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New tools to extract cork from *Quercus suber* L.: increasing productivity and reducing damage

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Abstract

Aim of study: The aim of this study is to test new tools designed to debark cork oak trees: mechanized tools to perform cutting operations (IPLA-Morell, Stihl MC200 and COVELESS) and manual tools to separate and extract the cork (cork pincers, MIJURO).

Area of study: Southwestern Spain.

Material and methods: One of the longstanding problems affecting the sector is the shortage of skilled labor to perform debarking due to the difficulty of handling axes and the temporary nature of the work. To overcome these problems, four debarking systems using the new tools were designed according to the morphological properties of cork oak. The viability of the debarking systems were evaluated based on productivity (kg · person^{-1} · hour^{-1}), production costs (€ · t^{1}) and percentage of pieces smaller than 400 cm^2 (%), and compared with the traditional system. Debarking quality and operator experience were also evaluated. A total of 204 trees were debarked.

Main results: The new systems obtain better results: productivity is higher, the percentage of pieces is slightly lower and production costs are reduced, except for one system. Debarking quality improves with the new tools as cork is extracted in a more precise and cleaner manner, thus permitting cork manufacturers to obtain higher yields from the cork planks.

Research highlights: Semi-skilled operators using the new tools obtain very similar results to skilled operators using axes. This would therefore resolve the problem of the lack of skilled labor, while improving the working conditions of operators.

The results demonstrate that the new tools are viable for cork debarking and can bring potential benefits to the sector.

Key words: *Q. suber* L.; cork debarking; mechanization; productivity; cork stripping damage; axe; IPLA_Morell, Sthil MC 200, COVELESS.

Introduction

Cork oak forests constitute an ecosystem that is home to one of the richest biotypic habitats in the European Union and are one of the main economic drivers in many Mediterranean rural areas (Pinto-Correia, 2000). These forests form part of multifunctional systems known as *montado* in Portugal and *dehesa* in Spain (Joffre *et al.*, 1988). Cork is the main product in these areas and accounts for 0.2% of Spain's GDP (Sanchez-Gonzalez *et al.*, 2008; Costa *et al.*, 2010; Santiago, 2009).

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Cork is the bark of the cork oak tree and is regenerated by the tree after extraction, thus ensuring the sustainability of subsequent cork extractions at intervals of 9 years (Graca and Pereira, 2004; Montero *et al.*, 1996; Oliveira and Costa, 2012). Natural stoppers are the highest value-added cork product on the market and are obtained from the third and subsequent cork harvests (Leal *et al.*, 2008; Sanchez-Gonzalez *et al.*, 2008; Almeida *et al.*, 2010; Pereira, 2007). Cork planks of less than 400 cm^2 in size are known as "pieces", while the cork extracted from the first 10-20 cm at the base of the tree stem are called "footers" (Pereira, 2007; CELIÈGE, 2005) and is not suitable for the manufacture of natural cork stoppers.

Operations to cut, separate and strip cork from the tree (debarking) have traditionally been performed with simple tools such as a cork axe and a "burja" (Pereira, 2007). A cork axe is a stripping axe with a curved cutting blade and a relatively long wooden handle that has a chiseled end, while the burja is a long handled wooden arm also with a chiseled end (Pereira, 2007). Axes are used to cut the cork, while the handle of both the axe and the burja are used as a lever to separate the cork from the lower and upper parts of the tree, respectively. In trees with debarking heights of over 2 m, a ladder is used to reach the upper parts of the tree (Ribeiro and Tome 2002; Moreira *et al*. 2007). The profitability of this traditional debarking system is highly variable, and depends mainly on the state of the cork oak tree, operator expertise, the percentage of pieces, and the percentage of footers. The mean productivity of the traditional system is around 95-120 kg · person^{-1} · hour^{-1}, and the percentage of pieces normally accounts for 5.1-5.5% (Peralta, 2003) and 4.2% (Celis and Caseras, 2009) of total extracted cork in weight.

Cork debarking is a highly skilled and dangerous operation that requires very specific training and the shortage of skilled labor is an endemic problem in the sector. Moreover, the labor force is now of an advanced age, with the cork strippers union in the south of Spain currently composed of men aged 46 years old on average (Prades *et al*., 2009). Temporality is another factor that impacts negatively on the labor force as the legal time limit in Spain for cork debarking is restricted to three months due to the physiological conditions of the trees (Diario Oficial de Extremadura [D.O.E] Nº 40 de 15 de mayo de 1986; Boletín Oficial de la Junta de Andalucía [BOJA] Nº 79 de 11 de octubre de 1988).

Debarking affects the physiological state of cork oak trees, mainly by reducing diameter growth (Costa *et al*., 2004) and present and future cork production. The damage caused to the tree during debarking further aggravates these negative physiological effects and reduces the yield obtained in subsequent extractions in the affected areas (Oliveira and Costa, 2012). Moreover, trees no longer produce cork in areas where the cork generating layer has been removed (Pereira, 2007). To address these problems, various devices have been developed over the last 15 years to improve the working conditions of cork strippers and streamline their work. From a physiological point of view, these tools aim to minimize the potential damage that cork stripping may cause to the tree and the cork generating layer, thus ensuring extractions in subsequent years (Costa *et al.,* 2004; Peralta, 2003; Antolin *et al*., 2003; Celis and Caseras, 2009).

New equipment has been specifically designed to carry out two operations that have been traditionally performed with an axe: power saws for cutting the cork without damaging the tree, and manual tools to separate the cork from the tree (Fig. 1).

a) The power saws that have been designed to cut cork incorporate an automatic system to regulate the depth of cut according to the caliber or thickness of the cork. This system measures differences in electrical conductivity between the cork and the wood, which have a very different moisture content (Marat-Mendes and Neagu 2003; Ilic, 2001). A sensor placed at the end of the saw and another on the tree stem send data to a microprocessor that detects the current and activates an adjustable skate which sets the depth of cut. The tools in this group include (Fig. 1a):

— IPLA-Morell: This is a 720 W jigsaw weighing 3.8 kg fed by a 1000 W gasoline-powered electric generator with an operating voltage of 220 V. Although this is a lightweight and easy-to-handle power tool that can be used on the upper part of the tree, the weight of the generator and the cords connecting the various elements hinder movement within the forest. This tool was first developed in the mid-nineties (Antolin *et al*., 2003).

