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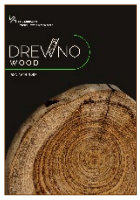

Modelling the productivity and economic feasibility of bioenergy production in a Mediterranean oak coppice

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The possibility of further exploiting the national bioenergy supply chain in Italy is hindered by a lack of economically sustainable mechanization. Large enterprises can rely on brand-new and advanced machinery to improve productivity and maximize revenue. On the other hand, small enterprises often resort to custom-built machinery to accomplish the same tasks. The performance of an excavator equipped with forest shears was used to model its productivity and economic feasibility in an oak coppice in central Italy. The oak coppice harvesting operations required 29%, 19%, 22%, 20% and 10% of total time respectively for clearing, moving, felling, bunching and delay. The linear model highlighted a strong influence of diameter at breast height (DBH) on the total productivity, with a p value lower than 0.001 and an adjusted R^2 of 0.64. Felling and bunching operation costs ranged from 10.89 to 31.45 EUR t^{-1}, the latter value corresponding to a DBH of 9 cm. Hence, our findings indicate the minimum stand requirements necessary to ensure the economic sustainability of excavator-based harvesting in these specific conditions.

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Introduction

Increasing global energy demand is prompting governments to seek alternative energy sources, as they aim to reduce dependence on foreign energy markets and mitigate greenhouse gas emissions (EU, 2014; European Parliament, 2015; Opia et al., 2021). Achieving the goal of having 30% of European domestic energy production come from renewable sources by 2030 is a tangible challenge, but it can be achieved through the proper utilization of forest residual biomass and low-value wood (European Commission, 2012; Lindegaard et al., 2016; Łukawski et al., 2022). In this regard, a potential and still underexploited contribution to meet the energy demand may come from Mediterranean oak coppices.

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Italy has a rich tradition of coppice silviculture, with coppices covering approximately 35% of the country's area and accounting for over 19% of total European coppice area (Di Marzio, 2020; Mairota et al., 2016; UNECE and FAO, 2000). Coppice management represents a low-energy-input system (Camponi et al., 2022; Vanbeveren et al., 2019; Vanbeveren et al., 2017) that also provides essential ecosystem services, including creating suitable conditions for endangered species (Latterini, Mederski, et al., 2023; Manetti et al., 2020; Müller-Kroehling et al., 2020). However, the full potential of the supply chain remains underutilized. In fact, according to ISTAT 2014 data, wood-fuel demand in Italy was estimated at 17.7 Gg in 2013, with most of it being imported from Eastern European and Balkan countries (ISTAT, 2014; Masiero et al., 2013). This situation is neither economically nor environmentally sustainable.

To address this, the Italian coppice supply chain needs improvement to minimize imports and maximize the mobilization of domestic wood fuel (Haavikko et al., 2022; Holzleitner et al., 2013; Michalski et al., 2023). However, a significant bottleneck lies in the low level of mechanization, which results from local constraints and limited budgets (Bustos-Letelier et al., 2022; Latterini, Venanzi, et al., 2023; Spinelli et al., 2010). While advanced harvesting systems rely on modern equipment such as harvesters, forwarders, and tower yarders (Apăfăian et al., 2017; Borz et al., 2021; Spinelli et al., 2017a), these technologies are often beyond the reach of medium and small enterprises conducting logging operations in central and southern Italy (Proto et al., 2017).

In these regions, Mediterranean coppice management diverges from practices in the rest of Europe (Unrau et al., 2018; Spinelli et al., 2021; Cataldo et al., 2020). Such factors as environmental constraints, slope, harvest type, machine availability, and harvesting costs influence the methods and machinery used. Conventional approaches, relying on motor-manual felling (chainsaws) and low-mechanized extraction methods (mules and/or agricultural tractors), prevail (Cataldo et al., 2020).

Over the past few years, fully mechanized harvesting has become increasingly common in Italy. This trend often involves adapting various kinds of machinery for forestry operations. For instance, excavator-based felling has gained prominence, where typical excavators are equipped with specialized felling heads or shears (Palander et al., 2012; Spinelli et al., 2020, 2021). The first examples of fully mechanized harvesting of oak from coppices in Italy are based on this system.

