Operational and Environmental Comparison of Two Felling and Piling Alternatives for Whole Tree Thinnings in Quercus Coppices for Bioenergy Use

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Abstract

A comparative study of motor-manual and mechanized felling and bunching was conducted when thinning dense coppice stands of the two most important oak species in Spain to obtain biomass for bioenergy use. In particular, the study matched chainsaw felling and manual piling against the work of a drive-to-tree feller-buncher in the very same sites. Productivity functions for felling and piling are fitted for each species. The derived unit cost functions show that the felling-bunching costs are lower for the motor-manual option in both species stands, particularly for the smaller tree sizes. Nevertheless, when the strongly reduced loading times in forwarding associated to the mechanization are taken into account, the total harvesting cost is often lower for the mechanized option. That is true for all tree sizes *Q. ilex*, and for trees larger than 13 cm diameter at breast height (DBH) for *Q. pyrenaica*. Residual stand damage was low to moderate, but always significantly greater for the mechanized option compared with the motormanual one. Soil damage was very low for both alternatives. The stumps experimented significantly greater damages in the mechanized felling and bunching, but further research is needed to determine if those damages have any impact on stump mortality, sprouting capability and future plants vigor. The greater productivity and level of tree damages found in *Q.ilex* when compared to *Q. pyrenaica* are likely due to the narrower and lighter crown of the latter.

1. Introduction

Social and economic changes during the second half of 20th Century have led to the reduction of the profitability of coppice systems in Europe, so that they have been largely abandoned in most Countries [1]. Abandonment has brought about the underutilization of this relevant natural resource, as well as a loss in the biodiversity associated with traditional silvicultural practice [2]. Aging and densification have increased vulnerability to natural disasters such as windthrow and wildfire, that have become more frequent during the last Century [3] and are estimated to provoke annual losses close to a million cubic meters in Europe by 2030 [4].

Coppice thinning would reduce wildfire suppression costs, especially if whole-tree harvesting (WTH) is adopted, because complete biomass removal reduces potential fire severity compared with other harvesting methods that leave large amounts of branches and tops within the stand [5]. Developing and operationalizing fuel treatment options that are technically possible, but not yet widely deployed has been pointed out as a priority in future research for woody biomass utilization [6]

In Spain, coppice forests cover roughly 4 M ha and represent 20% of the total forest area, with Holm oak (*Quercus ilex* L.) and Melojo oak (*Q. pyrenaica* Willd.) as the dominant species [7]. Hence, coppices are a potential major source of biomass for bioenergy or bioproducts.

Choosing site-appropriate techniques and equipment is essential for the economic sustainability of the entire supply chain [8]. This is particularly important for coppices, where operators must face small stem sizes and stump crowding, which increase operational costs [9].

Coppice harvesting technology is evolving toward increased mechanization and larger and more efficient equipment [10]. Mechanization leads to higher productivity and lower unit costs for woody products from coppice forests [11]. Moreover, increasing the mechanization level in forest operations contributes to reducing both the severity and the frequency of accidents and/or occupational diseases [12].

The mechanized harvesting of coppice forests is technically and economically complex, due to the difficulty encountered by a felling head when approaching stems that are gathered in a clump on the same stump [13]. Also the undesired potential effects of mechanization – damage to soil, residual stand and stumps – have raised concern among forest managers and scientists [14, 15], and must be considered when implementing a mechanized harvesting technology.

One of the available technologies for mechanized felling consists of a feller-buncher head equipped with a disk saw. Its advantage lies in the high cutting speed and in the ability to manage multiple stems in a single pass. This type of felling head has been tried recently in Mediterranean coppices, where it has proved less effective than in SRC but especially capable to contain stump damage, when compared with shears [13].

The Spanish forest company SOMACYL began the field trial of a drive-to-tree disc saw feller-buncher for use in coppice harvesting for whole tree bioenergy use, which provided an ideal opportunity for conducting carefully designed time and motion studies with the purpose of evaluating operational productivity, cost, product recovery and site damage. The results were presented in [16].

Alongside mechanized felling, the same enterprise also deployed motor-manual felling and bunching, which is still the traditional mainstream method: therefore, the collection of data on motor-manual felling in a second phase of the study allowed a comparison of the two systems.

Thus, the main goals of the present phase of the study are:

- Developing productivity equations for motor-manual felling and bunching and for both coppice types (i.e. *Q. ilex* and *Q. Pyrenaica*)
- Using these equations to estimate the operational cost of motor-manual felling and bunching
- Comparing the cost of motor-manual felling and mechanized felling under varying tree size conditions for both coppice types (i.e. *Q. ilex* and *Q. pyrenaica*) and for the felling and bunching only, as well as for the whole operation – from standing trees to cut trees piled at the landing.
- Assessing the environmental impacts of the motor-manual option on the soil, the remaining trees and the stumps, and comparing these impacts with those previously recorded for the mechanized system.
- Estimating biomass collection efficiency (percentage of available biomass actually collected) and comparing this figure with those previously obtained for the mechanized option.