— Stihl MC200: This is a 1.7 kW gasoline-powered chainsaw weighing 6.1 kg with a 35 cm^3 displacement, and an operating voltage of 24 V. The chainsaw and the conductivity sensor are connected by a cord to a processor that is carried on the operator's back (Fig. 2). It functions at high speeds and is easy to handle, but cannot be used in the upper part of the tree due to its greater weight and for safety reasons. This chainsaw was first developed in 2003.

— COVELESS: This is a lightweight and cordless electric saw weighing 3 kg that is powered by 18 V 3.0 Ah lithium batteries. The end of the saw acts as an electrical capacitive sensor. Given that the processor is coupled to the machine itself, it can be used to work in the upper part of the tree. The most recent prototype of this electric saw was developed by the COVELESS Ingeniería S.L. Company in 2010.

— Manual tools to separate cork were first designed in 2004 by the Instituto del Corcho, la Madera y el Carbón Vegetal of Extremadura (ICMC). Since then, trials have been underway to calibrate and evaluate the tools (ICMC, 2007) (Fig. 1b).

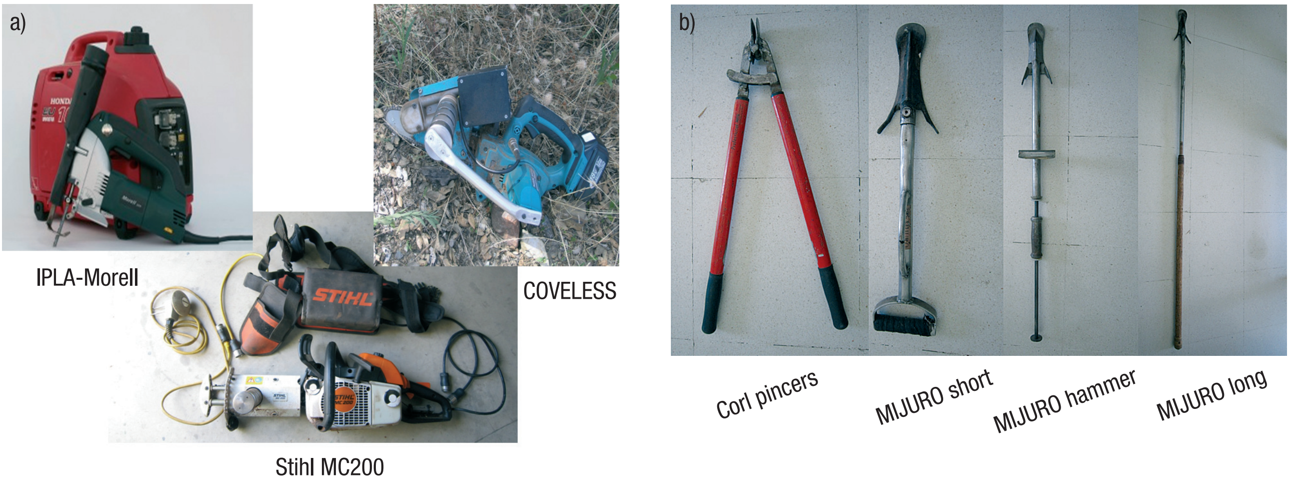

Figure 1. Debarking tools. a) Mechanized tools for cutting cork. b) Manual tools for separating and extracting cork.

— Cork pincers: The pincers are inserted into the cut made in the cork. When the operator closes the pincers, the end inserted into the cork opens to separate the cork from the tree.

— Mijuro: This is a pry bar with a blunt, duck-billed end that is fitted with hooks to hold the cork planks and separate them from the tree. The tool is available in three versions:

• Short Mijuro: This 80 cm long pry bar is used on the lower part of the tree.

• Long Mijuro: This 200 cm long pry bar is used on the upper part of the tree.

• Mijuro hammer: This is a variant of the short Mijuro which is fitted at one end with a steel hammer head that separates tightly adhered cork from the tree without damaging the cork generating layer.

— IPROCOR ladder: This ladder is used to reach the upper part of the tree and can be anchored directly to the tree to reduce the risk of falling. The top of the ladder can also be folded out to form a platform to ensure operator safety.

These tools provide an alternative to traditional axes and have been used experimentally in recent years by different agencies and institutions. The results of preliminary trials run at local scale have confirmed their viability (Antolin *et al.*, 2003; Peralta, 2003; Pereira, 2007; Celis and Caseras, 2009) given that they do not damage the cork generating layer; a fundamental requirement for their use. However, before they can be used in cork stripping, new debarking systems must be developed and evaluated by comparing the results of the new systems to the traditional system. The interest and originality of this study lies in the fact that it

