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Analysis of cork quality and cork tree health in stands of western Spain

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A R T I C L E I N F O

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A B S T R A C T

Good knowledge of the factors that influence cork quality and the health of forests is essential when making decisions regarding the management of productive cork oak forests. The quality of cork planks depends on: plank thickness, plank porosity and the presence of anomalies. So far, no studies have evaluated cork quality based on cork anomalies, partly due to the difficulty of obtaining adequate data. In 1985, it was developed the first Cork Quality Field Assessment Plan (CQFAP) to provide information about the quality of harvested cork by collecting data of very high quality. This work analyzes the anomalies present in 2049 cork sampling units collected from ten stands under the CQFAP for the period 1986–2012 in three consecutive cork stripping cycles. Data on diseases, pests and stripping damages are also analyzed in the 654 trees where cork sampling units were collected in the third stripping cycle. Additionally, mean monthly temperature and precipitation values for the 35 years covering the three stripping periods were calculated. A progressive deterioration of cork quality was observed in the sampled cork oak stands. It was found a positive relationship between cork thickness and temperature indicating that the cork growing period could be extended when temperatures are moderate. Sampled cork oaks were more affected by *Cerambycidae* attacks and *Coraebus undatus* indicating their prevalent nature. The presence of *Coraebus undatus* were higher in stands with good health status. The studied diseases were *Biscogniauxia mediterranea*, *Phytophthora* sp. and fungi of the family *Botryosphaeriaceae*, finding a not previously reported correlation between the presence of *Crematogaster scutellaris* and the three studied diseases. Stripping damages increase with smaller cork thickness but climate is not a decisive factor for a proper stripping. Although having room for improvement, the CQFAP is proving to be an effective tool for assessing the quality of cork, the health status of cork oak forests and the evolution of these forests over time. The information provided could be also used to identify places worthy of further studying. The main recommendation for improving the CQFAP would be to monitor the same trees in each consecutive sampling for properly monitoring cork thickness and the presence of defects to be used as a proxy for tree health. Regarding forest management, the main recommendations would be to extend the length of stripping cycles to enhance cork production, and to use the new tools and systems for cork stripping to reduce damage.

1. Introduction

Cork is a natural and renewable product. Defining cork quality is one of the most important aspects in the cork sector due to the difficulty of establishing objective criteria that can be applied in different commercial and industrial contexts. Until the end of the 20th century, cork quality was assessed in the field by experts and manufacturers, which made it difficult for owners of cork oak forests to determine the economic value of the cork they produced. In the cork preparation or first transformation industry, cork was and continues to be classified based on an external analysis of boiled planks. Specialized operators classify the cork by means of a combination of two variables: the caliper or thickness of the cork and its visual appearance or quality (García de Ceca et al., 2000; Gonzalez-Adrados et al., 2000; González-Adrados and Pereira, 1996). In more advanced stages of the industrial process when cork stoppers and discs are manufactured, classification is automated using image analysis and other techniques (Gómez-Sánchez et al., 2013; Oliveira et al., 2015).

One of the objectives of the sector has been to link the industrial quality of cork to site quality evaluation (state of cork oak forests and

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trees) and has been approached from different perspectives and by different management bodies. In 1985, the recently created Institute for the Promotion of Cork (IPROCOR) of the Regional Government of Extremadura, Spain, now the Cork, Wood and Charcoal Institute (ICMC) of the Institute for Scientific and Technological Research of Extremadura (CICYTEX), launched the Cork Quality Field Assessment Plan (hereinafter Sampling Plan), with the aim of providing producers and manufacturers information on the quality of the cork produced in the cork oak forests of Extremadura. The Sampling Plan was pioneer in tackling this challenge (Gamero Guerrero, 1993; Carrasco et al., 1997). The objective of the Sampling Plan was to improve traditional sampling techniques employed by cork buyers to determine the quality of a cork oak stand using statistical analyses and a defined working methodology. Additionally, a database of great value for producers, industry, researchers and government technicians was developed under the plan.

From a sampling based on the variability between cork oak trees and the variability of the cork on the tree, a series of cork sampling units were collected and classified in the laboratory into nine quality classes combining five thickness classes and seven visual quality classes (1 to 6 and raw cork waste). In the first stage of the Sampling Plan, data on alterations in the cork sampling units, cork thickness and the visual quality classes were obtained. In 1993, IPROCOR developed the Q quality index, which is calculated as the average of the Q quality index of all the cork sampling units collected in a stand. The IPROCOR Q index varies between a theoretical maximum of 19.5 (if the cork sampling unit is of the best class) and a minimum of 1.5 (the cork sampling unit is raw cork waste). These values are based on the quality class of the cork quality sampling unit, which is a combination of thickness classes and visual quality classes (Figure SM1, Table SM1) weighted by a coefficient that represents the commercial value of that quality class (based on the price of baled cork of each class in 1993) (Gamero Guerrero, 1993; Pozo-Barrón and Cardillo-Amo, 1997). This index is a well-known quality reference in the sector and is used to analyze the quality of cork produced in different regions (González Montero, 2004; Dehane and Chorana, 2022).

In 2007, the Sampling Plan began to incorporate data on the sampled plots and trees and information on land use, vegetation, harvesting, pests and diseases. The latest novelty of the Sampling Plan, introduced in 2008, consisted of incorporating a large georeferenced database of cork oak stands and plots into a geographic information system known as SIGSUBER (Martín Collado et al., 2009) to further exploit the Sampling Plan data by means of geostatistical applications and the generation of thematic maps. Since 1985, approximately 1000 sampling campaigns have been conducted and approximately 55,000 cork sampling units are stored in the ICMC's cork repository (Figure SM2).

The Cork Quality Field Assessment Plan was implemented in Andalusia, Spain, in 1995 and in Portugal in 1991. Under the plan, several European research projects have been conducted to assess and model cork production and quality in the field in line with the Codes of Good Practices of the European Cork Confederation (CELIEGE), particularly the International Code of Cork Stopper Manufacturing Practices (Celiège, 2006) and the Código Internacional de Prácticas Suberícolas (International Code of Cork Production Practices [CIPS], 2005). SYSTECODE, which was created in 1999, is the quality assurance system for the cork industry that accredits compliance with the CIPT, which is now widely implemented in companies in the sector. However, because the CIPS is a forest certification system designed specifically for cork oak forests, it has not yet materialized as it overlaps with the Programme for the Endorsement of Forest Certification (PEFC) and the Forest Stewardship Council (FSC) forest certifications.

The quality of cork planks depends on three fundamental characteristics: plank thickness, plank porosity and the visual appearance of the plank, which is determined by the presence of anomalies or defects. Previous studies have analyzed the factors that influence the thickness of cork planks at the end of the stripping cycle (Sánchez-González et al., 2007; Paulo et al., 2017), assessed cork plank porosity using image analysis (Pereira et al., 1996), compared porosity in different cork-producing regions (Ghalem et al., 2016) or analyzed variations along the trunk of the cork oak tree (Costa et al., 2021). Others have examined cork thickness and porosity simultaneously (Ferreira et al., 2000; Lauw et al., 2018) and the influence of factors such as stand density (Pizzurro et al., 2010), soil composition (Pestana and Gomes, 2014) and irrigation (Poeiras et al., 2022). Some studies have focused on methods to detect certain anomalies, examined the anomalies present in cork sampling units from a descriptive point of view to characterize the cork produced in a region (Chorana et al., 2019) or developed a qualitative system for classifying cork planks (Gonzalez-Adrados et al., 2000; González-Adrados et al., 2005). However, no studies have evaluated cork quality based on the anomalies found in analyzed cork sampling units. This is partly due to the difficulty of obtaining adequate data on both cork quantity and cork quality since classifying cork sampling units requires a great deal of knowledge about cork. However, the data collected under the Sampling Plan are of very high quality and therefore very useful for this purpose.

Many of the anomalies commonly found in cork planks are caused by diseases and pests. Therefore, knowledge of these anomalies can serve to determine the health status of cork oak forests (Dehane et al., 2013). To date, the relationship between symptoms of disease in cork oak trees and the anomalies found in the cork sampling units collected from them has not been studied and could significantly contribute to our knowledge about one of the main threats to cork oak forests: a generalized decline caused in part by a multifactorial forest disease known as Iberian oak decline, which affects different *Quercus* species in the Iberian Peninsula (Brasier et al., 1993).