2. Material And Methods

Both test stands were located in the Palencia province (Central Spain): one of them was dominated by Holm oak (*Quercus ilex*) and the other by Melojo oak (*Quercus pyrenaica*).

Mechanized felling and bunching was conducted with a John Deere 643J (130 kW, 12.7 t) carrier, equipped with a JD FD45 disc-saw accumulating head. This was a drive-to-tree feller-buncher, without a boom arm.

Motor-manual felling was conducted by a three-men team. Whereby two workers directionally felled trees using medium-sized chainsaws, and a third worker formed trees into bunches ready for collection.

In both cases, trees were moved to the roadside landing with a John Deere 1910E forwarder (186 kW, 19 t loading capacity), connected to a compressing trailer Dutch Dragon PC-48.

Both the feller-buncher and the motor-manual team worked on 34 paired 25x25 m^2 plots equally distributed between the two coppices and considered as replications in the statistical analysis of results. That amounted to 8 and 9 replications per machine treatment and coppice type.

Both forests were inventoried before and after harvesting using conventional forest mensuration techniques and tools.

2.2.1. Pre-harvest inventory

17 pairs of 25x25 m^2 square plots were randomly allocated, 9 of the pairs in the *Q. ilex* coppice and the remaining 8 pairs in the *Q. pyrenaica* forest. The diameter at breast height (DBH) of all trees was measured. To estimate the dry weight of the felled trees, a weight table was fitted in the previous study by weighing and measuring around 30 trees per each specie and sampling them for assessing moisture content, accordingly to the ISO 18134-3:2015 standard. Measured trees and plots borders were marked.

2.2.2. Time study and produced biomass evaluation.

The previous feller-buncher time study [16] was performed on a cycle level using a Husky Hunter field computer fitted with the software Siwork3 [17]. For the motor-manual time study, the activity sampling method was adopted instead, because three workers had to be simultaneously studied [18]. Both methods would still return the same information.

To assess the biomass extracted from each plot, the forwarder piled the whole trees coming from each plot in a separate pile at the roadside. Each pile was chipped, transported and weighed separately, and the chips from each pile were sampled for determining moisture content according to the gravimetric method.

To fit the productivity function, a multiple linear regression analysis was performed, using the data from 14 out of the 17 studied plots (one was felled before the work study, other two were rejected because of the out-of-range studentized residuals). Tested independent variables were: species (as a dummy variable); dry weight per tree (initial stand); dry weight per extracted tree (removals only); dry weight per ha; initial number of trees per ha; extracted number of trees per ha; extracted basal area; percentage of total basal area actually extracted.

During forwarding, one whole shift was time-studied for each work system (mechanized and motor-manual), measuring the number of trips and piles in order to get an estimate of average extraction productivity. To assess harvesting cost per unit product, actual machine rates and worker costs were provided by the involved enterprise, SOMACYL.

2.2.3. Post-harvest inventory and damage assessment

The DBH of all remaining trees inside each plot was determined.

The damage to the remaining trees were characterized inside each of the 25x25 m^2 plots, following the methodology proposed by [19].

Soil damage levels were determined according to the methodology proposed by [20], applied to 4 m radius circular sub-plot whose center was located in the crossing points of every square plots diagonals.

The stumps inside those subplots were also counted, measuring their heights and assessing the occurrence, type and severity of any eventual damage.

2.2.4. Measurement of biomass collection efficiency.

Inside the above-mentioned sub-plots, the biomass left on the terrain was collected and weighed, taking two samples for moisture content estimation. That would offer a measure of eventual harvesting losses and – indirectly – of overall harvesting efficiency.

3. Results

3.1. Coppice inventory and treatment description

The initial density of the *Quercus ilex* coppice was 5,310 trees·ha^{-1}, with a mean DBH of 5.9 cm, a mean height of 4.1 m, and a mean basal area of 14.3 $m^2 \cdot ha^{-1}$. The average number of stools per ha was 886, with an average number of 6.0 sprouts per stool. The treatment consisted on the removal of 90% of the trees number and 63% of the basal area, leaving 545 remaining trees per hectare.

The *Quercus pyrenaica* coppice had a mean initial density 3,868 trees·ha^{-1} and a mean DBH of 6.7 cm. Mean height was close to 6.0 m and mean basal area was 13.6 m^2·ha^{-1}. The mean number of stools·ha^{-1} was 1,004, with an average number of sprouts per stool of 2.8. There were also 2,564 isolated oaks·ha^{-1}. The treatment led to the extraction of an 81.5% of these trees and a 47% of the initial basal area, leaving 716 trees·ha^{-1}.

The removed weight ranged between 18 and 59 dry tonnes (odt)·ha^{-1} in the *Q. Ilex* coppice (averaging 40 odt·ha^{-1}) and between 6 and 38 odt·ha^{-1} (averaging 21 odt·ha^{-1}) for *Q. pyrenaica*. Therefore, the harvest was twice as large in the *Q. ilex* stand, compared with the *Q. pyrenaica* stand.