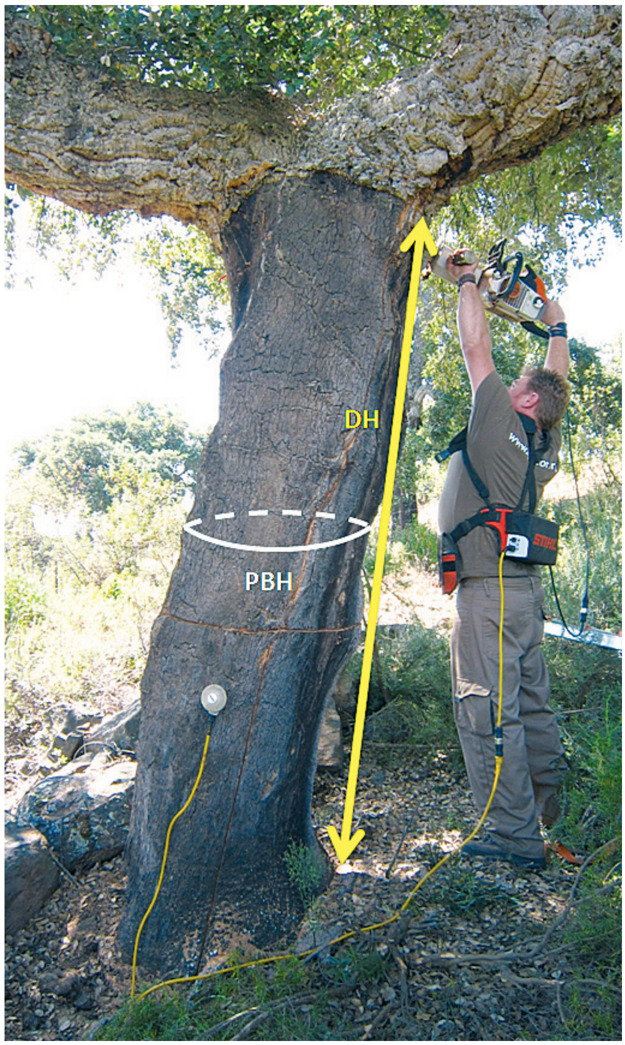

Figure 2. Debarking system 3 using the Stihl chainsaw in trees with DH < 2 m.

analyzes the suitability of each of the tools in terms of their productivity, the damage they may cause to the tree and the skills required to handle them in a wide range of debarking systems. Furthermore, no previous studies have been published using this approach.

The tools analyzed provide new debarking alternatives that should be taken into consideration. A possible alternative is to make a circular cut at the bottom of the stem at a height of 5 or 10 cm from the base called "the lower collar". Although this is a time-consuming and delicate operation that does not yield a larger quantity of cork planks, it permits footers to be left on the tree and reduces the percentage of pieces. While footers have traditionally been extracted to prevent the accumulation of water, possible rot and insect galleries, these problems can be overcome through clean, straight cuts. This operation offers other advantages such as the extraction of cork planks with uniform lower edges, thus making it unnecessary to trim the planks to separate the cork from the footers when manufacturing natural cork stoppers (Pereira, 2007).

Because it is more costly to debark parts of the tree that are not accessible from the ground, some cork may be left on the tree. However, as this is usually good-quality cork it is important to determine the most appropriate system and tool for extracting it.

Although under current legislation cork extraction is restricted to certain months of the year for physiological reasons, the new tools may allow cutting operations to continue over a longer period of time, thus lengthening the cork extraction season.

The use of the new tools for debarking could also mitigate problems caused by the shortage of skilled labor and reduce debarking costs, while allowing footers to be left on the tree. It may also be necessary to consider increasing the debarking period in order to perform cutting operations.

The aim of this study is to evaluate the feasibility of these newly developed tools to improve two operations that have been traditionally performed with an axe: the cutting and separating of cork from the tree. The tools are evaluated in terms of productivity, damage caused to the tree, the skills needed to perform the operations, and their potential to reduce damage to the tree and the cork generating layer. Depending on the debarking height and dendrometric characteristics of the cork oak, four debarking systems using the tools described are proposed and evaluated. The results are then compared to each other and to the traditional system.

Material and methods

The study was carried out in southwestern Spain. A total of 204 trees were debarked; 102 by the traditional system and 102 by the mechanized systems. Five trees were ruled out due to errors in data collection.

The most appropriate debarking tool was selected for each tree according to tree size and debarking height. A series of dendrometric variables, time variables, and variables related to the debarking system were measured in the field in order to evaluate cork yield, and perform a comparative analysis of the different systems (Peralta, 2003; Prades, 1996).

Description of the debarking systems

Each system is defined according to the tools required to perform a given cutting operation depending on the debarking height (DH). Due to the weight of the Stihl chainsaw, this tool cannot be used when standing on ladders or in the stem bifurcation. However, the speed with which it operates makes it a very powerful tool for working in the lower part of the tree from ground level. Therefore, for a DH under 2 m, the Stihl chainsaw is used. When the DH is above 2 m, the IPLA-Morell jigsaw or axes are employed in the upper part of the tree. These tools can be used while standing on ladders or in the stem bifurcation.

Once cuts have been made in the cork, the appropriate manual tool is used to separate and extract cork planks from the tree depending on the DH.

Based on these premises, we developed four debarking systems (Table 1) using the new equipment according to the DH: two systems which are applied to trees with a DH > 2 m and two systems which are applied to trees with a DH < 2 m. The traditional system was applied to trees of all sizes. The systems are briefly described below:

System 1 is applied to trees with a DH > 2 m with debarked branches. In this system, the Stihl chainsaw is used on the tree stem, while the IPLA-Morell jigsaw is used on the lower collar of the tree. System 2 is used on trees with a DH > 2 m and branches that have been debarked, employing a Stihl chainsaw on the stem and an axe on the upper part of the tree. System 3 is applied to trees with a DH < 2 m and employs only a Stihl chainsaw (Fig, 2), while system 4 is applied to trees with a DH < 2 m using the COVELESS electric saw. The latter system is in the experimental stage given

Table 1. Debarking system and tool used

System	N	PBH (cm)	DH (cm)	DS (m²)	Tool			
					Cut		Separate and Extract	
					DH < 2 m	DH > 2 m	DH < 2 m	DH > 2 m
1	57	105.05	176.04	1.95	Stihl	IPLA-Morell	Pincers Short M.	Long M.
2	22	175.75	279.58	5.33	Stihl	Axe	Pincers Short M.	Axe Long M.
3	12	129.54	150.23	1.98	Stihl	—	Pincers Short M.	—
4	6	120.83	136.67	1.82	COVELESS	—	Pincers Short M.	—
Traditional	102	160.73	285.05	4.78	Axe		Axe and burja	

M.: Mijuro.

that the equipment is currently in the process of being developed. In the traditional debarking (system 5) all operations are performed with a burja and an axe, which are used to both cut and extract the cork.