Cork stripping practices, known as "quality of cork stripping" when properly executed, have been shown to influence the health status of the cork oak, its future production and the yields obtained from the cork planks during industrial transformation (Beira-Dávila et al., 2014). Knowledge of the damage caused to cork oaks due to poor cork stripping practices is of key importance to ensure the proper management of cork oak forests.

The climate is an additional factor to consider since rainfall and temperatures during the stripping cycle affect the quality of the produced cork. Several studies have examined the influence of climate on cork growth and hence on the thickness of the cork at the end of the cycle (Caritat et al., 1996; Caritat et al., 2000; Pizzurro and Maetzke, 2009; Almeida et al., 2010; Costa et al., 2016; Oliveira et al., 2016; Ghalem et al., 2018; Leite et al., 2018; Leite et al., 2019; Costa et al., 2022). However, no studies have addressed the influence of climate on cork anomalies.

To the best of the authors' knowledge, this is the first study to evaluate cork quality based on anomalies in cork sampling units and link these anomalies to the health status of the trees that produced the cork taking into account climate data and damage caused during cork stripping. To this end, cork sampling units collected in the same areas in three consecutive stripping cycles over a period of 26 years between the first and last strippings are used. The study considers a very broad context that includes dendrometric, phytosanitary and meteorological variables to understand the effects of climate on cork oak forests and the evolution of cork quality.

The main objective of this work is to further elaborate on information generated in the period 1977–2012 and analyze the factors that influence cork quality and the health status of trees in cork oak stands located in western Spain, specifically in the region of Extremadura. This main objective will be achieved through the following specific objectives:

1. Describe changes in anomalies during the three consecutive cork stripping cycles in the sampled stands.
2. Study the relationship between the variables used to define cork quality and the health status of cork oak trees.
3. Describe the incidence of pests and diseases and damage due to stripping during the third sampling.

4. Study the relationship between meteorological and dendrometric variables and the variables that define cork quality.
5. Study the relationship between meteorological and dendrometric variables and the variables that define the health status of the cork oak trees.

The results and diagnosis of this work can provide useful information for strategic and tactical cork oak management and actions aimed at improving the phytosanitary status of cork stands.

2. Material and methods

2.1. Data collection

Data were obtained from 2049 cork sampling units collected from ten cork oak stands located in Extremadura over the period 1986–2012 under the Sampling Plan (Gamero Guerrero, 1993; Carrasco et al., 1997). The cork sampling units were collected over three consecutive cork stripping cycles in different cork oak stands. One cork sampling unit was extracted per tree; different trees were sampled in each stripping cycle. In each stand, cork sampling units were collected following a sampling methodology that has changed over time:

- Early years (1985–1998): Cork sampling units were taken at regular intervals (every 50–150 m) along a transect throughout the whole stripping area. The number of collected cork sampling units in each stand depended on its size.
- Period 1999–2000: During this period, a two-phase plot sampling method was established. The first phase of the plot sampling was a systematic grid on the whole stripping area with 4 to 10 points. In the second phase, a cork sampling unit was taken in the 10–15 trees closest to the selected points. Plots were circular of variable radius. The number of collected cork sampling units in each stand depended on its size and ranged from 50 to100. In some stands the previously explained transect-based sampling method was still applied.
- Between 2001 and 2004 the number of points in the plot sampling method were gradually set to five and the number of cork sampling units taken was set to 15 in each point. In some stands the previously explained transect-based sampling method was still applied. Since then a maximum of 75 cork sampling units is collected in each stand depending on its size.
- From 2005 in those stands where the plot sampling method was applied, along with the cork sampling unit in each tree were also collected tree location data, dendrometric data and data on the health status of cork trees and damage caused by stripping. At the time the cork sampling units were collected symptoms of the main pests and diseases affecting the cork oak forests, as well as tree damage caused by stripping were also recorded. The over cork circumference, trunk stripping height, stripped length on one of the branches and number of stripped branches were also measured in the trees. The total stripping height was calculated as the sum of the trunk stripping height and the branch stripping length. Stand density was calculated using the distance from the plot center to the 6th tree.

The stands used for the present study were selected according to three criteria. Firstly, that the cork trees had been stripped and sampled by IPROCOR on at least three consecutive occasions and that all the cork sampling units had been collected during the stripping period or cycle (9–11 years) but prior to stripping. Cork oak stands may have several harvesting areas (up to 10), so the second criterion was that the cork sampling units had been obtained from the same areas in each stand. The third criterion was that a minimum of 45 cork sampling units had been collected in each area. All the cork sampling units were obtained from the trees at a height of 1.3 m above ground level and measured 10 × 10 cm following the Sampling Plan methodology.

The cork sampling units used for the study were provided by the ICMC cork repository. Each cork sampling unit had been prepared and classified by at least five expert workers the year it was collected between the first and the last stripping over a 26-year period (1986–2012). The cork sampling units were prepared by immersing the cork in boiling water without additives to clean it, extracting the water-soluble substances and making the cork suitable for processing following the usual industrial procedure (ISO-633, 2019) The traditional classification system is completely manual, involves a high degree of subjectivity and has proved to be highly variable (Barros and Pereira, 1987; Melo and Pinto, 1989; Lopes and Pereira, 1998; García de Ceca, 2001). Therefore, prior to carrying out this study, the cork sampling units were prepared again to classify them more homogeneously.

The cork sampling units were boiled and trimmed again, and a single operator graded them over several weeks following the traditional system of measuring the thickness and assessing the visual appearance and anomalies to obtain the final quality classes for each cork sampling unit. Fig. 1 shows the anomalies considered in this study. The cork sampling units had not been classified according to their visual appearance (values of 1–7) in the first classification. Finally, based on the quality of the cork sampling units collected in each stand, the mean Q quality index was obtained for each cork stand, which is defined as (González Montero, 2004):

$$Q = \sum_{i=1}^{9} Q_i \cdot \frac{n_i}{n}$$

where Q_i is the quality index assigned to each cork sampling unit which represents the economic valuation of each quality class on a scale of 1.5–19.5 ($Q_1 = 11; Q_2 = 19.5; Q_3 = 7; Q_4 = 19; Q_5 = 6.5; Q_6 = 12.75; Q_7 = 5; Q_8 = 12; Q_9 = 1.5$), n_i is the number of cork sampling units of Q_i in the stand and n is the total number of cork sampling units in the stand.

It should be noted that the ISO cork vocabulary standard (ISO 633: 2019) is used in this study to describe cork anomalies, although previous studies have used other terms. For example, some studies have referred to green cork (Q_GREEN) as “wetcork” (Parameswaran et al., 1981; Pereira, 2007), while González-Adrados *et al.* (2000) used the term “clay” to refer to very earthy cork or “pasmo” (Q_PASM), “pore” to refer to earthy cork (Q_EARTH), “bofe” to refer to folded cork (Q_FOLD) and “nail” to refer to lignified cork (Q_LIGN).

Additionally, meteorological stations closest to each of the stands with similar physiographic conditions that had the complete data series for the years of interest were selected (Fig. 2). Data on monthly temperature and precipitation for the 35 years covering the three stripping periods in all the stands were requested from the Spanish Meteorological Agency (AEMET). The means of these variables were calculated at different levels for each complete stripping cycle, each year of the stripping cycle and each season of the year as well as the mean values for each month (Table SM2).

Table 1 includes a list of all the variables analyzed together with their descriptions and the type of data they store. The cork anomalies are referred to in accordance with the ISO vocabulary standard for cork (ISO 633: 2019). Table 2 shows a summary of the quantitative data and Fig. 3 shows the frequency histograms of anomalies, symptoms of diseases and pests and cork damage for each stand and sampling. This information is also available tabulated as supplementary material (Table SM2 and SM3).

2.2. Statistical analysis

Since depending on the year in which cork sampling units were collected the sampling was conducted using either a plot method or a transect-based method, the statistical analysis regarding cork quality were done at stand level. The statistical analysis regarding cork oak health were done at tree level.