3.2. Time study

In *Q.ilex*, the productivity of motor-manual felling and bunching ranged between 2.5 and 3.5 odt per productive hour (odt·Prodh^{-1}), for the team of three workers. Delays were almost zero, as no incident or other breakdowns occurred during the time study. Average productivity inside the studied plots was 2.85 odt·Prodh^{-1}.

In *Q. pyrenaica*, productivity for the same team ranged between 0. 9 and 3.2 odt·Prodh^{-1}. No delays or incidents were recorded here, either. Average productivity reached 2.18 odt·Prodh^{-1}.

3.3. Productivity equation for motor-manual felling and bunching

Significant explanatory variables were: tree species and dry weight per tree. The former was introduced as an indicator variable for *Q. ilex*, with *Q. pyrenaica* as the null baseline, while the latter was the estimated mean tree weight for the initial stand, before thinning. All other variables tested turned out as not significant or less significant than their competitors (in the case where two independent variables would express the same general property and could not be introduced together into the same equation under pain of nullity due to autocorrelation).

The fitted regression curve is:

$$Productivity(odt \cdot Prodh^{-1}) = 0.945 + 0.867 \cdot Qilex(0/1) + 0.082 \cdot DryWeightPerTree(kg_{MS} \cdot tree^{-1}) \quad (1)$$

Its regression statistics are shown in Table 1.

Table 1: Fitting statistics of the productivity regression curve

Multiple regression – Productivity				
Dependent variable: Productivity (odt·ProdHour-1)				
Independent variables:				
Qilex (1 if Species = *Quercus ilex*, 0 if Species = *Q. pyrenaica*)				
Dry Weight ·Tree^{-1} (average odkg·tree^{-1} before thinning)				
Observations number: 14				
Parameter	Estimation	Standard error	T-Statistic	P-Value
Constant	0.945	0.399	2.37	0.0372
Qilex	0.867	0.205	4.23	0.0014
odkg·tree^{-1}	0.082	0.024	3.45	0.0055
ANOVA				
Source	Squares sum	DF	Average Square	F-ratio
Model	2.86	2	1.43	11.24
Residual	1.40	11	0.127	
Total (Corr.)	4.26	13		
R-square = 67.2 %				
R-square (adjusted by d.f.) = 61.2 %				
Standard est. error = 0.36				
Medium Absolute Error = 0.24				
Durbin-Watson Statistic = 2.32 (P=0.60)				

Using the average values of productivity and the average removal per ha, the required time per ha in the studied coppices conditions was estimated as 14.0 productive hours (16.5 Workh)·ha^{-1} for *Q. ilex* and 9.6 productive hours (11.3 Workh)·ha^{-1} for *Q. pyrenaica*.

3.4. Unit cost estimation.

Hourly cost for the workers team (21 €·$Workh^{-1}$ per worker, or 63 €·$Workh^{-1}$ for the three-men team, including chainsaws) was provided by [21]. The company also produced the rental costs of the forwarder case (€·$Workh^{-1}$) and the chipper (€·fresh $tonne^{-1}$). Transportation cost was estimated for a distance of 80 km one way, as had been done for the mechanized system.

All following estimates of revenues and cost were based on the following measurements: average water mass fraction of chips equal to15.3 and 34.5%, for *Q.ilex* and *Q.pyrenaica,* respectively; machine utilization (ratio of productive work time to total paid time for the workers team) equal to 85%. The study also accounted for the longer loading time of the forwarder when under the motor-manual treatment, that brought about a drop in productivity comparing to the mechanized option. Basing in the forwarding follow-up study during a whole work shift per stratum, the extraction productivity decreased from 7.0 to 4.3 odt·$Prodh^{-1}$ for the *Q.ilex* coppice and from 6.6 to 3.9 odt·$Prodh^{-1}$ for the *Q. pyrenaica* stand, consequent to the less efficient bunching. Cost calculation results are reflected in Table 2.

Table 2: Operational costs and total unit costs for motor-manual operations

Operation/s	Hourly cost Team / machine (€·$Workh^{-1}$)	Hourly cost Team / machine (€·$Prodh^{-1}$)	Average productivity (odt·$Prodh^{-1}$)		Unit cost renting (€·fresh $tonne^{-1}$)	Unit cost (€·odt^{-1})	
			Q-.ilex	*Q. pyrenaica*		*Q. ilex*	*Q. pyrenaica*
Felling/bunching	63.0	74.1	2.85	2.18	—	26.00	33.99
Extracting w/forwarder	71.5	79.4	4.28	3.88	—	18.56	20.46
Chipping	—	—			11.0	12.99	16.79
Chip transport (dist = 80 km)	—	—	—	—	7.46	8.81	11.39
Total (direct unit cost)	—	—	—	—	—	66.36	82.63
+15% overheads	—	—	—	—	—	**76.31**	**95.03**