Since axes can only be used by highly skilled workers and one of the objectives of this study is to evaluate the possibility that less experienced operators can also use the new tools, operator experience was included in the system performance analysis. Specifically, operators are classified as being either semi-skilled or skilled depending on their degree of expertise in handling the various tools.

Description of variables

In what follows, we describe the variables used to evaluate the different systems. The variables are grouped according to the type of information they provide. These include variables related to the debarking system, dendrometrics, time required to perform the operation, production and costs.

Variables related to the debarking system

— Debarking system (D_SYS): Systems 1, 2, 3, 4, or 5.

— Debarking quality (Q): Qualitative assessment of the debarking process according to the damage caused to the tree as a result of debarking in earlier (PREV_Q) and current extractions (ACT_Q) (1 poor, 2, 3, 4, 5 excellent). Class 5 corresponds to trees that have not suffered any damage, while class 4 refers to trees with wounds due to cutting, but where the generating layer remains intact. Class 3 includes trees that present wounds from cutting in which the generating layer has become detached from the tree. In class 2, the trees present multiple wounds which produce bumps and calluses, the generating layer has become detached, and cork pieces remain adhered to the tree. In class 1, the damage is similar to that of class 2 but more extensive.

— Giving Away (GA): Ease with which cork is stripped off the tree (1 difficult, 2, 3, 4, 5 easy). Values 1 and 2 indicate that it is not possible to extract most or only a small portion of cork from the debarking surface, respectively. In class 3, all the cork can be extracted without damaging the generating layer but with some difficulty. In classes 4 and 5, the cork is extracted with ease or extreme ease, respectively.

— Worker experience (W_EXP): Workers are classified as 1 if they are semi-skilled and are learning to handle the tools and 2 if they are skilled and have worked with the tools during several debarking seasons.

— Cork ladders (LAD): Use of ladder (1 use, 0 no use).

Dendrometric variables

These variables include tree code (COD); perimeter at breast height over cork (PBH) measured at 1.30 m in height and expressed in cm (Fig. 2); debarking trunk height (DTH) measured in cm; number of debarked branches (NB); and length of the longest branch (BL) measured in cm. The following variables are derived from the previous variables:

— Debarking height (DH) (Fig. 2), $DH(cm) = DTH + BL$.

— Theoretical debarking surface (DS), $DS\ (m^2) = PBH \cdot DF/10{,}000$.

— Debarking coefficient (DC). This indicates debarking pressure by means of linear variables. The value of the coefficient must be lower than 3 (CELIEGE, 2005). $DC = DH/PBH$.

Time variables

These variables indicate the time in minutes required to perform each operation during the different debarking phases for each tree, specifying the tool used.

— Preparation time (T_PREP): Time employed to clean scrub in the work area in order to perform the debarking operations with greater ease.

— Cutting time: Time employed to make the vertical and horizontal cuts in the cork:

- For each tool: Stihl (T_STHIL), IPLA-Morell in the lower collar (T_IPLA_DOWN) and in the upper part of the tree (T_IPLA_UP) and COVELESS (T_COVE).
- Total: Sum of cutting times in a given debarking system (T_TOTAL_CUT).

— Time required to separate and extract cork:

- For each tool: Cork pincers (T_PINCERS), short MIJURO (T_MIJ_SHORT), long MIJURO (T_MIJ_LONG), MIJURO hammer (T_MIJ_HAM).
- Total: Sum of time employed to separate and extract cork in a given debarking system (T_EXTRACT).

— Amount of time the axe is used (T_AX).

— Debarking time (T_DEB): $T\_DEB = T\_PREP + T\_CUT + T\_EXTRACT + T\_AX$.

Production variables

— Cork weight (W_CORK) in kg. This is the sum of the combined weight of the cork planks (W_PLANKS) and cork pieces (W_PIECES).

— Percentage of cork pieces (%PIECES) with respect to cork weight.

— Theoretical cork surface density (W_M2): $W\_M2\ (kg \cdot m^{-2}) = W\_CORK/DS$.

— Productivity (PROD): Amount of cork extracted per hour of work: $PROD\ (kg \cdot h^{-1}) = (W\_CORK/T\_DEB) * 60$.

Cost variables

To obtain the production costs and the hourly cost of each system, the fixed and variable costs of equipment and manpower are calculated (Mederski, 2006; Miyata, 1980). The fixed costs include the initial investment in equipment and tools (allowing for a service life of 2500 hours for cutting equipment and 5000 hours for manual tools) (Nieto and Soria, 1995) and daily wages of operators (€90 for 7 hours of work in 2010 according to industry sources). Variable costs include maintenance costs (70% of the cost of equipment during service life) (Miyata, 1980) and the costs of fuel and lubricant.

The hourly cost (HC) of the tools is expressed in €/h. The hourly cost is calculated for each debarking system (SYS_HC) based on working time and hourly cost (equipment, tools and labor) in each system.

— The production costs (PC) for a ton of cork for each debarking system are calculated as $PC(€ \cdot t^{-1}) = SYS_{HC} * PT$.

Data collection protocol

Prior to debarking, and depending on the DH and characteristics of the tree, the operator selects the debarking system (D_SYS). The quality of previous extractions is evaluated (PREV_Q) by means of visual inspection of the cork oak tree and dendrometric variables are measured. The next step is to make the cuts and remove the cork using the tools selected and record debarking times.

Finally, the extracted cork is weighed (W_PLANKS and W_PIECES) immediately after extraction to prevent moisture loss. The ease with which the cork has been stripped off the tree is recorded (GA), and the debarked surface is examined to evaluate the quality of the current debarking (ACT_Q).