To describe differences in the total number of anomalies detected in each of the stands, a simple correspondence analysis was performed. To

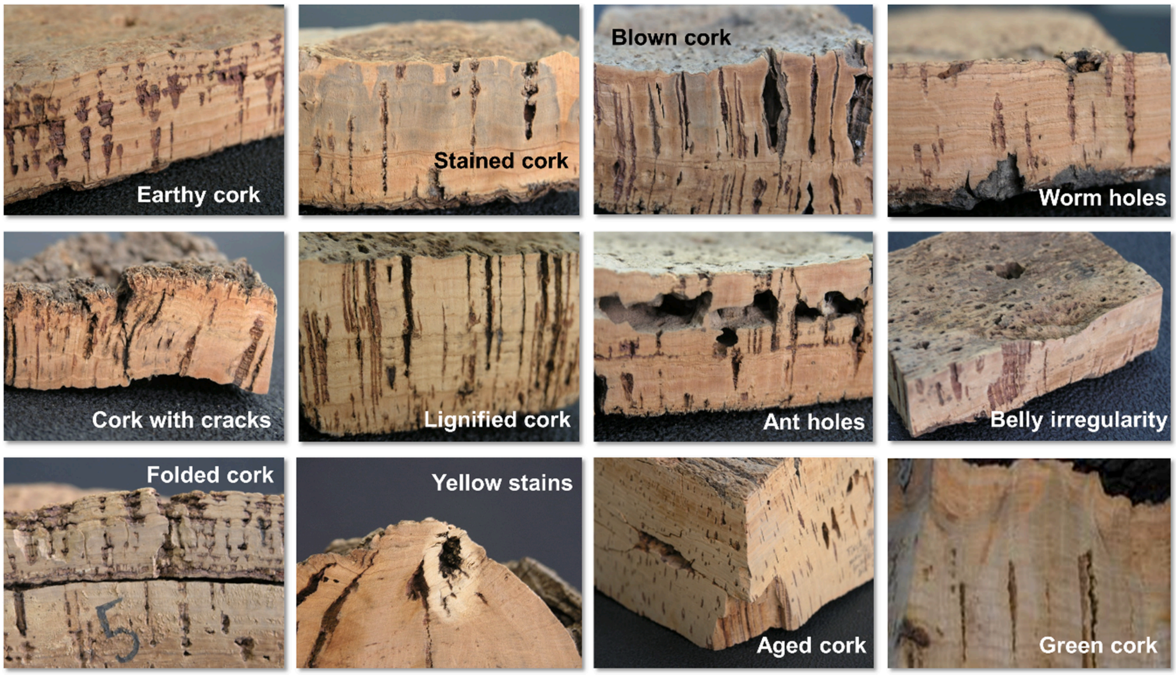

Fig. 1. Anomalies considered in this study described according to the ISO vocabulary standard.

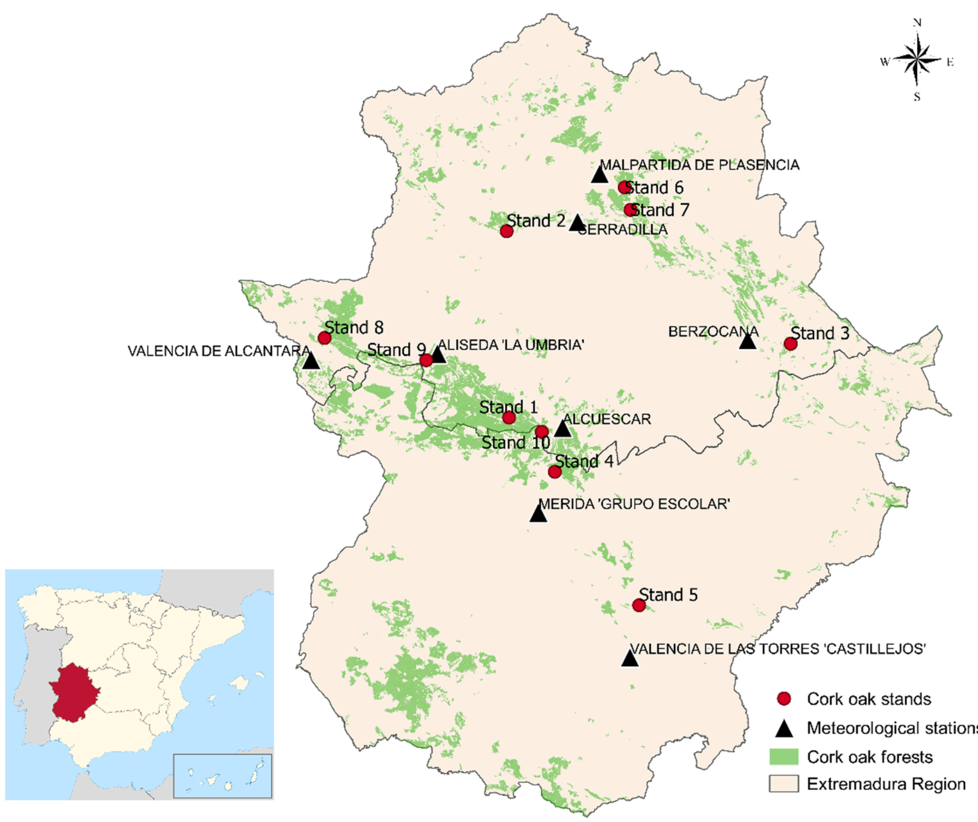

Fig. 2. Map of the studied region with the location of the sampled stands and the meteorological stations.

this end, all the anomalies detected in each cork oak stand and stripping cycle (frequency data) were added together and weighted by the number of total cork sampling units collected in each stand and stripping cycle. The same technique was then used to detect differences in each stand and stripping cycle according to the type of anomaly. The incidence of pests and diseases and damage due to stripping in the sampled stands was also compared by means of a correspondence analysis. All correspondence analyses were performed using the SAS "corresp" procedure.

To analyze the relationships between cork quality, cork oak health and the meteorological and dendrometric variables, a univariate correlation analysis was performed. To analyze the correlation between two dichotomous variables, Pearson's Phi coefficient was calculated (*Phi*).

Table 1
Descriptions of the variables used. In the first column the number of subjects sampled is shown between parenthesis.

