation cycle. The effects on applying crop-tree management should be evaluated with a longer time perspective in further studies. Indeed, the larger canopy gaps related to crop-tree management are expected to trigger natural regeneration. In this case, the following harvesting entry, expected in about 15 years, would be more delicate, because the operators should drive tractors in order to limit damages to the established saplings, with possible decreased working productivity. Therefore, the present study should be repeated also to assess the influence of crop-tree management on work productivity, costs and emissions along all the rotation cycle.

5. Conclusions

Crop-tree management has been very much investigated in the last decades as a possible solution to improve Sustainable Forest Management in Europe. This study specifically aimed at assessing the potential of an alternative thinning method, applied with the SFOs approach and based on the concept of crop-tree management, under the aspects of economic and environmental sustainability.

Therefore, a comparative study on working time, productivity and costs between the alternative thinning method and the one traditionally applied (based on the shelterwood system) was carried out in three different study areas in Italy.

The alternative method showed increased work productivity and decreased harvesting costs in the study areas in which extraction operations were performed in a mechanized way. Decreased pollutant emissions were achieved only in one study area. Future studies should shed light on the damage various wood extraction practices have on human health, on the ecosystem quality and resource availability.

Regarding extraction operation using animals, there was no difference between the alternative and traditional thinning methods, including the economic aspects.

Tailoring thinning interventions according to the concept of crop-tree management showed increased cost-effectiveness of forest operations. In order to achieve lower emissions, different solutions should also be considered, such as electric tractors or electric chainsaws. These are worth taking into consideration, although the market still lacks the specific professional devices and tools for these purposes.

To conclude, the obtained results are encouraging for the implementation of crop-tree management as option in Mediterranean beech forests. However, future studies in the topic should be carried out to evaluate the effectiveness of crop tree management along all the rotation cycle, investigating both economic and environmental aspects of the application of this treatment also in the presence of established saplings after the previous interventions.

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