Delivered cost was 66 €·odt^{-1} for *Q. ilex* and 83 €·odt^{-1} for *Q. pyrenaica* chips. If these figures are increased by 15% to cover overheads (e.g. relocation, indirect and structural costs), actual delivered cost grows to 76 €·odt^{-1} and 95 €·odt^{-1}, respectively. The cost for *Q. ilex* is slightly lower than that estimated for the mechanized option (78 €·odt^{-1}, in [16]); this is partially due to the chips' observed moisture in the motor-manual treatment, quite low. This fact reduced the transport and chipping costs, paid on a fresh tonne basis. For *Q. pyrenaica*, the motor-manual cost is clearly much lower than the estimated for the mechanized option, 120 €·odt^{-1} [16].

Regarding the influence of the explanatory variables on cost, the Productivity equation (1) (Table 1) can be obtained using the team hourly cost combined with the mentioned equation, as:

$$Unit\ cost\ (€ \cdot odt^{-1}) = 63 \cdot [0.945 + 0.082 \cdot DryWeightPerTree\ (kg_{MS} \cdot tree^{-1}) + 0.867 \cdot Qilex(1/0)]^{-1} \quad (2)$$

Total operational cost per tonne for the average observed conditions can be transformed in a cost per hectare, that is equal to 3,052 €·ha^{-1} for *Q.ilex* (removal = 40 odt ha^{-1}) and 1,979 €·ha^{-1} for *Q. pyrenaica* (removal = 21 odt ha^{-1}). These figures exclude stumpage and contractor's profit.

Current prices (end of 2020) for a fresh tonne of whole tree chips with moisture contents of 15.3% and 34.5%, as in the studied coppices, are 63 and 46 €, respectively. Those correspond to 74 and 70 €·odt^{-1} [21]. Under such conditions, the net operational balance is negative and equal to -92.0 €·ha^{-1} for *Q. ilex* and -509 €·ha^{-1} for *Q. pyrenaica* – and that without accounting for stumpage and contractor's profit. Losses are much smaller for *Q. ilex* due to the larger removal and especially to the production of drier chips, which had a positive effect on pricing and transportation efficiency.

3.5. Environmental impacts.

The frequency and severity of residual tree damage is shown in Table 3, separately for each species. Damages frequency is significantly higher for *Q.ilex*, especially for damages that affect the wood and are caused by chainsaw felling. That might depend on the higher stand density, the smaller size and the thinner bark of *Q. ilex* trees, when compared with *Q. pyrenaica*.

Nevertheless, injures are mostly small or medium-size (surface smaller than 200 cm^2), particularly in *Q. ilex.* In *Q. pyrenaica* forwarder traffic accounts for most damage, while in *Q.ilex* 25% of the damages are felling injures caused by the chainsaws.

The frequency of deep damage is small – close to 5% - and similar for both species. However, while deep damage in *Q. ilex* is mostly represented by chainsaw cuts digging into the wood, in *Q. pyrenaica* deep damage is mostly caused by the forwarder and results in larger wounds (exposed surface > 200 cm^2).

Table 3: Damages on remaining trees from motor-manual coppice harvesting by species (note: The different letters (a and b) indicate statistically significant differences (<5%) between the two species).

DAMAGES IN REMAINING TREES (% DAMAGED TREES OVER TOTAL NUMBER)														
Type	**Qi**	**Qp**	**Location**	**Qi**	**Qp**	**Height**	**Qi**	**Qp**	**Size**	**Qi**	**Qp**	**Cause**	**Qi**	**Qp**
Bark	4.0 a	6.2 a	**Stem**	10.6 a	9.5 a	**Low (0-0.3 m)**	2.0 a	0.0a	**Small (<50 cm^2)**	**12.1 a**	**5.9 b**	**Machine movement**	**75.0 a**	**100.0 b**
Wood	**5.2 a**	**0.3 b**												
Broken branches	4.8 a	4.5 a	**Crown**	3.6 a	1.5 a	**Medium (0.3-1.0 m)**	4.4 a	3.3 a	Medium-sized (50-200 cm^2)	1.6 a	2.1 a	**Cutting injure**	**25.0 a**	**0.0 b**
Destroyed crown	0.0 a	0.0 a												
Total	14.1 a	11.0 a	**Roots**	0.0 a	0.0 a	**High (> 1.0 m)**	7.3 a	7.7 a	**Large (>200 cm^2)**	**0.4 a**	**3.0 b**	**Others**	0.0 a	0.0 a
Severe	5.2 a	3.9 a												

Results from the survey of stump and soil are summarized in Table 4. Soil damage was not severe and mostly consisted of light superficial disturbance, such as litter scuffing and shallow rutting not deeper than 5 cm. Disturbance was recorded on 6% of the total surface in *Q. pyrenaica* and 16% in *Q. ilex,* but differences were not significant. In general, disturbance was blamed on forwarder traffic, potentially more intense in *Q. ilex* due to the larger removals and the bigger crown size.

