Original scientific paper

Productivity, Efficiency and Environmental Effects of Whole-Tree Harvesting in Spanish Coppice Stands Using a Drive-to-Tree Disc Saw Feller-Buncher

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Abstract

*Whole tree harvesting was conducted on two coppice stands with different tree composition (*Q. ilex *and* Q. pyrenaica*) in gentle terrain. Felling and bunching were performed by a drive-to-tree wheeled feller-buncher with disc saw head. Operations were analyzed on 17 plots 25x25 m^2 in order to develop productivity models and to assess operational costs. The study also aimed at determining biomass collection efficiency and evaluating the impact of the new harvesting method on the soil, the remaining trees and stumps. The treatment consisted in a strong coppice thinning leaving standards. Productivity ranged from 2.8 to 4.6 odt/pmh in the* Q. ilex *coppice, and from 0.9 to 2.6 in the* Q. pyrenaica *stand. Tree species, dry weight per tree and percentage of removed basal area were the main independent variables affecting productivity. Approximately 50% of the standards showed damages. Most wounds were light, caused by the drive-to-tree work pattern, followed through GPS tracking. Soil damage was also light; in no plots, deep disturbances were found. However, most of the stumps were damaged. Forwarding and chipping productivity and cost were also evaluated. The slash left on the terrain averaged 3.0 and 1.5 odt/ha in* Q. ilex *and* Q. pyrenaica*, respectively, including scrub debris. As a conclusion, while this heavy feller-buncher can be useful in coppice heavy thinnings with larger trees, it would be a good option to try lighter disc saw felling heads mounted on the harvester boom tip, which probably would reach better productivity and reduce the frequency of stand damage.*

Keywords: Whole tree harvesting system, Quercus ilex, Quercus pyrenaica, *harvesting damages, operational cost, work study*

1. Introduction

Coppice management has been abandoned in many European countries after WWII because of the social and economic transformation of European society, which has made traditional coppicing practices less profitable (Carvalho et al. 2017). Abandonment resulted in the underutilization of the large coppice forest resources and in the loss of biodiversity (Müllerová et al. 2015). The densification and aging of forests have made them more vulnerable to disturbances such as storms or wildfires, which have significantly increased during the past century (Schelhaas et al. 2003) and are estimated to increase by almost one million m^3/y in Europe by 2030 (Seidl et al. 2014).

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 slash within the stand (Corona et al. 2015).

In Spain, coppice forests cover roughly 4 M ha and represent 20 % of the total forest area; Holm oak (*Quercus* *ilex*) and Melojo oak (*Q. pyrenaica*) are the dominant forest species in Spanish coppice forests (Piqué and Vericat in Nicolescu et al. 2017).

The use of site-appropriate equipment and techniques is crucial to the financial sustainability of the whole supply chain (Enache et al. 2015). This is even more important for coppice forests, where operators must cope with small stem size and stump crowding, which increase operational costs (Spinelli et al. 2017a).

Coppice harvesting technology is evolving toward increased mechanization and larger and more efficient equipment (Spinelli et al. 2016). The growing mechanization level leads to higher productivity and lower unit costs for woody products from coppice forests (Laina et al. 2013). Moreover, increasing the mechanization level in forest operations contributes to reducing both the severity and the frequency of accidents and/or occupational diseases (Albizu et al. 2013).

Harvesting of coppice forests is technically and economically difficult, due to the difficulty encountered by a harvester head when approaching stems that are gathered in a clump on the same stump (Schweier et al. 2015). Also, the undesired potential effects of mechanization – damage to soil, residual stand, stumps and sprouting ability – have raised concern among forest managers and scientists (Pyttel et al. 2013, Spinelli et al. 2017b), 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. This technology has been tried with good results in SRC (short rotation coppice) by Iwarsson (2008). 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 proved less effective than in SRC but highly capable to contain stump damage, when compared with shears (Schweier et al. 2015).

In 2017, the Spanish forest company SOMACYL began the field trial of a drive-to-tree disc saw feller-buncher for use in coppice harvesting, which provided an ideal opportunity for conducting carefully designed time and motion studies for evaluating operational productivity, cost, product recovery and site damage.

The main goals of the present study were as follows:

⇒ developing productivity models based on significant explanatory factors and use the models to assess the operational costs

⇒ evaluating the impact of the new harvesting method on the soil, the remaining trees and stumps

⇒ determining biomass collection efficiency (percent of total available biomass actually recovered) and biomass retention (i.e. amount of biomass left on the terrain).