The measurement equipment consisted of a 2-meter tape measure with a precision of up to 1 cm (to measure circumference), a 1-meter ranging rod with a precision of up to 10 cm (to measure height), and a chronometer with a precision of up to one hundredth of a second.

The cork was weighed using an electronic scale with a precision of 0.01 g. Data were collected and recorded using a Trimble GPS GeoExplorer XM. All the values were then exported to a computer.

Analysis of variables

Each of the variables is described statistically by univariate analysis (mean, range, median, standard deviation and coefficient of variation). Tests of normality (Lilliefors test, sig = 0.05), homoskedasticity (Levene test, sig = 0.05) and linearity or independence (Martinez, 1999) were performed on the field variables.

Relationships between variables were analyzed using Pearson's correlation matrix. Principal component analysis (PCA) was used to reduce the number of variables and minimize data loss.

SYSTAT 10.2 and SPSS 8.0 statistical software were used for processing the data.

Analysis of the systems

Performance analysis was the main tool used to compare the systems and determine whether debarking can be improved by using the new technologies. Traditional debarking was carried out only by skilled operators, while both skilled- and semi-skilled operators used the mechanized systems.

Performance was evaluated according to the mean values of productivity PROD (kg · person^{-1} · h^{-1}), the percentage of pieces obtained (%PIECES), and production costs PC (€/t).

The percentage of pieces is an indicator of the amount of raw cork obtained from debarking and significantly affects the market value of cork. Cork pieces measuring less than 400 cm^2 (20 × 20 cm) are marketed at a much lower price than cork planks. During the cork stopper manufacturing process, cork planks are trimmed, thus decreasing plank yield. Less cork is lost if debarking is carried out properly and cork planks of uniform size with straight edges are extracted (Pereira, 2007).

Before analyzing overall performance, we analyze the differences between the four mechanized debarking systems by means of discriminant analysis and Wilks' lambda statistic. Discriminant analysis determines whether there are significant differences between the four systems with respect to the variables that satisfy the condition of homoskedasticity. Wilks' lambda statistic measures the discriminating power of the set of variables: the closer the highest value is to zero, the greater the discriminating power of the variables (Timm, 2002).

Results and discussion

Analysis of the variables

A description of the variables using the basic statistics is shown in Table 2. The average tree had a perimeter at breast height over cork (PBH) of 120.33 cm and a DH of 180.77 cm. The trees yielded 23.58 kg of cork weight (W_CORK), 22.53 kg of cork plank (W_PLANKS) and 1.06 kg of cork pieces (W_PIECES). The average total debarking time (T_DEB) was 12.27 min. The mean value of the PBH variable (120.33 cm) was similar to the mean value in Extremadura (130.38 cm), indicating that the sample was representative (Cardillo, 2000).

The Lilliefors test for normality shows that only two variables have a normal distribution (W_M2, DTH). However, subsequent multivariate statistical techniques support the non-normality of the data. Homoskedasticity was tested using SYST_D as a reference variable. The variables that meet this condition are PBH, W_PIECES, T_STIHL, PREV_Q, GA, while the variables that are very close to the threshold of significance are DTH, T_DEB, T_MIJ_LONG. All the variables that are not formed from a linear combination of the others satisfy the third assumption of linearity, and are therefore independent.

The Pearson correlation matrix (Table 3) shows the variables with correlations greater than or close to 0.7, with a significance level of 0.05. Other variables are also included in the table which allow for interesting, although less significant, conclusions.

As expected, debarking time (T_DEB) is highly correlated with total cutting time (T_TOTAL_CUT) ($R^2 = 0.74$) and extraction time (T_EXTRACT) ($R^2 = 0.82$), especially with T_STIHL ($R^2 = 0.671$), T_PINCERS ($R^2 = 0.797$) and T_MIJ_SHORT ($R^2 = 0.763$). Improving the performance of these tools would reduce total debarking time and therefore increase productivity.

The variables most related to productivity (PROD) are GA ($R^2 = 0.56$), W_M2 ($R^2 = 0.56$) and ACT_Q ($R^2 = 0.52$). This indicates that the thicker the cork, the easier it is to separate and extract from the tree; and the less damage done to the tree, the higher the productivity (PROD). The use of the IPLA-Morell jigsaw in the

Table 2. Univariate analysis of the different variables from basic statistics

Table 2.1. Mechanized debarking system variables

	N	Range	Mean	SD	C.V.
DEBARKING					
D_SYS	97	1.00-4.00	1.64	0.89	0.54
PREV_Q	86	1.00-5.00	2.59	0.90	0.35
ACT_Q	97	1.00-5.00	3.90	0.97	0.25
GA	86	1.00-5.00	3.99	1.04	0.26
W_EXP	97	1.00-2.00	1.39	0.49	0.35
LAD	97	0.00-1.00	0.22	0.41	1.91
DENDROMETRIC					
PBH	97	64.00-310.00	120.33	40.48	0.34
DTH	93	80.00-290.00	168.50	42.55	0.25
BL	97	0.00-300.00	10.98	39.47	3.60
NB	97	0.00-3.00	0.40	0.93	2.32
DH	97	80-540	180.773	66.346	0.367
DSt	97	0.7-16.74	2.367	1.975	0.834
DC	97	0.8-2.537	1.554	0.42	0.27
TIME					
T_PREP	97	0.00-3.25	0.36	0.57	1.58
T_STHIL	97	0.00-6.75	2.65	1.48	0.56
T_IPLA_DOWN	97	0.00-5.00	0.70	0.89	1.27
T_IPLA_UP	96	0.00-13.73	1.04	2.29	2.21
T_COVE	97	0.00-5.98	0.16	0.76	4.60
T_TOTAL_CUT	97	1.25-19.47	4.54	3.33	0.73
T_PINCERS	97	0.58-6.32	1.91	1.20	0.63
T_MIJ_SHORT	97	0.00-18.83	3.21	4.03	1.26
T_MIJ_LONG	97	0.00-14.00	0.49	1.76	3.58
T_MIJ_HAM	97	0.00-8.98	0.46	1.55	3.39
T_EXTRACT	97	1.07-33.75	6.08	6.79	1.12
T_AX	97	0.00-38.23	1.49	5.20	3.49
T_DEB	97	2.58-50.25	12.27	10.57	0.86
PRODUCTION					
W_PLANKS	97	5.40-173.50	22.52	22.17	0.98
W_PIECES	97	0.00-7.60	1.06	1.64	1.55
%PIECES	97	0.00-35.71	4.03	6.24	1.55
W_M2	97	2.75-19.51	9.48	2.35	0.25
PROD	97	15.92-345.41	130.51	63.85	0.49