GROUP	VARIABLE	DESCRIPTION	DATA TYPE
Cork quality: variables measured in cork sampling unit extracted in trees located in the same stands in three consecutive stripping cycles. Trees were different in each stripping cycle (2049)	Q_VIS	Visual appearance index based on porosity, the presence or absence of defects, density and color	Discrete (1–7)
	Q_THICK	Caliper / thickness	Continuous
	Q_Q	Cork quality index	Continuous
	Q_BELLY	Cork with belly irregularity	Discrete (0/1)
	Q_CRACK	Cork with cracks	Discrete (0/1)
	Q_EARTH	Earthy cork	Discrete (0/1)
	Q_LIGN	Lignified cork	Discrete (0/1)
	Q_BLOWN	Blown cork	Discrete (0/1)
	Q_GREEN	Green cork	Discrete (0/1)
	Q_WORM	Cork with worm holes	Discrete (0/1)
	Q_ANT	Cork with ant holes	Discrete (0/1)
	Q_STAIN	Stained cork	Discrete (0/1)
	Q_YELLOW	Cork with yellow stains	Discrete (0/1)
	Q_FOLD	Folded cork	Discrete (0/1)
	Q_AGED	Aged cork	Discrete (0/1)
	Q_PASM	Very earthy cork / pasmo	Discrete (0/1)
	Q_BIRD	Cork bored by birds	Discrete (0/1)
	Q_TERMITES	Cork with termite holes	Discrete (0/1)
	Q_VINEGAR	Cork with vinegar stains	Discrete (0/1)
	Q_THIN	Too thin (<18 mm)	Discrete (0/1)
Phytosanitary: variables measured in the trees from which cork sampling units were extracted in the 3rd stripping cycle (654)	P_CBX	Exit holes (greater than1 cm) in trunks and branches with small cylinders of excrement attirbuted to *Cerambyx welensii*, *C.Cerdo, Prinobius germari*	Discrete (0/1)
	P_COR	*Coraebus undatus* galleries	Discrete (0/1)
	P_WHITE	White-yellowish chlorotic spots visible on the bark due to *Coraebus undatus*	Discrete (0/1)
	P_CRE	Presence of ants on the trunk (*Crematogaster scutellaris* & others)	Discrete (0/1)
	P_DEN	Big holes in cork and wood (*Dendrocopos major* & others)	Discrete (0/1)
	P_PLT	Entry holes (<1 cm) in trunks and branches with abundant sawdust in the base of the trunk (*Platypus cylindrus*)	Discrete (0/1)
	P_DEF	Defoliation attributed to the most commonly encountered defoliating insects in Extremadura (*Lymantria dispar*, *Tortrix viridana & others*)	Discrete (0/1)
	P_BISC	Charcoal cankers with carbonaceous, perithecial stromata erupting through the bark attributed to *Biscogniauxia mediterranea*	Discrete (0/1)
	P_BOTR	Sunken cankers associated with wedge-shaped necrotic sectors and exudations attributed to pathogens of the *Botryosphaeriaceae* family	Discrete (0/1)
	P_PHYT	Root and collar rot, bleeding cankers and sudden death of nearby cork oaks attributed to *Phytophthora cinnamomi*	Discrete (0/1)
	P_GGS	General status of the tree in terms of health status. It is rated as 3 (good), 2 (mediocre) or 1(bad), depending on the presence of symptoms of diseases and pests, the presence of damages caused by pruning or stripping and the tree crown status	Discrete (1–3)
	P_OTHER	Other diseases	Discrete (0/1)
Stripping damage: (as the previous variables group)	D_PLOUGH	Plough damage	Discrete (0/1)
	D_OTHER	Other damage (fires, lightning & others)	Discrete (0/1)
	D_AX	Axe/cuts damage	Discrete (0/1)
	D_WOUND	Wound damage	Discrete (0/1)
	D_FRAG	Presence of fragments	Discrete (0/1)
	D_NECK	Poorly finished necks	Discrete (0/1)
	D_WEDGE	Poorly finished wedges	Discrete (0/1)
Dendrometric: (as the previous variables group)	T_PBH	Perimeter at breast height over cork	Continuous
	T_DH	Total stripping height	Continuous
	T_NB	Number of stripped branches	Continuous
	T_B	Any stripped branch	Discrete (0/1)
Meteorological: variables from 8 stations located nearby the 10 sampled stands	TM_MAX	Monthly mean of maximum daily temperature	Continuous
	TM_MES	Mean monthly temperature	Continuous
	TM_MIN	Monthly mean of minimum daily temperature	Continuous
	T_MAX_MIN	Highest minimum temperature	Continuous
	T_MIN_MAX	Lowest maximum temperature	Continuous
	T_MAX	Absolute maximum monthly temperature	Continuous
	T_MIN	Absolute minimum monthly temperature	Continuous
	ppmes	Mean monthly precipitation	Continuous

The correlation between two categorical variables when at least one of the variables had more than two categories was analyzed by means of Cramer's contingency coefficient or Cramer's V (*V*). The correlation between a dichotomous or categorical variable and a continuous

Table 2
Summary of continuous dendrometric and cork quality variables. N is stand density (tree/ha), n_t is the number of trees measured in the third stripping cycle, and n_c is the number of cork sampling units processed by stand and stripping cycle. n_c do not agree with n_t in some of the stands because 12 of the 654 cork sampling units collected from trees located in the 9 stands sampled after 2006 could not be processed.

STAND	STRIPPING CYCLE	N	n_t	T_PBH (cm)		T_DH (m)		T_NB	
				MEAN	STD	MEAN	STD	MEAN	STD
1	3	54.14	75	166.133	42.787	4.369	2.745	1.533	1.436
2	3	186.62	75	132.947	31.152	2.783	1.272	0.733	1.107
3	3	57.22	75	183.147	46.742	4.947	2.731	1.867	1.483
4	3	96.81	73	164.573	81.516	5.152	4.163	1.452	1.444
5	3	90.63	59	133.525	43.552	3.434	2.391	1.271	1.424
6	3	32.45	75	166.413	39.845	2.452	0.759	0.707	1.037
7	3	54.88	75	173.107	40.330	2.949	1.596	0.987	1.257
9	3	65.45	72	154.466	43.648	3.081	1.911	0.764	1.273
10	3	55.47	75	182.320	58.101	3.739	3.080	1.360	1.449

STAND	STRIPPING CYCLE	STRIPPING YEAR	n_c	Q_Q		Q_THICK (mm)	
				MEAN	STD	MEAN	STD
1	1	1993	113	8.507	6.953	32.416	8.046
	2	2002	75	6.430	6.369	30.000	8.303
	3	2011	74	7.910	7.177	33.107	7.175
2	1	1992	57	7.974	6.466	27.456	7.251
	2	2001	75	6.540	6.384	25.560	8.114
	3	2010	73	7.017	6.689	30.933	9.550
3	1	1990	46	8.065	6.617	31.609	6.784
	2	1999	75	8.487	6.778	30.133	9.644
	3	2008	74	6.150	6.171	25.213	6.979
4	1	1993	48	6.604	6.179	30.896	9.177
	2	2002	76	4.247	4.536	29.934	8.381
	3	2011	71	6.000	5.667	32.280	9.065
5	1	1994	44	7.869	6.972	27.227	8.098
	2	2003	61	9.258	6.369	27.639	7.294
	3	2012	59	7.581	5.815	28.932	7.244
6	1	1987	72	5.847	6.230	27.667	6.079
	2	1997	69	8.420	6.154	27.072	6.281
	3	2007	74	8.687	5.905	27.733	6.306
7	1	1988	80	6.884	6.297	31.163	7.430
	2	1998	77	6.994	5.972	26.883	6.639
	3	2008	72	7.649	5.911	28.419	6.046
8	1	1986	45	7.789	5.977	27.933	5.778
	2	1996	62	6.645	5.551	22.371	5.342
	3	2006	73	6.070	5.350	20.600	6.210
9	1	1992	65	7.858	6.410	28.754	8.619
	2	2001	74	8.236	7.012	30.459	6.437
	3	2010	71	6.390	6.107	28.205	6.733
10	1	1993	45	6.489	6.720	35.600	8.922
	2	2002	75	4.237	4.899	31.720	8.006
	3	2011	74	5.767	6.243	29.040	8.398

variable was analyzed by calculating the point biserial correlation (r_{pb}), while the correlation between continuous variables was analyzed using Pearson's correlation coefficient (r). This univariate correlation analysis was carried out by applying the "freq" and "corr" procedures of SAS.

The univariate correlation analysis was completed with a canonical correlation analysis (CCorA). This multivariate correlation analysis identifies the maximum correlation between matrices of variables. CCorA is appropriate when there is a set of intercorrelated variables, as is the case of the dendrometric and meteorological variables, that can explain another set of dependent variables, as is the case of the variables that determine the quality of the cork (i.e., the Q index, visual appearance, caliper or thickness and presence of anomalies) and the variables that explain the health of the cork oaks, that is, symptoms of diseases and pests and damage caused by stripping. The CCorA calculates eigenvalue matrices for each pair of variable matrices and then runs all possible linear combinations to maximize the shared covariance between them. The shared covariance is explained by the canonical correlations of each variable in the dependent set and the variance of each variable in the independent set. Both the canonical correlations and the covariance between variables are expressed as regular correlation coefficients (Thompson, 1984). The SAS "cancorr" procedure was used for these analyses.

3. Results

3.1. Presence of anomalies in the sampled stands by stripping cycle

The correspondence analysis shows differences in the total number of anomalies detected in each stripping cycle (Fig. 4A). Axis 1 of the correspondence analysis (explaining 69.44 % of the variance) shows distinction mainly between the first stripping cycles and the third one. Given their proximity to the origin, stands 3, 8, 9 and 10 are more similar in terms of cork quality, and stand 5 seems to be the most different from the others.