2. Material and methods

The selected base machine was a 130 kW John Deere 643J articulated carrier with a total mass of 12.7 tonnes, equipped with a felling head JD FD45, with 51 cm cut capacity, a 0.64 m^2 accumulation capacity and a total weight of 2.2 tonnes. The felling head was mounted on the carrier front lift, so that the machine had to drive towards each of the tree clumps targeted for felling (i.e. drive-to-tree feller buncher).

The machine was tested on two separate coppice stands, one dominated by holm oak (*Quercus ilex* L.) and the other by melojo oak (*Quercus pyrenaica* Willd.).

Both sites were measured and characterized before and after harvesting.

2.1 Pre-harvest inventory

Seventeen 25x25 m^2 plots were randomly distributed across each forest site, 9 in the *Q. ilex* stand and 8 in the *Q. pyrenaica* coppice. On each plot, the diameter at breast height (DBH) of all the trees was measured, and the trees were marked with color paint. The limits of the plots – N–S and E–W lines – were marked with colored plastic tape and painted wooden poles at their corners. The silvicultural treatment was performed around the plots prior to the time study, so that the machine operator could work in close-to-real conditions within the plots. This work was planned together with the operation managers working for the enterprise concerned, SOMACYL.

2.2 Post-harvest inventory

Just after the mechanized felling and piling, bunches were counted and the number of trees per bunch was estimated. The DBH and height of 10 felled trees per plot was determined, and 3–4 additional trees were weighed in order to fit the weight table. A sample was taken and weighed for moisture determination. The DBH of all residual trees in the original 25x25 m plots was also determined.

2.3 Characterization, height-DBH equation and weight table fitting

Treatment characteristics were obtained from the comparison of the pre- and post-harvest inventories. Height-DBH equations and weight tables were fitted using standard statistic software Statgraphics Centurion

XVII. The selected dependent variable for the weight tables was dry weight, after estimating the moisture content of samples with the gravimetric method, according to ISO standard 18134-3:2015.

2.4 Time study and production evaluation

A cycle-level time study was conducted on the feller-buncher, using a Husky Hunter hand-held field computer running the dedicated Siwork3 time study software (Kofman 1995). A cycle was defined as the time to process a single bunch. Productive time was separated from delay time.

To assess the production from each plot, the forwarder piled the whole trees from the plot in a separate roadside bunch that was marked and, afterwards, chipped and transported to the plant to be weighed and sampled for determination of moisture content.

An independent time-study of a complete work shift was performed outside the studied plots, in order to obtain a more reliable utilization factor than could be gained from the work on single 25x25 m^2 plots.

During the forwarder extraction, a whole day shift was time-studied measuring the number of trips and the loaded bunches to get an approximate estimation of the extraction productivity and cost.

The machines were rented by the contracting enterprise SOMACYL. The actual hourly rental cost – or the unit cost in the case of chipping and chip transport - were also recorded.

2.5 Damage assessment

To characterize soil and stand damage, an inventory for damages and stump status assessment was performed after the end of the extraction operation.

Damage to residual trees was determined by inspecting all remaining trees inside each of the 25x25 m^2 plots, following the methodology proposed by Tavankar et al. (2013) that classifies the damages to the remaining trees according to their location, size and intensity, as reflected in Table 4.

Soil damage was determined with the method proposed by McMahon (1995), who proposed soil damage classes according to litter and/or topsoil removal and, in case of rutting, depending on rut depths, as reflected in Table 5. Observations were conducted inside circular sub-plots with a radius of 4 m, centered in the diagonal crossing point of each of the 25x25 m^2 plots.

Researchers also counted the stumps within these same subplots, measuring their heights and evaluating their status.

2.6 Collection efficiency measurement

Inside these circular sub-plots, all the biomass left on the terrain was weighed, and a sample for moisture determination was collected in order to estimate the oven dry weight of the biomass. By doing so, it was possible to determine biomass retention and collection efficiency.

3. Results

3.1 Stand characterization

The holm oak (*Quercus ilex* L.) coppice had an average initial density of 5257 trees/ha, a mean DBH of 5.7 cm, a mean height around 4 m, and an initial basal area of 13.3 m^2/ha. The number of stools/ha was 956, with an average number of shoots per stool of 5.0. There were also 498 isolated *Q. ilex* oaks per ha. The treatment resulted in the removal of over 90 % of the trees and 70% of the basal area, and left 443 residual trees per ha.