lower part of the tree (T_IPLA_DOWN) shows a more negative correlation ($R^2 = -0.50$) due to the lower collar.

The quality of current debarking (ACT_Q) increases with the ease with which cork can be extracted from the tree (GA) ($R^2 = 0.62$), but decreases with increasing extraction time (T_EXTRACT) ($R^2 = -0.59$), especially when using the short MIJURO (T_MIJ_SHORT) ($R^2 = -0.54$). The percentage of pieces (%PIECES) increases when it is more difficult to separate cork from the tree (GA) ($R^2 = -0.68$), thus requiring the use of the MIJURO hammer (T_MIJ_HAM) ($R^2 = 0.62$).

Six factors with eigenvalues above 1 were obtained by principal components analysis (PCA) (Table 4.1). These factors explain 81.5% of the total variance of the sample (Fig. 3). Of these six factors, the first two account for 55% of total variance. In general, the variables in factor 1 with a higher factorial score are those which contain dendrometric information. The shape and size of the tree and the debarking height (*i.e.*, if the cork is accessible from the ground or not) are the most important parameters for selecting the debarking system and hence the most appropriate tools. The variables in factor 2 with the highest factorial scores

Table 2.2. Traditional debarking system variables

	N	Range	Mean	SD	C.V.
DEBARKING					
PREV_Q	102	1.00-4.00	2.58	1.16	0.45
ACT_Q	102	3.00-5.00	3.33	0.65	0.15
GA	102	1.00-5.00	4.63	1.08	0.23
W_EXP	102	2.00-2.00	2	0.00	0.00
DENDROMETRIC					
PBH	102	87-299	160.74	37.18	0.23
DTH	102	110-325	197,01	40.82	0.21
BL	102	0-245	88.04	67.37	0.77
NB	102	0-4	2.25	1.28	0.57
DH	102	145-460	285.05	77.15	0.27
DS	102	1.26-11.66	4.78	2.20	0.46
DC	102	0.97-2.63	1.79	0.34	0.19
TIME					
T_PREP	102	0-4	1.63	1.30	0.80
T_AX	102	3-34.5	12.27	6.81	0.55
T_DEB	102	3-34.5	12.46	6.98	0.56
PRODUCTION					
W_PLANKS	102	10.25-183	50.67	36.57	0.72
W_PIECES	102	0-8.25	2.61	2.02	0.77
%PIECES	102	0-16.78	5.57	3.84	0.67
W_M2	102	3.68-20.10	10.52	3.13	0.30
PROD	102	15.92-345.41	118.72	63.85	0.49

are primarily those related to working and debarking time (Q_ACT, GA) (Table 4.2).

Analysis of the four mechanized debarking systems

The variables that satisfied the condition of homogeneity of variances and productivity (PROD) were used in the multivariate analysis. The debarking system (D_SYS) was used as the grouping variable in the analysis. Wilks' lambda value ($\lambda = 0.13$) is assumed to be correct taking into account that the data set was established artificially and indicates differences between groups. The percentage of correctly classified cases is 85%. The prior establishment of four mechanized debarking systems is validated by means of discriminant analysis, which shows that there are differences between the four systems. Specifically, a clear difference can be observed between systems 1, 2 and 4, while system 3 overlaps to some extent with systems 1 and 2 (Fig. 4). The analogies are due to the fact that the Stihl chainsaw was used on tree stems in all four systems, while the differences arise from the tool used in the upper part of the tree (IPLA-Morell in system 1 and an axe in system 2).

When analyzing the data jointly, the mechanized systems obtain fairly high mean productivity values (130.5 kg · person^{-1} · hour^{-1}). However, some differences were detected between the different debarking systems.

System 2, which was performed on cork oaks with debarked branches, is the most productive (168.39 kg · person^{-1} · hour^{-1}). The productivity of system 3 (155.63 kg · person^{-1} · hour^{-1}), which was performed on trees without debarked branches, is slightly less than that of system 2, thus indicating that cork should not be left on tree branches for economic reasons. The percentage of pieces is similar in both systems, with 4.83% in system 2 and 5% in system 3. This highlights the importance of using the most appropriate tool to extract cork from the upper part of the tree.

System 1 was the least productive (108.78 kg · person^{-1} · hour^{-1}) and entailed higher production costs (128.23 € · t^{-1}), but %PIECES was lower (2.4%). It would be necessary to evaluate the long-term increase in production costs and physiological effects of cutting