Specifically, in coppice forests characterized by gentle slopes and low terrain roughness – such as those along the Tyrrhenian coast – logging enterprises are increasingly adopting the whole-tree harvesting system to produce wood chips. Although these coppices were traditionally managed for firewood production, the decision to invest in chip production is primarily driven by advancements in mechanization. These advancements simplify logistics and enhance safety in the work environment (Spinelli et al., 2019).

The typical harvesting system involves felling and bunching trees using an excavator equipped with a shear. Extraction is then carried out by a forwarder or a forestry-fitted farm tractor equipped with a trailer. Finally, chipping occurs at the landing site using a stationary chipper (Spinelli et al., 2016, 2017b, 2019). However, this system is still in its early stages of implementation in this geographical area. Consequently, there is strong demand from foresters and practitioners for the development of predictive tools to support loggers in decision-making. These tools should help assess the feasibility of applying excavator-based harvesting in specific forest parcels.

With this context in mind, our paper presents a case study in which we develop a work productivity model and simulation. Our goal is to identify the minimum stand requirements – specifically tree features – necessary for economically sustainable excavator-based harvesting. Specifically, we wanted to test the following research hypotheses: i) considering the particular characteristics of coastal oak coppices (gentle slope, low terrain roughness, good forest viability), it is possible to develop a work productivity model based solely on the dendrometric characteristics of the stand; ii) the dendrometric characteristics of the oak coppice in our study area are such as to permit cost-effective excavator-based harvesting.

Materials and methods

1. Study area

The study was conducted in central Italy, specifically in Tarquinia (VT) at coordinates 42°17'12" N, 11°51'72" E. The site was characterized by an average slope of 23% with peaks of 35%. The dominant species observed was the Turkey oak (*Quercus cerris* L.), with an age range between 16 and 17 years. The plant density in the stand was 1157 plants per hectare, with 335 stumps and 110 reserve. The average number of trees per stump was 3.45, with a DBH of 13.1 cm, an average height of 10.2 m, and a range of volumes between 0,01 and 0,39 m^3. Details of species composition are given by Del Giudice et al. (2022). Thanks to the presence of forest roads, which are typically constructed in coastal forest stands for fire prevention and firefighting interventions, the excavator was able to easily cover the entire surface of the forest parcel, limiting the bunching distance.

Fig. 1. Oak coppice during felling operation

2. Characteristics of machinery

Tree felling and bunching were carried out with a Woodcracker C450 hydraulic forest shear (Westtech Maschinenbau GmbH, Prambachkirchen, Austria) fitted to the arm of a 23.1 t Hitachi ZAXIS 240N tracked excavator (Hitachi, Tokyo, Japan) with 550 mm tracks, 129 kW power and 9.30 m maximum outreach. The length, width and height of the excavator were respectively 9.75, 2.48 and 3.02 m. The maximum cut diameter indicated by the shear constructor is 45–50 cm (Figure 1).

3. Characteristics of trees

A random sample of 50 trees was used to construct the predictive model. The height and diameter at breast height (DBH) of each plant were measured, utilising respectively a timber calliper and a professional ultrasound hypsometer (Vertex IV-360KIT).

Other parameters measured were the basal area (BA) and volume of each plant. Despite being random, the selection of the plants emulated the main diameter classes identified in the coppice, i.e. class 5, class 10, class 15, class 20, class 25, class 30, class 35.

For the volume calculation, the dendrometric table developed by Bianchi et al. (1984) for an oak coppice in Viterbo province was utilized (Bianchi et al., 1984). The table separates trees within the first coppicing cycle (1st turn – 1T) and those out of cycle left for forest regeneration (2nd and 3rd turns – 2T and 3T). For 1T, the following equation was used to estimate the volume:

$$V= -2.150 \times 10^{-3} + 3.869 \times 10^{-5} (D2 \times H) \quad (1)$$

For plants in 2T and 3T the volume was estimated using the following equation:

$$V= 8.224 \times 10^{-2} + 5.599 \times 10^{-5} \times (D2 \text{ x } H) - 3.893 \times 10^{-4} \times (D2) \quad (2)$$