The melojo oak (*Quercus pyrenaica* Willd.) coppice had an initial density of 4168 trees/ha, and a mean DBH of 7.1 cm, a mean height around 6 m, and a basal area of 16.8 m^2/ha. The number of stools/ha was 1078, with an average number of shoots per stool of 2.9. There were also 1025 isolated oaks per ha. The treatment resulted in the removal of 85% of the trees and 55% of the basal area, and left 603 residual trees per ha.

Total harvest ranged between 29 and 77 fresh tonnes/ha, for the *Q. Ilex* stand and between 13 to 37 fresh tonnes/ha for the *Q. pyrenaica* coppice. Corresponding dry weights were 22–56 odt/ha (mean 36 odt/ha) for *Q. Ilex* and 9–29 odt/ha (mean 17 odt/ha) for *Q. pyrenaica.*

3.2 Height-DBH equation and Dry weight table

To fit the height-DBH equation, 94 *Q. ilex* and 91 *Q. Pyrenaica* trees were measured. To build the dry weight table, 31 *Q. ilex* and 30 *Q. pyrenaica* oaks were measured and weighed, using different sample trees than those used for the height-DBH curve.

For the weight table, DBH and height were selected as independent variables, but the results showed the weak significance of height as an explanatory variable, so finally only DBH was selected as the main independent variable.

The best fit corresponds to the equations shown in Fig. 1.

3.3 Time study

In the *Q. ilex* stand, the productivity of felling and bunching ranged between 2.7 and 4.8 odt/pmh (oven