To analyze differences by stand and stripping cycle according to the type of anomaly found (Fig. 4B), anomalies detected in less than a total of 25 cork sampling units from all the stands and stripping cycles were excluded. Thus, cases of very earthy cork (Q_PASM), folded cork (Q_FOLD), cork with yellow stains (Q_YELLOW) and aged cork (Q_AGED) were excluded (Fig. 3). Anomalies that were detected in only one stand, such as other stains (Q_STAIN), were also excluded (Fig. 3). The correspondence analysis to describe differences that occurred over the three stripping cycles due to the presence of anomalies in the stands (Fig. 4B) shows that the presence of *Coraebus undatus* galleries (Q_WORM) and excessively thin cork (Q_THIN) determine the first axis

Fig. 3. Distribution of cork sampling units by studied anomalies in sampled stands and harvests (top), distribution of trees by diseases and pests in sampled stands (middle), and distribution of trees by stripping damages for trees in sampled stands. Description of variables can be found in Table 1.

(explaining 39.34 % of the variability), thus indicating that stands in which a larger number of cork sampling units with worm holes were detected had a lower proportion of cork sampling units of small thickness. Fig. 4B also shows that higher number of cork sampling units with thinnest than 18 mm (Q_THIN) were collected in stand 8 during the third stripping cycle.

3.2. Incidence of pests and diseases in the sampled stands

According to the correspondence analysis, the symptoms of pests and diseases detected in the trees sampled during the third stripping cycle were associated with the stands where the trees were located (Fig. 4C). For this analysis, the variable P_GGS, which evaluates the general health status of the tree, was broken down into three variables P_GGS1, P_GGS2 and P_GGS3 according to whether the tree was in a decrepit or decadent (1), regular or average (2) or optimal (3) state, respectively. In addition, symptoms of diseases and pests that were found in less than four stands were excluded (Fig. 3), as well as the variable P_GGS3, that is, trees in optimal health state (P_GGS = 3). The first two axes of the correspondence analysis explained more than 86 % of the variability in diseases and pests detected in each stand (Fig. 4C). The highest proportion of variance (29,4 %) was explained by the presence of white exudations in cork oaks trunks caused by *Coraebus undatus* (P_WHITE). Stands 4, 5, 6 and 7 were very similar in terms of symptoms of pests and diseases, while stand 3 was the most different from the others.

3.3. Incidence of stripping damage in sampled stands

According to the correspondence analysis, the damage detected in the trees sampled during the third stripping cycle was associated with the stand where the trees were located The first two axis explained more than 73 % of variability, being stand 9 the most different from the others in terms of stripping damages and stand 3 and 5 are very similar (Fig. 4D). The stripping damage that explained the highest proportion of variance (28,8 %) was poorly finished wedges (D_WEDGE).

3.4. Correlations between cork quality variables

The correlation analysis between the variables that define cork quality revealed significant relationships. This section shows all

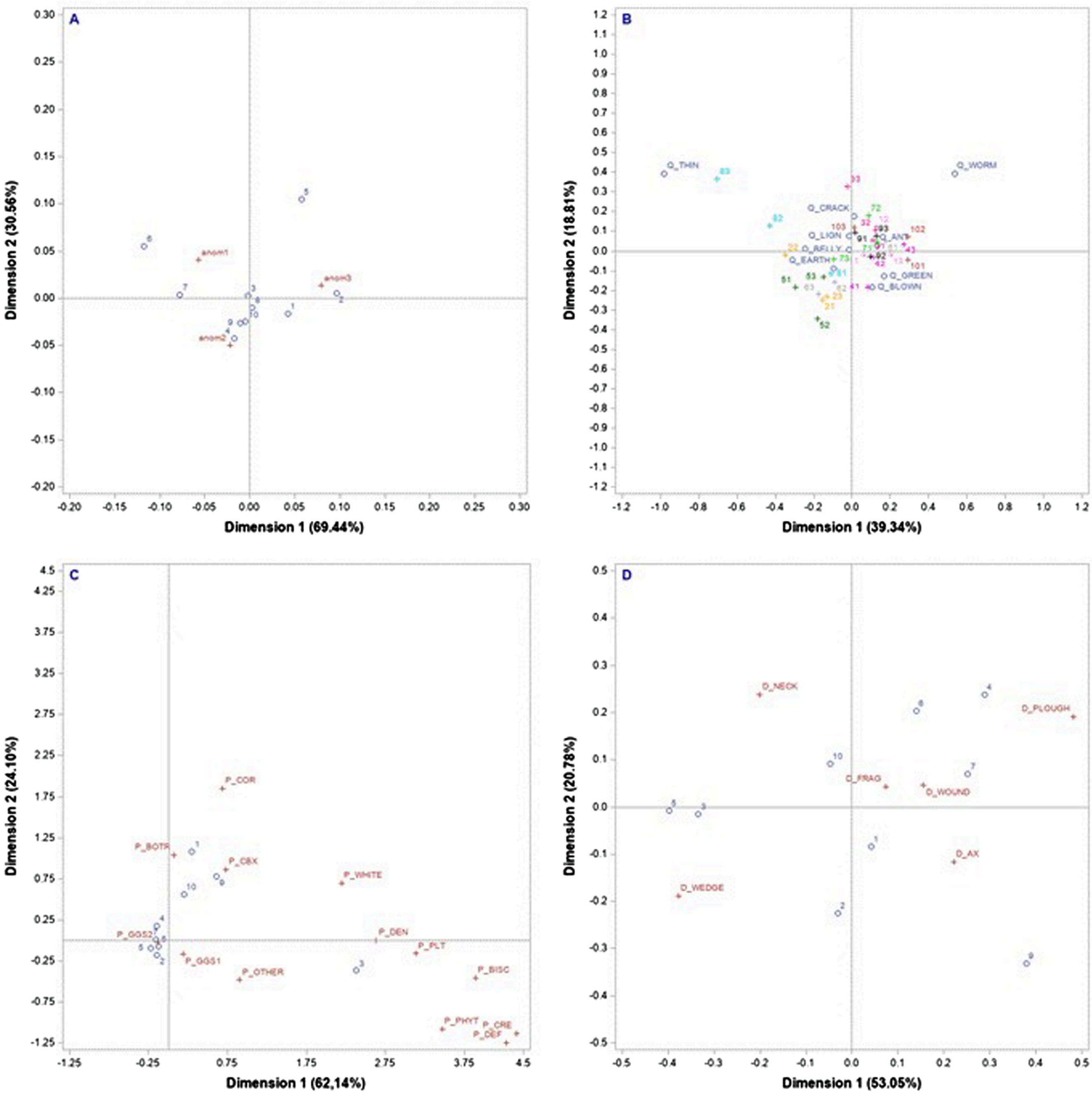

Fig. 4. Correspondence analysis showing: A. the change in the total number of anomalies found on each sampled stand in each harvest; B. the changes produced in the presence of each type of anomaly during the three stripping periods in the sampled stands; C. the changes found in the diseases and pests found in each sampled stand; D. the changes found in the damages carried out during the stripping in the sampled stands. Description of variables can be found in Table 1.

correlations greater than 0.2.

Specifically, the presence of anomalies in the cork sampling units collected in the three stripping cycles shows a significant correlation between the presence of cork with cracks appearing on the back (Q_CRACK) and belly irregularities (Q_BELLY) (*Phi* = 0.259$p < 0.001$), between the presence of blown cork (W_BLOWN) and green cork (Q_GREEN) (*Phi* = 0.268$p < 0.001$) and between the presence of yellow stains (Q_YELLOW) and aged cork (Q_AGED), which is somewhat higher than the rest (*Phi* = 0.370$p < 0.001$).

As expected, the value of the visual appearance index (Q_VIS) was strongly negatively correlated with the Q quality index (-0.8, $p < 0.001$) and was significantly correlated with the presence of ant holes (Q_ANT, $V = 0.263$, $p < 0.001$), belly irregularities (Q_BELLY, $V = 0.319$, $p < 0.001$), blown cork (Q_BLOWN, $V = 0.402$, $p < 0.001$), back irregularities (Q_CRACK, $V = 0.222$, $p < 0.001$), earthy cork (Q_EARTH, $V = 0.260$, $p < 0.001$), excessively thin cork (Q_THIN, $V = 0.291$, $p < 0.001$) and *Coraebus undatus* galleries (Q_WORM, $V = 0.291$, $p < 0.001$).