Stump damage was infrequent and generally minor: less than 10% of the stumps showed cracking or other severe damage, much less than those damages recorded in the previous study about the mechanized option [16].

Table 4: Soil and stumps damages after motor manual harvesting by species.

	SOIL DAMAGES, PERCENTAGE OF TOTAL SURFACE			
SPECIE	**No damage evidence**	**Present litter, slight alteration**	**Litter removed, surface soil exposed**	**Litter and Surface soil mixed, ruts deeper than 5 cm**
Quercus ilex	0.0	15.7	0.0	0.0
Quercus pyrenaica	0.0	6.4	0.0	0.0

	STUMP HEIGHT, % OF STUMPS NUMBER			**STUMP STATUS, % OF STUMPS NUMBER**				
SPECIE	<10 cm	10-20 cm	>20 cm	No damage	<50% bark separated	>50% bark separated	Cracked stump	Destroyed stump
Quercus ilex	45.6	50.6	3.8	58.7	26.0	6.8	3.4	5.1
Quercus pyrenaica	28.9	59.8	11.3	71.1	17.5	3.1	5.2	3.1

3.6. Efficency in biomass collection.

Biomass harvesting efficiency ranged between the 83 and 99% (*Q. ilex* and *Q. pyrenaica*, respectively), taking as a reference the theoretical weight estimated through the inventory. Biomass losses averaged 3.7 odt·ha^{-1} for *Q. ilex* and 2.1 odt·ha^{-1} for *Q. pyrenaica*., including shrubs left on site.

3.7. Comparison with the mechanized option.

3.7.1. Felling-bunching costs

For the purpose of this comparison, only the data for felling and bunching were extracted from the previous study, since differences in wood moisture content between the two studies would unduly affect the results for all subsequent operations, and especially transportation. In the latter case, even the necessary normalization of data to the dry weight basis would not produce a satisfactory result, because moisture content would affect actual payload and therefore reflect on transportation performance despite normalization.

Furthermore, the analysis also took into account the impact of different felling techniques (i.e. motor-manual or mechanized) on extraction, due to the different characteristics of bunches obtained from the two different treatments, whereby the mechanized treatment would produce larger and better aligned bunches compared with the motor-manual treatment

Data for mechanized felling and bunching were analyzed the same way as for motor-manual felling and bunching obtaining the same type of regression equation, capable of estimating productivity as a function of species, unit dry weight and percentage of removed basal area [16]. This equation was used to estimate the productivity of mechanized felling for the same mean tree size values found in the motor-manual study and the same mean percentage of removed basal area, equal to 70% and 45% respectively for *Q. ilex* and *Q. pyrenaica*. Trying to use an explanative factor simpler and easier to measure than the unit dry weight per tree, the weight tables developed as a function of DBHs by [16] are used to substitute the initial explanative variable (unit weight) by the DBH.

As the forwarder hourly cost was 79.4 €·Prodh-1 (Table 2), the increased forwarding productivity of the mechanized option (4.3 to 7.0 odt·Prodh^{-1} for *Q.ilex* and 3.9 to 6.6 odt·Prodh-1 for *Q. pyrenaica*) brought about increments of unit costs for forwarding in the motor-manual operation, that reached 7.2 €·odt^{-1} for *Q. ilex* and 8.4 €·odt^{-1} for *Q. pyrenaica*. These costs were added to the direct costs of felling and bunching in the motor-manual case to compare both options having into account these over costs. The result of the direct cost comparison is shown in Figures 1 and 2, respectively for *Q. ilex* and *Q. pyrenaica*.

In the *Q. ilex* case (Fig. 1), felling and bunching – having into account their influence in forwarding cost – is less costly for the mechanized option, particularly for the larger DBHs (for the observed range, the difference is small). In fact, in the studied case and for the mean DBH, the unit cost for felling and bunching alone was 31.5 €·odt^{-1}, for the mechanized option and 26.0 €·odt^{-1} for the motor-manual one. However, once the additional forwarding cost resulting from motor-manual felling is accounted for, then the motor-manual system is a slightly (6%) more expensive chain, at 33.2 €·odt^{-1}.

In the *Q. pyrenaica* coppice, the mechanized option is generally more expensive, particularly for small trees such as the observed ones. The difference decreases with increasing tree size, break-even being achieved at around 13 cm – DBH out of the observed range, and that after the differences in extraction cost have been taken into account. For trees larger than 13 cm DBH, the mechanized option would be slightly preferable: however, *Q. pyrenaica* stands are dense coppice formation of generally smaller trees than that.

Therefore, for the average conditions encountered in the studied *Q. pyrenaica* coppice, the mechanized option would have an average felling and bunching unit cost of 69.0 €·odt^{-1}, clearly more expensive than the motor-manual option (direct cost 34.0 €·odt^{-1}; adding the 8.4 €·odt^{-1} forwarding extra cost it would be 42.4 €·odt^{-1}).