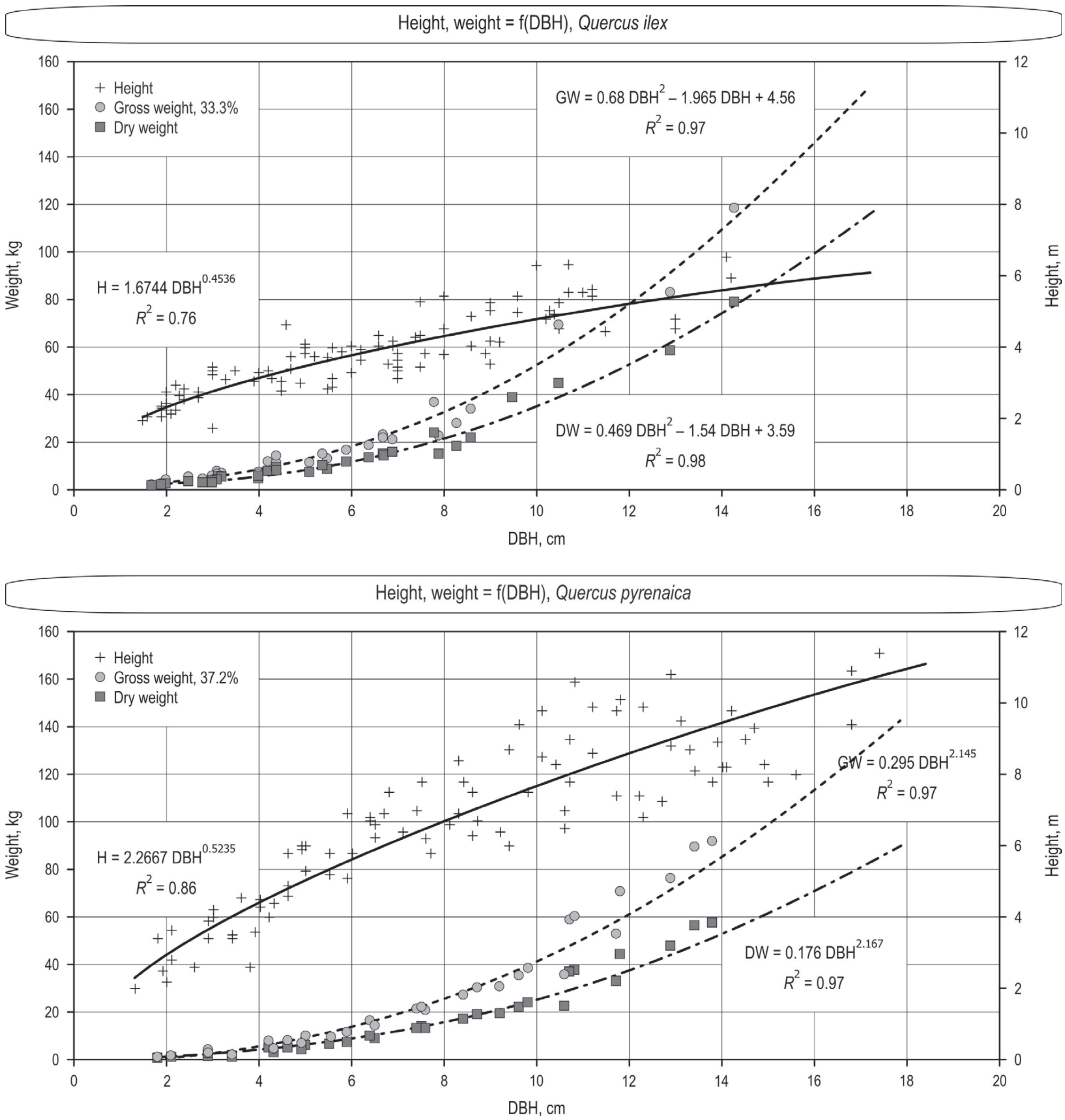

Fig. 1 Height, fresh and dry weight curves for the studied oaks as a function of diameter at breast height (DBH)

dry tonnes per productive machine hour). Delays were mostly absent from the felling time in the plots, because no incidents occurred during the study conducted there. The average productivity of mechanized felling was 4.0 odt/pmh inside the experimental plots.

In the *Q. pyrenaica* stand, the productivity of felling and bunching ranged between 0.9 and 2.9 odt/pmh. Delays accounted for 5% of total worksite time. The average productivity of mechanized felling was 1.8 odt/pmh inside the experimental plots.

Besides the short-time study inside the plots, a longer time-motion study was conducted outside the experimental plots in order to get a better estimate of machine utilization. This longer study covered a full shift and showed that delays (including daily preparation

Table 1 Ranges of productivity and explanative variables

	Species	DW/tree, kg	%ExtractedAB	Prod. ODT/PMH
Range	Q ilex (Holm oak = 1)	7.4–15.9	51–88	2.7–4.9
	Q. pyrenaica (Holm oak = 0)	9.9–22.5	21–69	0.9–2.9

Table 2 Productivity model for the feller-buncher in the studied coppices

Multiple regression – Prod odt/PMH
Dependent variable: Prod odt/PMH
Explicative variables
Dry W/tree
%ExtractedBA
Holm oak (1/0)

Parameter	Estimation	Standard error	*t*-statistic	*p*-value
Constant	–1.66	0.83	–2.001	0.0667
%ExtractedBA	0.0464	0.009	5.110	0.0002
Dry W/tree	0.105	0.038	2.752	0.0165
Holm oak	1.105	0.283	3.902	0.0018

ANOVA

Source	Squares sum	DF	Aver. square	*F*-ratio	*p*-value
Model	21.817	3	7.27233	39.31	0.0000
Residual	2.40526	13	0.18502		
Total (Corr.)	24.2223	16			

R-square = 90.1%
R-square (adjusted by d. of. f.) = 87.8%
Estim. standard error = 0.43
Average absolute error = 0.26 odt/hProd
Durbin-Watson Coefficient = 2.47

and maintenance activity) accounted for 10% of total worksite time.

The forwarder used to extract the whole trees was a 186 kW John Deere 1910E, with a load capacity of 19 tonnes. The forwarder was equipped with a compressing load deck designed to facilitate handling of bulky loads (Dutch Dragon PC-48). The forwarder was studied during a complete shift (8.7 pmh). Forwarder productivity was 7.0 odt/pmh. The incidence of delay time was 12%, including daily maintenance.

3.4 Feller-buncher productivity model

Multiple regression analysis was performed using the data from the 17 studied plots. The analysis tested the impact on productivity (dependent variable) deriving from the following independent variables: Tree species, Dry weight per tree – initial stand, Dry weight per extracted tree, Extracted dry weight per hectare, Initial number of trees per hectare, Extracted number of trees per hectare, Extracted basal area and Percentage of extracted basal area. Significant variables were Species (introduced as a dummy variable, with *Q. pyrenaica* as the baseline and *Q. Ilex* as the dummy), Dry weight per tree and Percentage of extracted basal area. The range of the variables for the two studied species is shown in Table 1, while the equation parameters are shown in Table 2.

$$Prod(odt/PMH) = -1{,}66 + 0.0464\ \%ExstractedBA + 0.105\ dryW/tree + 1.105\ Holm\ oak\ (1/0) \quad (1)$$

Using the average productivity and the average removals, the required felling and bunching time in hours per hectare was estimated as 11.3 pmh (12.6 smh)/ha for *Q. ilex* and 11.9 pmh (13.2 smh)/ha for *Q. pyrenaica*.