Table 3. Pearson's correlation matrix

	ACT_Q	GA	T_STIHL	T_IPLA_DOWN	T_CUT	T_PINCERS	T_MIJ_SHORT	T_MIJ_HAM	T_EXTRACT	T_DEB	%PIECES	W_M2	PROD
ACT_Q	1												
GA	0,62	1											
T_STIHL	–0,33	0,36	1										
T_IPLA_DOWN	–0,42	–0,1	0,01	1									
T_CUT	–0,44	–0,31	0,59	0,58	1								
T_PINCERS	–0,48	–0,4	0,58	0,39	0,76	1							
T_MIJ_SHORT	–0,54	–0,68	0,47	0,3	0,67	0.69	1						
T_MIJ_HAM	–0,46	–0,53	0,16	0,16	0,24	0.43	0.47	1					
T_EXTRACT	–0,59	–0,67	0,53	0,35	0,73	0.8	0.95	0,66	1				
T_DEB	–0,51	–0,53	0,67	0,24	0,74	0.8	0.76	0,44	0,82	1			
%PIECES	–0,37	–0,68	0,23	–0,02	0,1	0,18	0,45	0,62	0,47	0,39	1		
W_M2	0,09	0,14	0,28	–0,44	0,05	0,09	0,1	–0,01	0,12	0,21	–0,06	1	
PROD	0,52	0,56	–0,12	–0,5	–0,32	–0,32	–0,41	–0,37	–0,44	–0,26	–0,32	0,56	1

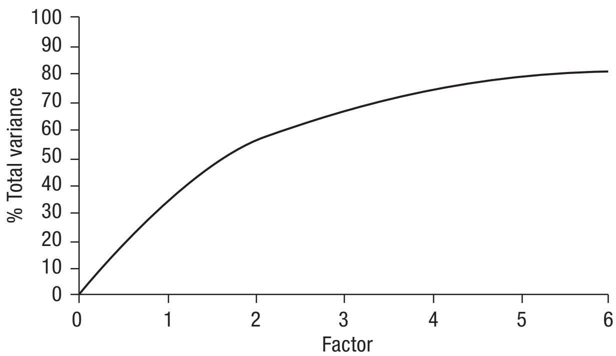

Figure 3. PCA. Percentage of variance explained by factors with eigenvalues above 1.

the lower collar and leaving footers on the cork oak. System 4 achieved high productivity (148.13 kg · person^{-1} · hour^{-1}), but %PIECES (4.87%) was similar to systems 2 and 3.

In general, the new equipment and tools improve the parameters normally used to assess debarking, especially productivity and production costs (Antolin *et al.*, 2003; Celis and Caseras, 2009). The drawbacks to using such tools are primarily due to their drive systems, cords and accessories. Tool battery life conditions the work performed, while the weight of the generator restricts the movement of operators in the forest. Moreover, the cords and accessories, as well as the weight of the equipment, affects work safety and ergonomics, especially when debarking is performed in the upper part of the tree. The use of the COVELESS saw, which is currently under development, is limited due to the short duration of the battery and a defect in the system that regulates the depth of cut. However, as the COVELESS saw is cordless and weighs much less, ergonomic aspects are improved and operators can work more safely. Solving these problems would improve the applicability of the COVELESS saw in debarking operations. The COVELESS saw could be a suitable tool for working at all heights.

The study of productivity according to operator experience shows that when the new debarking tools were used, skilled operators achieved higher productivity (151.24 kg · person^{-1} · hour^{-1}) than semi-skilled operators (117.15 kg · person^{-1} · hour^{-1}). However, %PIECES obtained by semi-skilled operators was lower (3.23%) than that obtained by skilled operators (5.23%) given that the semi-skilled operators debarked many trees using system 1 with a lower percentage of cork pieces (2.90%), while the skilled operators debarked most trees using systems 2 and 3.

Debarking quality improves with the new tools. In all cases, the mean quality of debarking for the four systems increases from 2.59 (PREV_Q) when using an axe to 3.90 (ACT_Q) using mechanized debarking. The statistical analysis using the Levene test (0.05 level of significance) shows that there are significant differences between the two variables and that the quality of debarking using the new tools is greater than

Table 4. PCA Results

Table 4.1. Factors with eigenvalues above 1

Factor	Eigenvalue
1	10,979
2	7,127
3	3,84
4	2,498
5	1,398
6	1,069

Table 4.2. Factorial scores of variables for factors 1 and 2

	Factor	
	1	2
PBH	0,93	0,181
DTH	0,504	0,422
DS	0,924	0,173
BL	0,856	0,022
NB	0,804	0,046
DH	0,84	0,267
DC	–0,19	0,136
W_PLANKS	0,931	0,108
W_PIECES	0,682	0,316
%PIECES	0,124	0,41
W_CORK	0,938	0,123
T_PREP	–0,198	0,382
T_STIHL	0,484	0,521
T_IPLA_UP	–0,434	0,59
T_IPLA_DOWN	0,044	0,779
T_COVE	0,158	–0,126
T_CUT	0,14	0,853
T_PINCERS	0,244	0,824
T_MIJ_SHORT	0,091	0,843
T_MIJ_LONG	0,132	0,687
T_MIJ_HAM	–0,078	0,556
LAD	0,665	0,383
T_EXTRACT	0,099	0,914
T_AX	0,862	–0,096
T_DEB	0,57	0,803
PROD	0,474	–0,628
D_SYS	0,758	–0,306
PREV_Q	0,212	–0,347
ACT_Q	0,03	–0,681
GA	–0,04	–0,642
W_EXP	0,661	–0,104

when using an axe in all cases. Debarking quality is lower with the IPLA-Morell jigsaw (ACT_Q = 3.39), although this result may be due to the fact that the quality of previous debarking was also lower (PREV_Q = 2.31). The highest quality was obtained with the COVELESS saw (ACT_Q = 4.6), which

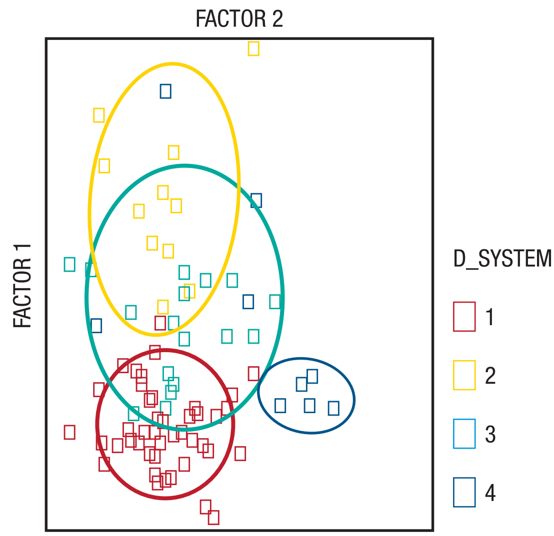

Figure 4. Discriminant analysis of mechanized debarking systems (1, 2, 3, 4) according to factors 1 and 2.

supports the tool's high potential (Table 5). Specifically, cork extraction was performed with greater precision and cleanliness, thus improving the health of the cork oak and increasing cork plank yield during manufacturing. The mean debarking coefficient (DC) (1.55) did not exceed the recommended values in any case and is far from the threshold of 3 (CELIÈGE, 2005; Montero *et al.*, 1996).