3.7.2. Treatment quality and environmental effects.

Treatment conditions regarding thinning intensity and selectivity has been quite similar in the plots mechanized with feller-buncher if compared to the felled and bunched motor-manually.

The frequency of residual tree damage in *Q. ilex* was 14 and 54%, respectively for the motor-manual and the mechanized system. If only severe wounds larger than 200 cm^2 and/or affecting the wood are taken into account, then frequency is 5.2% and 10.0%, respectively. However, these differences are not statistically significant, due to very wide variation in damage level from one plot to another.

The same trends are true for *Q. pyrenaica* as well, although the numbers are smaller: 11.0 and 22.4% for the motor-manual and the mechanized treatments respectively, in terms of total wounded tree frequency, regardless of wound type and severity. When only sever wounds are taken into account, then frequency drops to 3.9 and 10.3%, respectively. This time, differences between treatments are statistically significant.

Soil disturbance was negligible for both treatments and stand types, probably because of the flat terrain and the sandy soils, which was quite dry during the harvesting operations. These conditions make the soil especially resistant to disturbance, which was once again verified on occasion of our study.

Mechanized felling resulted in extensive stump damage, and so did motor-manual felling although in a smaller measure. The consequences of such damage are still unclear and require further investigation [14].

4. Discussion And Conclusions

Tree size (DBH, unit volume or weight) is the most common explanatory variable in any productivity equations for felling and bunching [10, 13, 22, 23, 24, 25, 26]. That was verified in this study, as well. However, this same study could not find any significant association between productivity and removal (mass per hectare or basal area), as reported in many other studies [10, 16]. Probably the range of variation in the studied coppices was not wide enough for such association to emerge.

The influence of tree species is likely explained by the different crown structure of *Q. ilex* and *Q. pyrenaica* [27], which may have had an effect on handling efficiency during felling and bunching.

The study also clearly shows that a proper evaluation of different mechanization levels must cover the whole chain and cannot be restricted to one link, only. Otherwise, mechanized felling would generally prove a poor alternative to motor-manual felling, since it generally results in a higher felling cost. In fact, the financial benefits of mechanized felling are generally accrued during extraction, due to the much better characteristics of the bunches, which are larger, more coherent and better aligned. This has been already observed in past comparisons, whereby mechanized felling turned out to offer no cost savings for itself, but was instrumental to a dramatic reduction of extraction cost [28, 29].

As exposed in the Results, the studied operations would all incur financial losses, although work in *Q. ilex* was very close to breaking even. Using the studied technologies, the possibilities to reach the self-financing require applying them to coppices with bigger trees – which are not available in most cases, except for very aged coppice stands. On the other hand, profitability could possibly be achieved by reducing costs – for instance by owning and managing the machinery instead of renting it, or by allowing for a better drying of the trees before chipping, in order to increase transportation efficiency.

The break even of unit cost between the motor-manual and the fully mechanized harvesting options for *Q. pyrenaica* is consistent with former similar studies, comparing motor-manual and mechanized felling and processing [30].

Concerning residual tree damage, the lower performance of mechanized felling and bunching contradicts the results of previous similar studies, which have found mechanized felling to cause less damage than motor-manual felling [18, 31]. However, the quoted studies were conducted with larger trees, using swing-to-tree feller-bunchers, which worked from corridor and were able to accurate control tree fall, so as to avoid impact with the surrounding trees. In the present study, trees were much smaller, and the issue of them impacting residual trees was not as crucial. What is more, the feller-buncher deployed in this study was a drive-to-tree type, which would maneuver extensively in order to approach the trees, bumping against surrounding residual trees much more often than normal for a swing-to-tree machine [16, 32].

Few studies offer accurate information about the stump damage caused by mechanized felling in coppice stands. Most of them point at a the rough handling of stumps and the higher damage level when compared with traditional motor-manual felling [13, 22]; although the future relevance for the vigor and growth of the regeneration has not been found to be clear [14].

The main conclusions of the present work are the following:

- roductivity equations for motor-manual felling and bunching in *Quercus* coppices harvested for bioenergy use have been developed, the main explanatory factors in these equations are: species and the average tree weight, as recorded in the pre-harvest inventory.
- The economic balance of the studied operations is generally negative and the operation incurs financial losses, although one may get very close to break even it in the case of *Q. ilex* when resorting to fully mechanized operations. However, the study identified measures to reduce losses and lead to profitability. This said, harvesting this type of low-yielding coppice stands remains a low-profit operation, which may find its main motivation in the need for land management and landscape preservation, rather than in the interest for sustained profits.
- Mechanized felling and bunching has a higher cost than the motor-manual equivalent operations. Nonetheless, the mechanized bunching allows for a significant reduction of extraction cost. In *Q.ilex*, this leads to mechanized harvesting being less costly than motor-manual harvesting, especially when dealing with tree sizes in the higher end of the range In *Q. pyrenaica*, mechanized harvesting is less expensive only when the average tree DBH is greater than 13 cm, having the mechanized operations very high costs for the smaller diameters inside the studied range.
- Although the silvicultural results of the treatments have been similar and adequate to the management prescriptions for all mechanization levels, damage to the residual stand and stumps is significantly more frequent for the mechanized option. This has been particularly true with *Q. ilex* trees, which have bulkier crowns with thicker branches. Nevertheless, severe damages – larger than 200 cm^2 or affecting wood tissue – were found on less than 10% of the remaining trees in all studied cases and will not be much relevant considering the destination of harvested wood – chips for energy.
- The stump damages were more severe with mechanized harvesting: to date, very little scientific evidence is yet available on the effect of stump damage on stump mortality and resprouting vigor, and the little such evidence points at a substantial indifference. Even so, it would be safer to extend this study to a follow-up of stump regeneration.