4. Working time and machine productivity

To build the predictive model, it was necessary to determine the real productivity of the machine during the felling of sample trees. The methodology adopted was based on a study of working times for the operations of moving, felling and bunching (Gülci et al. 2021; Leitala et al. 2022). The moving time commenced when the machine approached the plant and concluded when the machine's head rested on the plant. The felling time began during the cutting and felling phase and ended when the plant touched the ground. Subsequently, the bunching time started when the plant hit the ground and concluded when the plant was placed on the tree pile. To study moving, felling, and bunching times, we timed 50 cycles of shear operation. The sum of these three operational times (cycle time) was used, along with tree volumes, to calculate the mean productivity per productive machine hour (m^3 PMH^{-1}). It should be noted that productive machine hours did not include clearing times or delays incurred during harvest operations, as these factors can vary based on the operator, machine maintenance, and environmental conditions. The following formula, taken from Muhammad et al. (2013), was used for the calculation:

$$\text{productivity} = (\text{volume/cycle time}) * 60 \quad (3)$$

where:
volume (m^3) is the calculated volume of the tree;
cycle time (min) is the total time of moving, felling, and bunching;
60 is a factor used to convert time from minutes to hours;
productivity (m^3 PMH^{-1}) is the mean productivity per productive machine hour, not including delays.

5. Model development

The database for modelling consisted of the data on dendrometric features of the sampled trees (DBH, height, BA and volume) and the related productivity for moving, felling, bunching and total operation. To address multicollinearity in our model, we initially examined correlations among the various variables by constructing a correlation matrix and calculating the Pearson correlation coefficient. We employed the corrplot package (Wei et al., 2017) within the R software environment (R Development Core Team, 2023). As anticipated, dendrometric characteristics exhibited strong correlations with each other (see Figure 3 in the Results section), as did the various productivity values (also shown in Figure 3). Consequently, we decided to streamline the analysis by focusing on a reduced set of dependent and independent variables. Our dependent variable was total productivity, which holds paramount importance from an operational perspective. As an independent variable, we selected diameter at breast height (DBH). DBH, along with tree volume, was selected because it had the highest Pearson correlation coefficient in relation to total work productivity. Moreover, DBH is a straightforward dendrometric feature to measure. Given that our research was based on a case study without data nesting, we opted for an approach centred on modelling fixed effects only. After verifying data normality and homoscedasticity using the Shapiro–Wilk and Levene tests, respectively, we employed the lme4 package (Bates et al., 2015) to fit a linear model. This allowed us to calculate model coefficients, 95% confidence intervals, and the R^2 coefficient of determination. Finally, we used the ggeffects package (Lüdecke, 2018) to visualize the model results.

6. Cost calculation

The machinery costs were estimated using the Harmonized European Costing Model developed under EU COST Action FP0902 (Ackerman et al., 2014). To derive the cost assumptions, we conducted interviews with local enterprises and referred to previous publications concerning the same machine operating in a different context (Sperandio et al., 2021). The calculated productive machine hour (PMH) costs and the components used for cost calculations are provided in Table 1.

Table 1. Components of cost calculations for the machines. PMH refers to productive machine hour, not accounting for delays

Cost component	**Excavator + shear**
Investment price (EUR)	130,000.00
Salvage value (EUR)	32,501.71
Service life (years)	12
Annual use (h $year^{-1}$)	1,200
Operator wage (EUR h^{-1})	16.00
Interest (%)	8
Depreciation (EUR yr^{-1})	8,124.86
Interest (EUR yr^{-1})	6,500.07
Insurance (EUR yr^{-1})	325.00
Maintenance (EUR yr^{-1})	8,666.67
Fuel and lubricant (EUR yr^{-1})	23,437.44
Personnel (EUR yr^{-1})	19,200.00
Overhead and profit (%)	20
Overhead and profit (EUR yr^{-1})	13,262.81
Total (EUR yr^{-1})	79,576.84
Total (EUR PMH^{-1})	66.31

After calculating an average felling and bunching cost based on the average productivity, we used the previously developed productivity model based on DBH to identify a threshold value of DBH defining the economic sustainability of using excavator-based harvesting. For this purpose, we retrieved from the literature the average market price for the final product (i.e., wood chips) (Latterini et al., 2022), the average cost for forwarding oak trees from Mediterranean coppices in similar working conditions, and the average cost for chipping oak wood at the landing site (Tolosana et al., 2023).

Results and discussion

1. Shear performance

The study of the time cycle, including moving, felling, and bunching operations, revealed an almost balanced time distribution for each operation. Felling was slightly more impactful, accounting for 22% of the total time (see Table 2 and Figure 2). On average, total productivity reached 6.96 t h^{-1}, but significant variability was observed across the analysed time cycles. Notably, although delays and clearing times were not factored into the research due to their dependence on various factors, the clearing operation emerged as the most time-consuming step (Figure 2).