3.5 Cost estimation

The renting cost of the machines was established on an hourly basis (€/smh) for felling and bunching, and on a fresh tonne basis (€/fresh tonne) for chipping and chip transport to the power plant (transportation distance = 80 km, one way).

Unit cost estimates were based on the following assumptions: average moisture content of the chips produced in the study equal to 25 and 22%, respectively, for *Q.ilex* and *Q.pyrenaica* (wet basis) and machine utilization equal to 90%. The results of the calculations are reported in Table 3.

Total delivered cost was 68 €/odt for *Q. ilex* chips and 104 €/odt for *Q. pyrenaica*. If these figures were

Table 3 Average operational unit costs based on renting costs

Operation	Renting hourly cost, €/smh	Renting hourly cost, €/pmh	Average productivity, odt/pmh		Average unit cost – chipper renting & transport €/fresh tonne	Average unit cost, €/odt	
			Q. ilex	*Q. pyrenaica*		*Q. ilex*	*Q. pyrenaica*
Felling and bunching	90	100	3.18	1.45	–	31.45	68.97
Forwarding	71.5	79.4	6.99	6.99	–	11.36	
Chipping	–	–	–	–	11.0	14.80	14.14
Chip transport (dist. = 80 km)	–	–	–	–	7.66	10.31	9.85
Total (direct cost)	–	–	–	–	–	67.92	104.32
+ 15% indirect and fixed costs	–	–	–	–	–	78.11	119.98

inflated by 15% to reflect indirect and fixed costs, then the actual cost would increase to 78 €/odt for *Q. ilex* and 120 €/odt for *Q. pyrenaica*.

Regarding the influence of the significant independent variables on this cost, if the productivity eq. 1 (Table 2) were corrected using the ratio between the average, it would become:

$$Prod(odt/PMH) = -1.31 + 0.0367\ \%ExstractedBA + 0.083\ dryW/tree + 0.873\ Holm\ oak\ (1/10) \quad (2)$$

And the unit cost of felling and bunching:

$$Unit\ cost(€/odt) = 100/[-1.31 + 0.0367\ \%ExtractedBA + 0.083\ dryW/tree + 0.873\ Holm\ oak\ (1/0)] \quad (3)$$

Therefore, the total operational costs – without considering any revenues - in the average conditions for each of the studied stand types can be transformed in cost per hectare after adjusting for the different removals (36 odt/ha for *Q. ilex* and 17 odt/ha for *Q. pyrenaica*). The result would be 2820 €/ha for *Q. ilex* and 2076 €/ha for *Q. pyrenaica*.

3.6 Environmental effects

The frequency and severity of residual tree wounding are shown in Table 4, separately for the two stand types. Different letters (a and b) for the two species show a statistically significant difference. The results indicate a greater level of damage in the *Q. ilex* stand, with special reference to crown damage (broken branches higher than 1 meter above the ground level). Fortunately, injuries were mostly small and medium sized (surface smaller than 200 cm^2). The main cause for such injuries was machine movement (bumping against the trees), while the accidental contact with the disc saw accounts for less than 10% of total wounding.

Soil and stump damages are summarized in Table 5. Soil damage was not severe (equal or less than 5% of the total surface showed disturbance deeper than 5 cm, even when the machine is moving all over the plot surface). Stump height was lower than the prescribed 10 cm in most of the cases (two thirds in *Q. pyrenaica*, three quarters in *Q. ilex*). Around 10% of the stumps were taller than that, but within the 20 cm mark, and only 10% exceeded this limit. Most of the stumps were severely damaged. In the *Q. pyrenaica* stand, over half of the stumps were split or fragmented, and the proportion increased to 70% in the *Q. ilex* stand.

3.7 Biomass collection efficiency

Regarding collection efficiency, the actual harvest (chips dry weight) was between 70 and 90% of the estimated table weight for *Q.ilex* and *Q.pyrenaica*, respectively.

The slash left on the terrain averaged 3.0 odt/ha in *Q. ilex* and 1.5 odt/ha in *Q. pyrenaica*, including scrub debris.