Results of the mechanized debarking systems compared with the traditional debarking system[

The productivity of the traditional system is similar to that obtained in previous works (Celis and Caseras, 2009; Antolin *et al.*, 2003). Overall, mean productivity is higher when using mechanized systems (130.5 kg · person^{-1} · hour^{-1}) as opposed to using the traditional system (118.72 kg · person^{-1} · hour^{-1}) (Table 5).

The study of productivity according to operator experience shows that when skilled operators use these new tools, they achieve a similar productivity (117.15 kg · person^{-1} · hour^{-1}) to skilled operators using the traditional debarking system (118.72 kg · person^{-1} · hour^{-1}) (Peralta, 2003). In the new systems, however, higher operator productivity is associated with a higher percentage of cork pieces. Because it takes less time to learn how to use the mechanized tools and they are also easier to handle

Table 5. Results for productivity (kg · person^{-1} · hour^{-1}), pieces (%), production costs (€ · t^{-1}) and debarking quality by debarking system

D_SYS	PROD (kg · person^{-1} · hour^{-1})	%PIECES	PC (€ · t^{-1})	PREV_Q	ACT_Q
1	108.78	2.90	128.23	2.31	3.39
2	168.39	5.00	80.72	2.75	4.08
3	155.63	4.83	79.87	3.13	3.86
4	148.13	4.87	90.22	3.4	4.6
Traditional	118.72	5.50	108.37	—	3.333

Table 6. Results for productivity (kg · person^{-1} · hour^{-1}) and pieces (%) according to operator experience

D_SYS	W_EXP	PROD (kg · person^{-1} · hour^{-1})	%PIECES
Mechanized (1, 2, 3, 4)	Semi-skilled	117.15	3.23
	Skilled	151.24	5.27
Traditional (5)	Skilled	118.72	5.50

than axes, these new technologies can facilitate the training of workers without compromising productivity (Table 6).

The percentage of pieces (%PIECES) ranges from 2.90% to 5.50% for all systems. The lowest value (2.90%) corresponds to system 1 because the cork of the footers is not extracted. For the rest of the new systems (3, 4 and 2), the percentage of cork pieces (4.83%, 4.87% and 5%, respectively) is very similar to that of the traditional system (Peralta, 2003).

The analysis of production costs (PC) (€ · t^{1}) shows that, with the exception of system 1, production costs are lower when using mechanized debarking systems as opposed to using the traditional system. The higher costs of system 1 are due to operations in the lower collar of the tree and the cost of using two different tools (IPLA-Morell and Stihl). However, it would be necessary to evaluate the increase in the market value of cork in future extractions in order to reach any conclusions about the profitability of this system.

In sum, the new debarking systems provide better results than the traditional system: productivity (kg · person^{-1} · h^{-1}) is higher, the percentage of cork pieces (%) is slightly lower, and production costs (€ · t^{-1}) are lower, with the exception of system 1 (Table 5). In all cases, the quality of debarking improves with the new tools. When cork is extracted with an axe, trees present multiple wounds, the generating layer becomes detached and cork pieces are left on the tree. In contrast, the new tools decrease the number of wounds inflicted and generating layer detachment is less pronounced or simply does not occur.

Conclusions

The results of this study demonstrate the viability of using the new debarking tools and the potential benefits they can bring to the sector. The new equipment and tools improve the quality of debarking. Cork extraction is performed with greater perfection and cleanliness, thus reducing damage and impacting positively on the future production of cork and the health of the tree.

The drawbacks to using these tools are primarily due to their drive systems, cords and accessories. As all the cutting tools were found to have significant limitations at debarking heights above 2 m, axes are still needed for debarking, regardless of the system used.

In general, the new equipment and tools improve the parameters normally used to assess debarking, especially productivity and production costs. Higher productivity is obtained when using the chainsaw on the stem in conjunction with an axe in the upper part of the tree. From an economic standpoint, debarking can be performed at heights of over 2 m, without increasing harvesting costs; an important factor due to the high quality of the cork on the branches.

When cork can be stripped away easily from the tree, the percentage of cork pieces decreases, productivity increases, and damage to the tree is reduced, thus indicating the importance of debarking at the appropriate time. When cork is not extracted easily from the tree, the use of manual tools reduces damage, although it increases debarking time and decreases productivity.

As regards raw material, the new tools allow cutting more uniform sized cork planks with straight edges. The percentage of pieces is similar except when debarking is performed on the lower collar and footers are left on the tree. Because this operation increases harvesting costs, it would be necessary to evaluate the increase in raw material obtained for the manufacture of natural cork stoppers and the physiological effects on the tree.

The study of productivity according to operator experience shows that when semi-skilled operators use the new tools they obtain very similar results to those of skilled operators working with the traditional system. This equipment would therefore help in overcoming problems arising from the lack of skilled labor and improve working conditions without compromising productivity.

Due to the higher quality of the cuts made with these tools, the cutting period could be extended, which would reduce the temporality of debarking work. From the physiological point of view, this would allow for the cork to be separated and extracted from the tree at the optimum time.

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