2. Productivity model

As previously mentioned, we observed a strong correlation among various dendrometric features and different productivity measures (see Figure 3). Given the high correlation between moving, bunching, felling, and total productivity, we chose to focus our model solely on total productivity, which holds the greatest operational significance. To address multicollinearity, we narrowed down the independent variables. Specifically, we examined the variables with the highest Pearson correlation coefficient in relation to total productivity. Diameter at breast height (DBH) and tree volume stood out, with correlation coefficients of 0.81 and 0.82, respectively. Considering that DBH is the quickest and simplest dendrometric feature to assess and measure, we opted to use only this parameter as the independent variable in our model.

The developed linear model revealed a strong influence of diameter at breast height on the total productivity, with a p value lower than 0.001 and an adjusted R2 value of 0.64 (Table 3 and Figure 4).

The results obtained in our study confirmed our research hypotheses. Firstly, we demonstrated that the diameter at breast height (DBH) serves as a reliable predictor of work productivity for an excavator equipped with a forest shear. DBH is a straightforward variable to measure, and our model, which relies solely on it, provides a valuable tool – not for detailed productivity predictions (which can be challenging in operational forestry), but primarily for understanding trends and major drivers of work productivity in our specific context.

Many authors concur on the significance of piece size and tree dimensions in mechanized felling and felling-processing (Tolosana et al., 2018; Visser et al., 2012). While productivity in tree felling is influenced by various factors (Miyajima et al., 2021), the dimensions of the biomass directly impact machinery utilization and, consequently, costs and potential enhancements in harvesting yards (Louis et al., 2022).

Table 2. Descriptive statistics of the time elements and forest shear productivity

Time element	Unit	Mean	Min	Max
Bunching	min.	0.43	0.08	1.97
Felling	min.	0.30	0.07	1.55
Moving	min.	0.22	0.08	0.72
Volume				
Single tree	m^3	0.13	0.01	0.39
Productivity				
PMH	m^3 PMH^{-1}	8.70	0.92	46.33
PMH	Mg PMH^{-1}	6.09	0.64	32.43

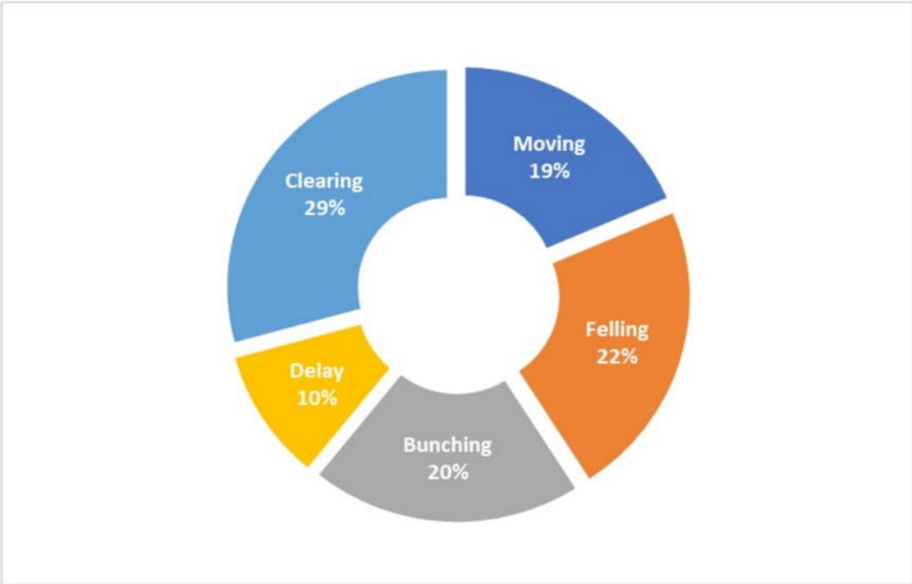

Fig. 2. Time elements of the oak coppice harvesting operations. Delays and clearing were not included in the productivity model calculation