Also as expected, a significant relationship was found between the Q quality index and cork size ($r = 0.300$, $p < 0.001$). Cork thickness (Q_THICK) was significantly and negatively correlated with excessively thin cork as expected (Q_THIN, r_{pb} = -0.435, $p < 0.001$) and positively correlated with blown cork (Q_BLOWN, $r_{pb} = 0.276$, $p < 0.001$) and green cork (Q_GREEN, $r_{pb} = 0.375$, $p < 0.001$). The cork quality index (Q_Q) was significantly and negatively correlated with the following anomalies: ant holes (Q_ANT, r_{pb} = -0.225, $p < 0.001$), cork with irregularities on the back (Q_CRACK, r_{pb} = -0.210, $p < 0.001$) and belly

(Q_BELLY, r_{pb} = -0.286, $p < 0.001$), blown cork (Q_BLOWN, r_{pb} = -0.372, $p < 0.001$), excessively thin cork (Q_THIN, r_{pb} = -0.231, $p < 0.001$) and *Coraebus undatus* galleries (Q_WORM, r_{pb} = -0.282, $p < 0.001$).

3.5. Correlations between cork quality and meteorological variables

No significant relationships were found between the Q index and the meteorological variables. However, significant and positive relationships were found between cork thickness (Q_THICK) and the values of certain meteorological variables, although these relationships were weak (≤0.16). The temperatures for which a correlation value of at least 0.15 was found, were the mean monthly temperature and the mean maximum temperatures in the 6th year after stripping, the maximum minimum temperatures in the fall and winter, the mean temperature in October and the maximum minimum temperatures in October and December.

As regards the correlations between the mean values of the meteorological variables and the anomalies present in the cork sampling units collected in the three stripping cycles, a significant relationship was only found for the presence of other stains (Q_STAIN), particularly with the maximum minimum temperature (T_MAX_MIN) and the minimum daily temperature (TM_MIN) in April and June and the absolute minimum temperature (T_MIN) in October. Moreover, the temperatures in the 5th, 6th and 7th years after cork stripping had the strongest effect on the presence of cork stains (Figure SM3).

The univariate correlation analysis was completed with a multivariate correlation analysis. To this end, a CCorA was performed between

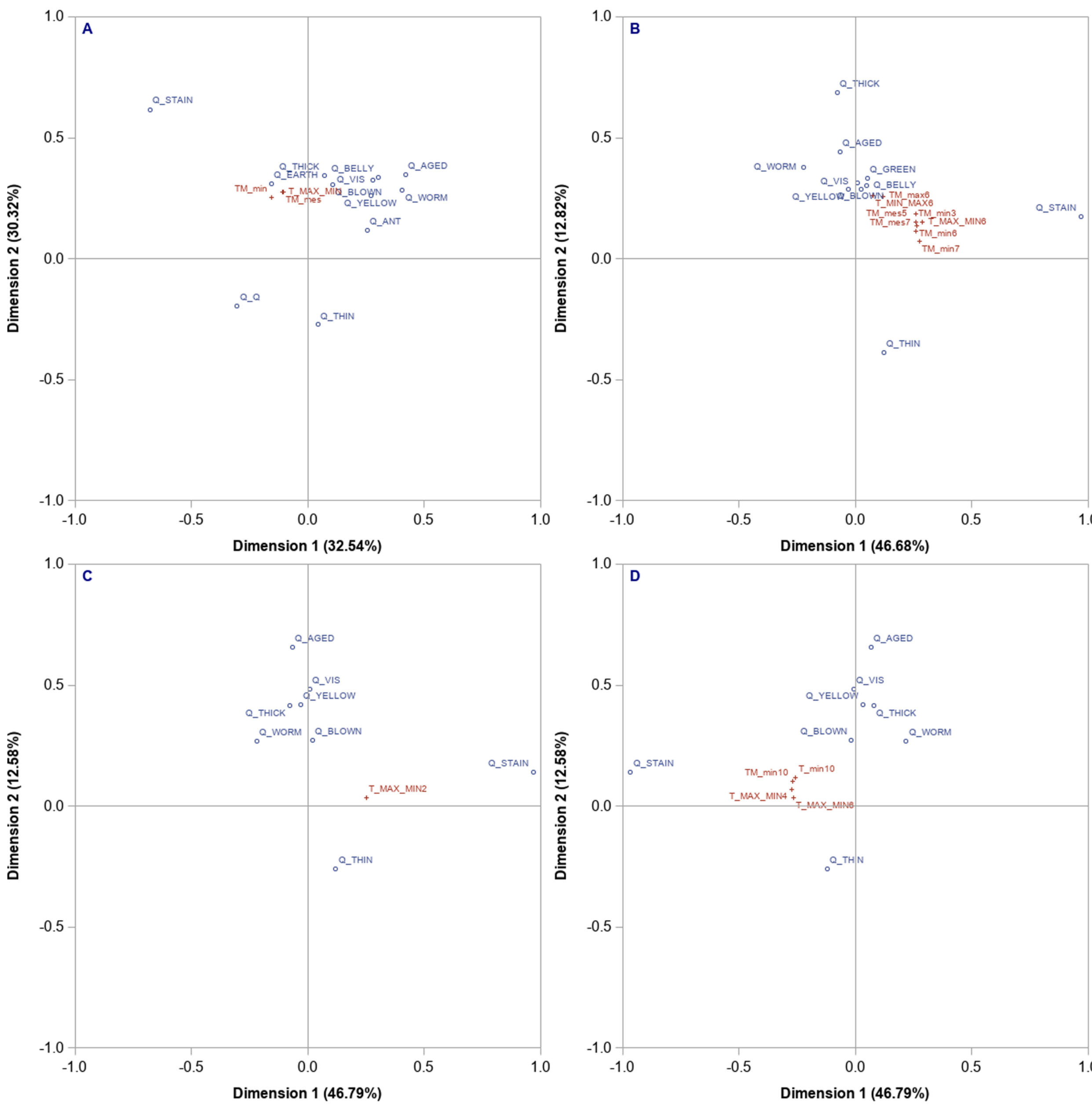

Fig. 5. First and second canonical variants resulting from the CCorA made between the variables that define cork quality and the mean meteorological variables: A. for each stripping cycle; B. for annual mean meteorological variables (the number after each variable indicates the year of the cycle in an ordinal way); C. for seasonal mean meteorological variables (C, 1 indicates spring, 2 summer, 3 autumn and 4 winter); D. for monthly mean meteorological variables (the number after each variable indicates the month). The percentage of variability explained by each canonical variant is shown in parentheses on each axis. To facilitate the visualization of the results, only those variables whose coefficient of the canonical structure is greater than 0.25 are shown. Description of variables can be found in Table 1.

the cork quality variables and the meteorological variables grouped at different levels. All the models were significant according to the Wilks' Lambda test ($p < 0.001$), although the models that included the meteorological variables as monthly mean values of the cork stripping cycle, annual mean values of the cork stripping cycle and seasonal mean values of the cork stripping cycle explained greater than 46 % of the variability of cork quality. When the total mean values of the cork stripping cycle were used, the model only explained < 12 % of the variability. The presence of stains (Q_STAIN) was highly correlated with the first canonical variant (greater than0.9) in all the models. The key meteorological variables associated with cork quality were identified from the CCorA (Fig. 5).

To determine if including the normal circumference over cork, cork height and number of stripped branches improved the explained variability, a CCorA was performed using the data from the cork sampling units collected in the third stripping cycle. The analysis was performed with and without these variables and the Wilks' Lambda test showed that both models were significant ($p < 0.001$). However, the variability explained improved very little (from 58.17 to 58.37).

Regarding the differences between this analysis and the previous one (Fig. 5), which includes data from all the cork sampling units collected in the three stripping cycles, only the CCorA varies between the variables that define cork quality and the mean monthly meteorological variables (Fig. 6). This indicates that the meteorological variable most strongly associated with the second canonical variant was mean precipitation in June, which was positively correlated with cork thickness (Q_THICK), but also with the presence of earthy cork (Q_EARTH) and green cork (Q_GREEN).