4. Discussion

The applied silvicultural operations were delayed – as both coppices were older than 35 years – traditional »mixed coppice« treatment, leaving a greater number of residual trees than in the »coppice with standards« traditional silviculture (Short and Campion 2014).

The studied harvesting system (multi-tree handling WTH) is one of the main trends for the mechanization of fuelwood harvesting (Erber et al. 2017).

The selected heavy drive-to-tree disc saw feller-buncher has not been previously studied in the harvesting of Mediterranean coppice stands, despite the fact that powerful felling heads with a wide opening are considered necessary for work in coppice forests (Chakroun et al. 2016).

Table 4 Damages affecting the remaining trees, %

Damage conditions, remaining trees, %														
Type	Qi	Qp	Location	Qi	Qp	Height	Qi	Qp	Size	Qi	Qp	Cause	Qi	Qp
Bark	25.8 a	19.7 a	Bole	18.0 a	19.0 a	Low (0–0.30 m)	10.6 a	8.2 a	Small (<50 cm^2)	16.1 a	7.3 b	Machine movements	91.4 a	96.4 a
Wood	4.7 a	1.6 a												
Broken branches	12.9 a	3.3 b	Crown	17.3 a	5.9 b	Medium (0.30–1.0 m)	7.8 a	8.9 a	Medium (50–200 cm^2)	14.1 a	7.5 b	Sawdisk injuries	8.6 a	3.6 a
Destroyed	0.7 a	1.0 a												
Total	44.1 a	25.6 b	Roots	0.4 a	0.0 a	High (>1.0 m)	16.8 a	7.8 b	Large (>200 cm^2)	5.5 a	10.1 a	Other	0.0 a	0.0 a
Severe	5.4 a	2.6 a												

Qi = *Quercus ilex*

Qp = *Quercus pyrenaica*

Different letters (a/b) show statistically significant differences for p=95%)

Table 5 Soil damages and stump condition after the treatment

	Soil damage, % of total surface			
Specie	No damage evidence	Litter still in place, evidence of minor disruption	Litter removed, topsoil exposed	Litter and topsoil mixed, <5 cm depth
Quercus ilex	6.1	51.7	41.7	0.5
Quercus pyrenaica	0.0	56.2	38.8	5.0

	Stump height, % of stumps number			Stump status, % of stumps number				
Specie	<10 cm	10–20 cm	>20 cm	No damages	Bark slightly removed	>50 % bark removed	Cracked stump	Destroyed stump
Quercus ilex	76.5	19.4	4.1	1.8	7.2	10.8	69.4	10.8
Quercus pyrenaica	66.7	23.3	10.0	3.9	16.1	22.8	48.3	8.9

The DBH-to-height and DBH-to-weight models show that *Q. ilex* is less slender than *Q. pyrenaica*, and is considerably shorter for equal DBH (Fig. 1). Nonetheless, *Q. ilex* has a much more developed crown than *Q. pyrenaica* (Ruiz-peinado et al. 2012), and this is the reason why, despite having less height, *Q. ilex* oaks do have more weight than *Q. pyrenaica* oaks for the same DBH (Fig. 1). This fact can explain why one of the most significant factors explaining productivity is the species, because *Q. ilex* trees are bigger and allow reaching a higher productivity than *Q. pyrenaica* oaks (1.1 odt/PMH more, over the whole range of other explanatory variables).

As a matter of fact, tree size (DBH, tree volume, stump mass or tree mass), is an established explanatory variable in most felling and bunching productivity studies (Spinelli et al. 2007, Schweier et al. 2015, Erber et al. 2016, Chakroun et al. 2016, Spinelli et al. 2016).

Another very common explanatory variable for felling productivity in coppice operations is the removal (Spinelli et al. 2016), which is reflected in this study by the percent of the basal area.

The productivity of the disc saw felling head, tested in traditional Spanish coppice, is comparable with the productivity figures reported in other similar studies conducted on coppice stands across the Mediterranean region (Laina et al. 2013, Schweier et al. 2015). In fact, the figures reported here for *Q. ilex* might be slightly higher than those found in the literature, if one takes into account the very small tree size (average DBH smaller than 6 cm) and the selective character of the treatment, which resulted in the release of a dense residual stand.