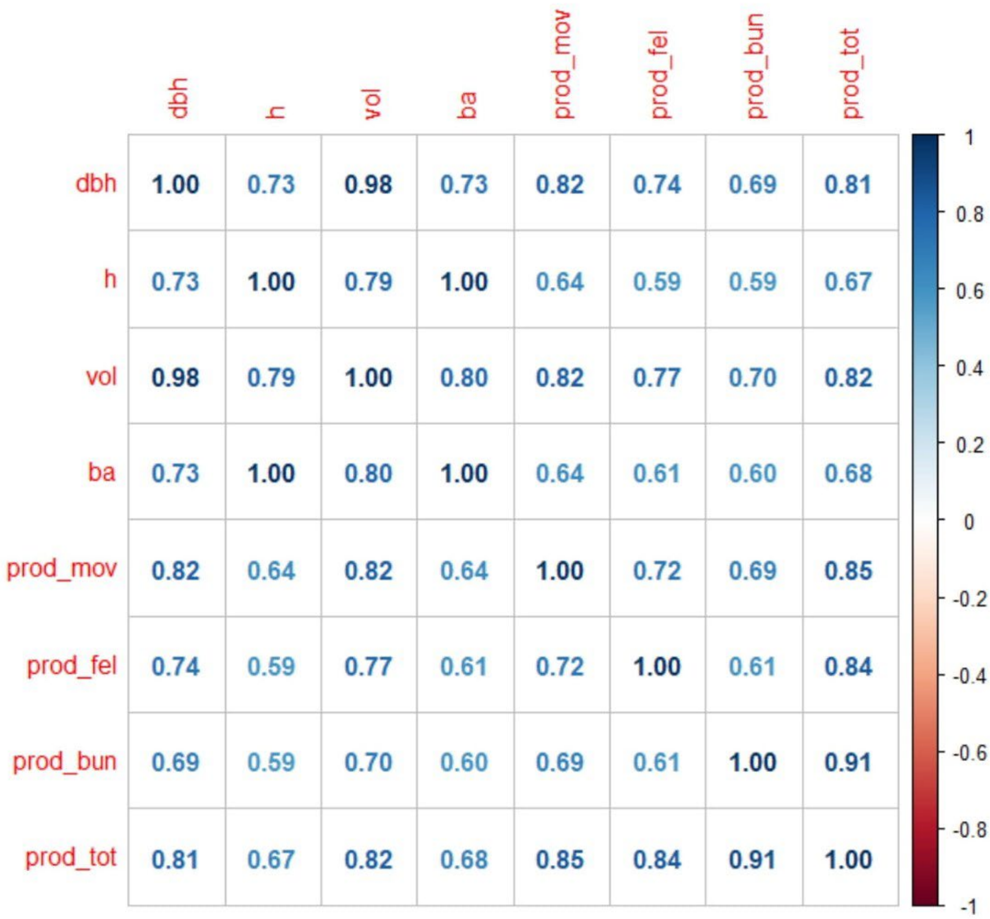

Fig. 3. Correlation matrix among the dendrometric features and the productivities. Acronyms: DBH: diameter at breast height (cm); h= tree height (m); vol= tree volume (m3); ba= tree basal area (m2); prod_mov= moving productivity (m3 h-1); prod fel= felling productivity (m3 h-1); prod bun= bunching productivity (m3 h-1); prod tot= total productivity (m3 h-1)

Table 3. Numerical results of the linear model. "***" indicates statistically significant differences at $p < 0.001$

Model coefficients				
	Estimate	Standard Error	t value	p value
(Intercept)	-4.02955	1.30914	-3.078	0.00344 ***
dbh	0.69282	0.07378	9.391	1.9×10^{-12} ***
Multiple R-squared: 0.6475, Adjusted R-squared: 0.6402				