3.6. Correlations between cork quality and cork tree health

The analysis of the relationship between cork quality and symptoms of disease in the trees sampled during the third stripping and the presence of anomalies in the cork sampling units collected from these trees only shows a significant expected relationship between the presence of galleries caused by *Coraebus undatus* larvae (Q_WORM) and the external signs that this pest leaves in the trees, the presence of *Coraebus undatus* galleries (P_COR, $Phi = 0.255$, $p < 0.001$) and the presence of white exudation on the trunk (P_WHITE, Phi = 0.222, $p < 0.001$). However, the relationship was weaker than expected (Phi = 0.255 and $Phi = 0.222$, respectively). Additionally, the value of the index used to evaluate the general health status of the trees (P_GGS) was significantly correlated with the presence of stained cork (Q_STAIN, V = 0.258, $p < 0.001$).

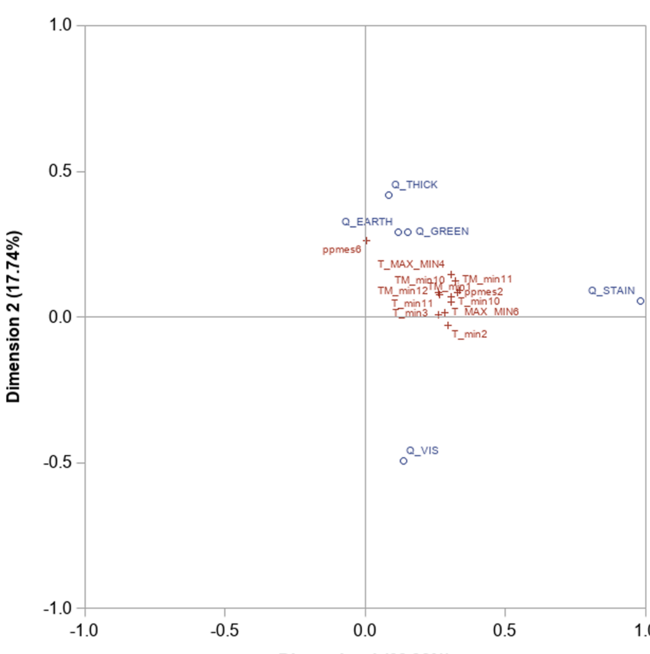

Fig. 6. First and second canonical variants resulting from the CCorA made between the variables that define cork quality and the mean monthly meteorological variables using only the cork sampling units collected in the third harvest. The number following each variable indicates the month. The percentage of variability explained by each canonical variant is shown in parentheses on each axis. To facilitate the visualization of the results, only those variables whose coefficient of the canonical structure is greater than 0.25 are shown. Description of variables can be found in Table 1.

3.7. Correlations between the variables defining cork tree health

The analysis of the univariate relationship between the presence of stripping damage and symptoms of disease in the trees sampled during the third stripping cycle shows some statistically significant relationships (Fig. 7). Among them, the correlation between the presence of damage caused by defoliating insects (P_DEF) and symptoms of *Platypus cylindrus* (P_PLT, $Phi = 0.512$, $p < 0.001$) and ants (P_CRE, $Phi = 0.527$, $p < 0.001$), the latter of which had white exudatio due to *Coraebus undatus* (P_WHITE; $Phi = 0.501$, $p < 0.001$).

Additionally, the value of the index used to evaluate the overall health status of the trees (P_GGS) was significantly correlated only with the presence of other diseases (P_OTHER, $V = 0.357$, $p < 0.001$).

3.8. Correlations between cork tree health and meteorological and dendrometric variables

Of the variables that define tree health (i.e., symptoms of disease or pests and damage caused by cork stripping), the following variables were found to be significantly related to a climatic variable in the univariate correlation analysis: the presence of ants of the species *Crematogaster scutellaris* (P_CRE), white exudation due to *Coraebus undatus* (P_WHITE) and damage caused by defoliating insects, mainly *Tortrix viridana* and *Lymantria dispar* (P_DEF). Ant damage increases with rainfall in January, March, April and October, particularly in the second year after stripping, and decreases with higher mean and maximum temperatures and lower minimum temperatures (Figure SM4). This relationship with temperature was similar for white spots caused by *Coraebus undatus* and defoliator damage (Figure SM5).

The analyses of the canonical correlations between the set of variables indicating the presence of diseases and pests and the set of dendrometric and meteorological variables grouped at different levels were significant according to the Wilks' Lambda test ($p < 0.001$). All of them explained greater than 85 % of the variability in the presence of symptoms of disease or pests. Although the first eight canonical variants of the presence of symptoms were significant in all the correlations, only the first one explains a percentage of variation of 76.95 %. In this first canonical variant, the pest that explains a greater proportion of inertia was *Crematogaster scutellaris* (P_CRE) with a coefficient of the canonical structure greater than 0.9, followed by *Tortrix viridana* and *Lymantria dispar* (P_DEF) and by *Coraebus undatus* (P_WHITE) with values around 0.6, thus confirming that the incidence of these pests increases with rainfall and decreases with higher mean and maximum temperatures and lower minimum temperatures (Figure SM6).

CCorA was performed to determine if there was a relationship between the set of variables that indicate damage due to stripping, the dendrometric variables and the mean meteorological variables in the stripping months (i.e., June, July and August) and damage due to cork stripping. The analysis revealed a significant relationship ($R_c^2 = 0.35$, Wilks' Lambda: $F = 8.21$, $p = <0.0001$). The first six canonical variants were significant. The first one explains 46 % of the variation and only the next two explain more than 10 %, 25.11 % and 14.24 %, respectively. The coefficients of the canonical structure show that poorly finished necks (D_NECK) and wedges (D_WEDGE) were positively