The present prices per whole tree chips tonne for a moisture content of 25 and 22% in the Spanish market are 54 and 58 €, corresponding to equivalent prices per dry tone of 72 and 74 €, respectively (SOMACYL 2018). In these conditions, the operation would not be economically sustainable, although one would get close to breaking even with *Q. ilex*. Using the present technology, the possibilities to achieve profitability would be with treating bigger sized stands – which are not usually available, except in the case of very old coppice forests – or by prescribing larger removals, leaving fewer residual trees, or none at all.

The difference between costs and revenues in the studied conditions would amount to a net loss of 221 €/ha for the *Q. ilex* stand and of 796 €/ha for the *Q. pyrenaica* stand.

Frequent residual tree wounding is partly due to the use of a large drive-to-tree machine in a dense residual stand. The working method resulted in the machine trafficking most of the plot surface (average length of the GPS track was 370 m inside the 625 m^2 plots). Crown damage was more frequent with *Q. ilex* due to the specific tree architecture. In any case, only 5% of the damage in the *Q. Ilex* stand – and even less in the *Q. pyrenaica* coppice – reached deeper than the bark and/or were greater than 200 cm^2.

Soil damage was not severe, despite the intense machine traffic. Both stands were located on flat terrain, on dry sandy soils - and the weather was dry for the whole duration of the study. However, it is reasonable to expect higher soil impact levels on steeper and/or wetter ground conditions.

Stump damage was quite frequent, as is common when mechanized felling is introduced to coppice (Spinelli et al. 2017b), but the consequence of stump damage on stump mortality and sprouting vigor is still unclear: several studies indicate that stump damage may have no negative effects on sprouting (Pyttel et al. 2013, Spinelli et al. 2017b).

Finally, the different biomass recovery efficiency between the two oak species may be related to different tree architecture: *Q. ilex* trees have compact crowns with thicker branches, which may minimize handling losses. In contrast, *Q. pyrenaica* has weaker and wider crowns, which may drop branches if the handling is rough. However, the difference between estimated mass and actual removal in the *Q. pyrenaica* coppice is too high, and it is not consistent with a relatively small quantity of biomass left on the terrain. Therefore, collection efficiency figures must be impacted by the inevitable estimation error of the DBH-to-weight models, and therefore these values must be considered as wide approximations.

5. Conclusions

Two DBH-to-height curves and DBH-to-weight table were developed for the two different coppice types, which are the most common in Spain. Although approximate, these curves provide an important tool for estimating biomass availability in these stands. The comparison between the curves shows that *Q. ilex* is less slender than *Q. pyrenaica* and has a denser and wider crown, ultimately offering a higher biomass yield for the same DBH. For this reason, coppice thinning is significantly more productive in *Q. ilex* coppices than in *Q. pyrenaica*.

Feller-buncher productivity has been modeled as a function of tree species, tree weight and percentage of the extracted basal area. The model shows that productivity increases with stem size and removal intensity.

The analysis of the unit costs, based on the renting cost of the machines, the transport cost to a power plant located at 80 km from the coppice forest, and considering a 15% of indirect and fixed costs, shows that harvesting these stands with this system results in a small financial loss, particularly in *Q. pyrenaica* stands: therefore, selection thinning in small-tree coppice stands is only justified by specific management goals (e.g. fire proofing) and should be subsidized.

On the other hand, one could try to restore the financial performance of these operations by reducing machine cost through the use of lighter and cheaper machines - for instance by installing a smaller disc saw model on a mini-excavator such as skid-steer loader or a mini-excavator, the latter capable of swing-to-tree operation (Spinelli and Nati 2009). Another possible opportunity for cost reduction could be the direct management of the operations – instead of renting the machines – and finally a reduction of the transportation distances.

Site damage was moderate but use of a heavy drive-to-tree feller buncher can cause a higher impact level than expected from a lighter swing-to-tree machine.

Most of the stumps were severely damaged, and even if the negative effect of stump damage on stump sprouting and shoot growth has not been ascertained, it would be safer to follow-up the regeneration on the study sites.

Acknowledgements

The authors are indebted to Rubén García and the operational managers and technicians Alberto Fernández-López and Carlos Martínez-Torres in SOMACYL public forest company in Castilla y León (Spain), whose help made possible the present study. Financial support for this research was provided by La Caixa through Fundación Patrimonio Natural de Castilla y León and also by the COST Action FP1301 (www.eurocoppice.uni-freiburg.de) within the scope of its STSM program.

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Received: April 25, 2018
Accepted: June 29, 2018