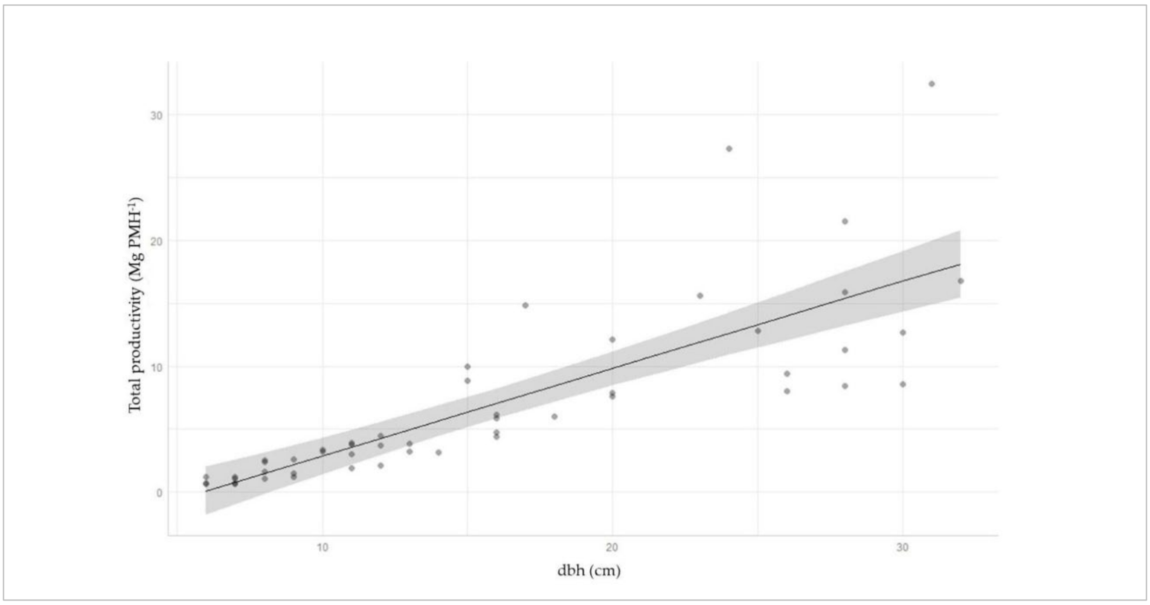

Fig. 4. Graphical results of the linear model. Black line represents the regression line, grey area represents the 95 confidence intervals, grey dots represent the individual data

It is noteworthy that the polycormic structure of coppice stumps may potentially affect shear efficiency. Thus, our confirmation of the direct relationship between tree diameter and work productivity represents an interesting and valuable finding from this study. This finding aligns with previous research investigating the performance of forest shears in Mediterranean coppices (Schweier et al., 2015). The productivity in our study was indeed higher (9.94 vs. 5.1 m^3 PMH^{-1}) than that reported by Schweier et al. (2015), even if the dendrometric features of the stand were very similar. The observed higher efficiency of the hydraulic forest shear, despite the presence of several suckers on the same stump that hindered shear movement and made felling difficult, underscores the critical role of operator technical skills. Proficiency with advanced forestry equipment significantly influences final productivity. While the advantage of reduced crew size associated with higher mechanization is evident, it must be balanced by a corresponding increase in operator competence. As reported by Visser and Spinelli (2012), operator performance can lead to a 20–50% variation in machine productivity.

The combined time for felling and moving accounted for nearly half (49%) of the operational time. This slightly exceeds the 40% observed by Nakagawa et al. (2007) for positioning, felling, and tree fall when using a harvester head attached to an excavator for whole-stem harvesting in Japanese larch stands. Conversely, our figure is lower than those reported by Schweier et al. (2015) and Miyajima et al. (2021), who recorded felling and moving times of 55% in Italian oak coppice and 70% in Brazilian eucalyptus plantations, respectively. Importantly, the latter study involved whole-tree harvesting using two feller-buncher models, and revealed differences in felling times and productivity between the machines. It should be emphasized that our study focused on a natural oak forest, resulting in irregular stump distribution. The specific site conditions significantly influenced our findings, as was also observed by Tolosana et al. (2023) in their research on Mediterranean oak coppice productivity.

3. Cost analysis

Based on the average work productivity of 6.09 t PMH[1], the average cost of felling and bunching operations performed by an excavator equipped with a forest shear was calculated as 10.89 EUR t^{-1}. Literature data collected in similar European zones include an average cost of 18.56 EUR t^{-1} for extraction by forwarder and a cost of 12.99 EUR t^{-1} for chipping; for comparison, the average market price of medium quality wood chips in Italy is identified as 63 EUR t^{-1}. On the basis of these data and the results obtained in our productivity model, we developed the regression model shown in Figure 5. The graph indicates that the threshold cost (economic convenience) for felling with the excavator-based forest shear is attained at 31.45 EUR t^{-1}, corresponding to a tree DBH of about 9 cm. This value is much smaller than the average DBH of the studied stand, which is highly representative of the coastal oak coppice of Central Italy.