In any case, the convenience of forest operations mechanization is undeniable, both because of the higher and sustained production capacity and of the dramatic improvement of workplace safety. Nevertheless, one may devote further effort to a better selection of specific machine types and models and to define the optimized work system for coppice harvesting for bioenergy production, despite their difficult conditions if compared to other stand types.

Declarations

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Conflicts of interest/Competing interests: The authors declare no conflict of interets

Availability of data and material : The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Authors' contributions: Conceptualization: Eduardo Tolosana, Rubén Laina; Methodology: Eduardo Tolosana, raffaele Spinelli; Data Curation: Eduardo Tolosana, Giovanni Aminti, Ignacio López-Vicens; Investigation: Eduardo Tolosana, Rubén laina, Giovanni Aminti, Ignacio López-Vicens; Resources: Eduardo Tolosana, Raffaele Spinelli; Writing – original draft: Eduardo Tolosana; Writing – review & editing: Raffaele Spinelli.

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Figures

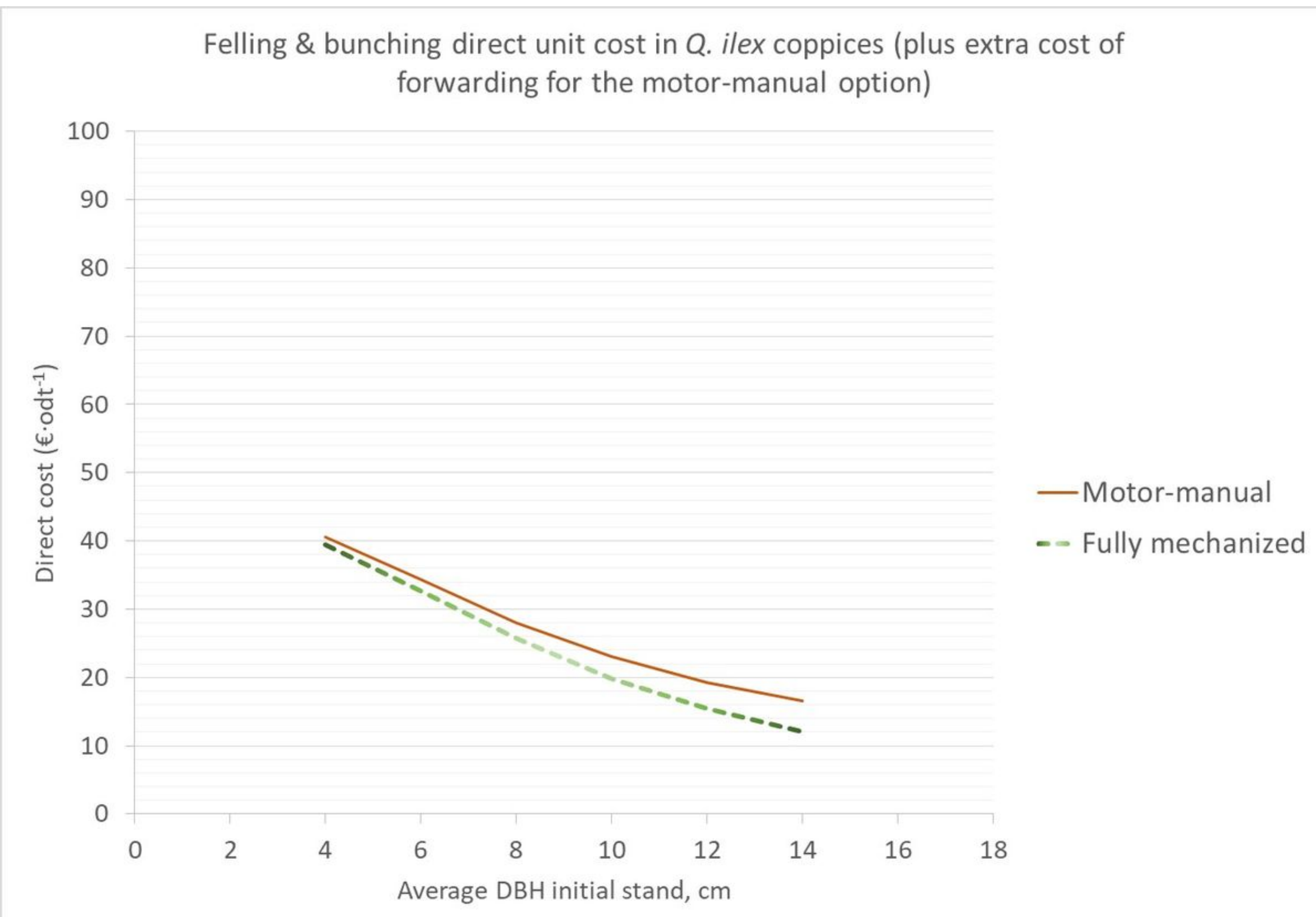

Figure 1

Unit direct cost of motor-manual and mechanized felling and bunching for Quercus ilex coppices.

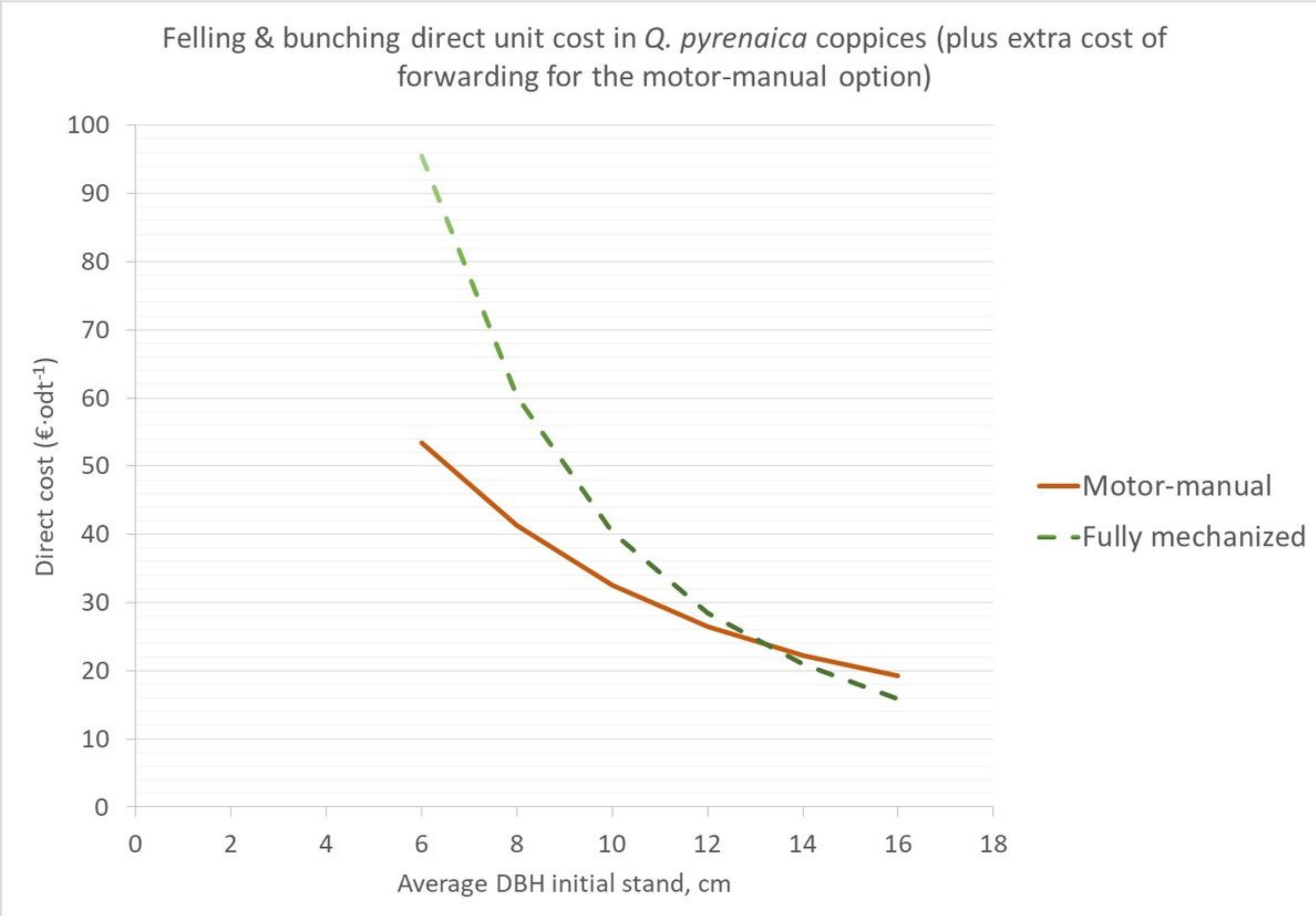

Figure 2

Unit direct cost of motor-manual and mechanized felling and bunching for Quercus pyrenaica coppices.