The lower work productivity reported by Tolosana et al. (2023) led to much higher felling costs (26 EUR t^{-1}), despite the very similar hourly machine costs between that case study and ours. Focusing carefully on the issue of costs, we confirmed that the application of excavator-based harvesting is a suitable option for central Italian oak coppices located on gentle slopes, like those generally found along the Tyrrhenian coast. Indeed, we found that this form of intervention ensures cost-efficiency when the average diameter at breast height of the stand is higher than 9 cm, a value which is achieved in almost all stands of at least the minimum rotation age (ranging from 16 to 18 years depending on the local forest regulations).

4. Study limitations

Despite the satisfactory results confirming our research hypotheses, it is necessary to acknowledge the study's limitations. Firstly, we have presented a case study, and it is well known that single case studies in the forestry sector do not provide findings that can necessarily be generalized (Janiszewska-Latterini et al., 2023; Latterini, Dyderski, et al., 2023; Latterini et al., 2024). However, the present case study represents a significant portion of coppice forests located along the Italian Tyrrhenian coast, specifically in such regions as Latium and Tuscany. Therefore, it offers valuable insights for foresters and logging companies in the study area.

Secondly, our model considered only dendrometric features and did not account for other potentially important drivers of work productivity, such as terrain slopes and bunching distance. This limitation arises from the specific characteristics of our study area. The constant 20% slope throughout the parcel and the limited bunching distance (approximately 10 metres) for each investigated tree – due to the presence of dendritic forest road networks used for tourism and fire-fighting – further emphasize the suitability of our case study in faithfully reproducing the conditions of the overall study area.

Despite these limitations, we believe that this preliminary research provides foresters with a valuable tool. It allows them to assess the cost-effectiveness of excavator-based harvesting in oak coppices and supports practitioners with a reliable decision support system.

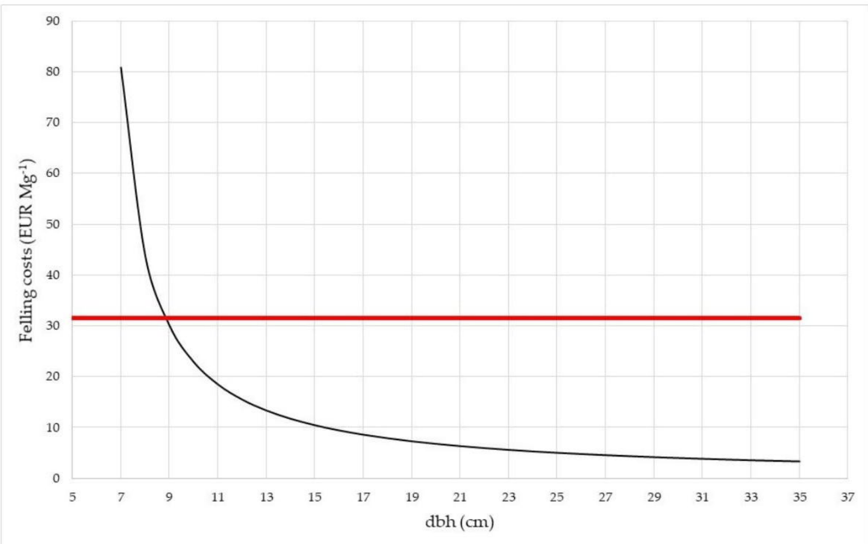

Fig. 5. Relationship between felling operation (including tree bunching) costs, derived from the productivity model in Figure 4, and the diameter at breast height of the felled trees. The red line indicates the threshold costs for economic convenience

Conclusions

While whole-tree harvesting for wood chips remains the most common method in central Italy, there is a growing trend toward customizing conventional machinery for forestry operations. Equipping excavators with shears, for example, has gained popularity. However, practitioners and foresters lack decision support systems for informed decision-making. In this case study, we aim to develop a work productivity model and an economic model based on the dendrometric characteristics of the analysed coppice.

Our findings suggest that diameter at breast height (DBH) serves as a reliable predictor of work productivity for an excavator equipped with a forest shear. Moreover, this same parameter can be used to predict the economic threshold necessary to ensure the economic sustainability of this type of operation. Given that DBH is a quick and reliable measurement commonly performed in forests, our findings offer a rapid decision support system for assessing the affordability of excavator-based harvest systems in similar contexts.

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