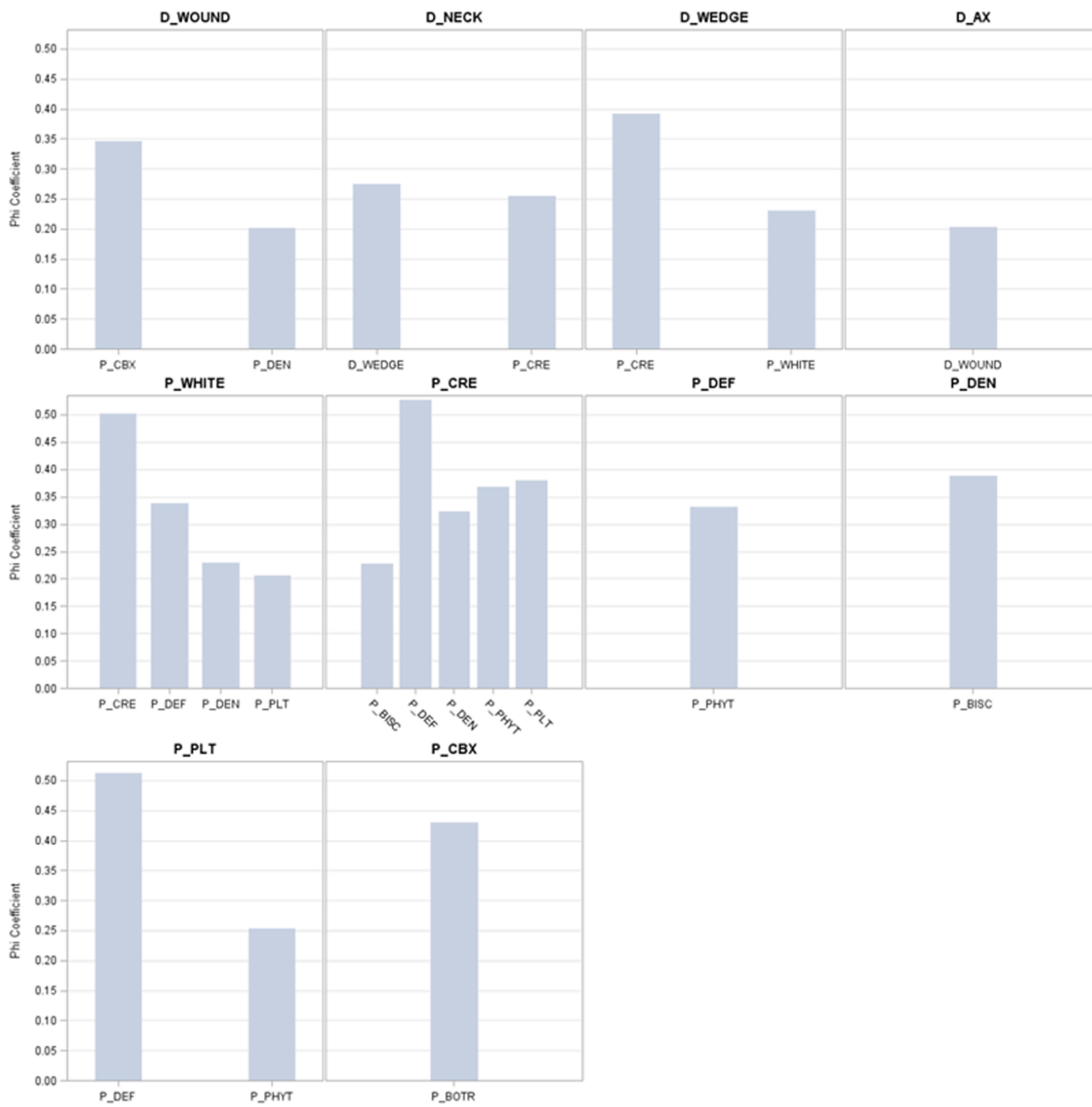

Fig. 7. Univariate correlations between the variables that define the health of cork oaks, that is, the presence of symptoms of diseases and damage from cork stripping. Description of variables can be found in Table 1.

related to the first canonical variant with values of greater than 0.7 and that this damage was negatively associated with the temperatures reached in the cork stripping months, especially the mean monthly temperature (TM_MES), the absolute minimum monthly temperature (T_MIN) and the monthly mean of minimum daily temperature (TM_MIN), which have coefficients of < -0.5 (Fig. 8).

4. Discussion

4.1. Cork quality

The market value of natural cork was determined by its quality. The quality of cork planks depends on three fundamental characteristics: plank thickness, plank porosity and the visual appearance of the cork, which was determined by the presence of anomalies or defects. One of the challenges facing the cork sector is the decreasing quality and quantity of cork production (Castro et al., 2015; Sánchez-González et al., 2020). Lanzo et al., (2013) reported a deterioration of cork quality when analyzing the evolution of cork quality using data from the Extremadura Sampling Plan from 56 cork oak stands spread throughout the region. The data analyzed in this study also indicate this decrease in cork quality, as a larger number of anomalies have been detected in the successive cork stripping cycles and individually in many of the anomalies analyzed (Fig. 3). This decrease was also observed when comparing the mean quality index (Q_Q) for the studied cork sampling units by stripping cycle: 7.44 for the first stripping cycle and 6.89 for the other two stripping cycles. The mean quality index obtained by Lanzo et al., (2013) in the periods 2010–2012 and 1985–2012 were 6.51 and 8.05, respectively. Fig. 9 shows a comparison of the percentages of cork sampling units by studied anomalies between our study and the one conducted by Lanzo et al., (2013). The percentages of affected cork sampling units were generally very similar, although higher in the 56 cork oak stands sampled in the period 2010–2012, especially, the percentage of cork with cracks (Q_CRACK) and with stained cork (Q_STAIN). The higher number stained cork sampled may be because the cork sampling units in our study were boiled a second time, which may have caused this anomaly to largely disappear.

The cork sampling units analyzed in our study were very low affected by pasmo (Q_PASM), folded cork (Q_FOLD), yellow stains (Q_YELLOW), other stains (Q_STAIN) and aged cork (Q_AGED). The presence of folded cork (Q_FOLD) occurs when the cork oak tree has been exposed to fire, severe drought or defoliating insects during the stripping cycle and

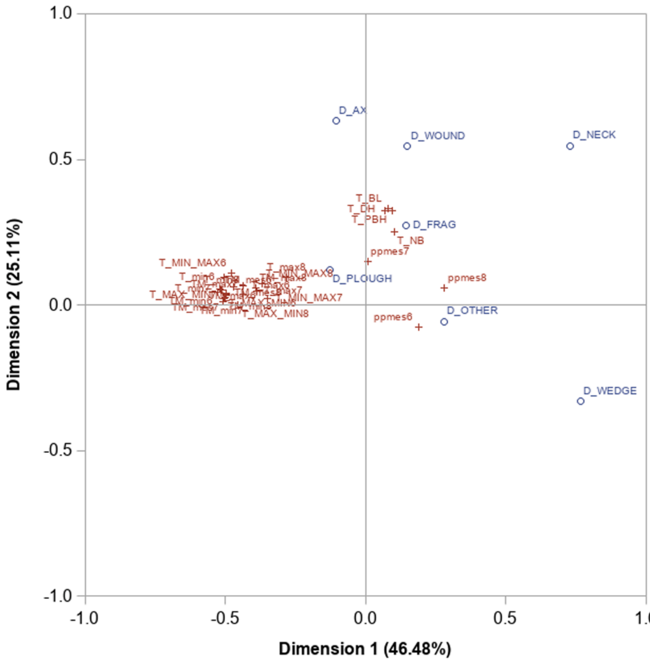

Fig. 8. First and second canonical variants resulting from the CCorA made between the variables that indicate stripping damage and the dendrometric variables and monthly average meteorological variables for the months of June, July and August. The number after each variable indicates the month. The percentage of variability explained by each canonical variant is shown in parentheses on each axis. Description of variables can be found in Table 1.

subsequently continues its normal growth. The low incidence of this defect indicates that the stands suffered no major disturbances that paralyzed tree growth during this period. The low or null incidence of damage due to the presence of fungi (Q_YELLOW, Q_STAIN and Q_VINEGAR) is important as it is related to 2,4,6-Trichloroanisole (TCA) which causes a musty taste that is transferred to wine (Juanola et al., 2005). The presence of fungi such as *Armillaria mellea* (Vahl. Ex Fr.) causes yellow stains and TCA biosynthesis (Moio et al., 1998). The low incidence of cork stains in these stands indicates that, based on this criterion alone, the cork is suitable for the manufacture of wine stoppers (Pereira, 2007a; Pérez-Terrazas et al., 2020). The low incidence of aged cork (Q_AGED) indicates that the cork was stripped from the tree at the appropriate time during the cycle.

A decreasing pattern was also observed for the mean cork thickness (Q_THICK) for the studied cork sampling units collected in all the sampled stands by stripping cycle: 30.20 mm for the first, 28.30 mm for the second and 28.47 mm for the third stripping cycle. The mean cork thickness obtained in our study for the whole period, 1986–2012 was 28.90 mm, which is similar to that obtained by Lanzo et al., (2013) for the period 2010–2012 (28.88 mm) and in the range of mean thickness for nine regions of provenance (RGP) for cork oak in Spain (26.66–37.96 mm). However, it is somewhat lower than the mean thickness of the RGPs where the stands under study are located: RGP1 (33.27 mm) and RGP2 (30.80 mm) (Sánchez-González et al., 2021). Compared to other cork producing regions, the mean thickness is slightly higher than in Algeria (26.50 mm) (Chorana et al., 2019) and slightly lower than in Portugal (33.9 mm) (Lauw et al., 2018).

The analysis of the correlations between the variables used to define cork quality shows the expected correlations. Specifically, a positive correlation was found between belly irregularities (Q_BELLY) and back irregularities or cracks (Q_CRACK). This is because the back has the same contour as the belly and reproduces axe cuts and wounds from previous cork stripping operations that have left their mark on the cork-generating layer. The positive correlation between blown cork (Q_BLOWN) and green cork (Q_GREEN) with thickness is also expected because both blown and green cork are associated with a marked growth in thickness due to the availability of water (Pereira, 2007; Santiago Beltrán et al., 2020). Likewise, the positive correlation between the presence of yellow stains (Q_YELLOW) and aged cork (Q_AGED) and between yellow stains and the stripping cycle is as expected, as it is common to find more yellow stains in cork that has remained on the tree for a longer period of time (SUBERNOVA, 2005). This is in line with Juanola et al. (2002) who studied the distribution of TCA in contaminated cork sampling units and found a clear gradient that increases from the younger inner part of the sampling unit towards the outer section.

The mean value of the variable used to assess the visual appearance of the cork (Q_VIS = 5.82) can be considered low given that aspect 1 is

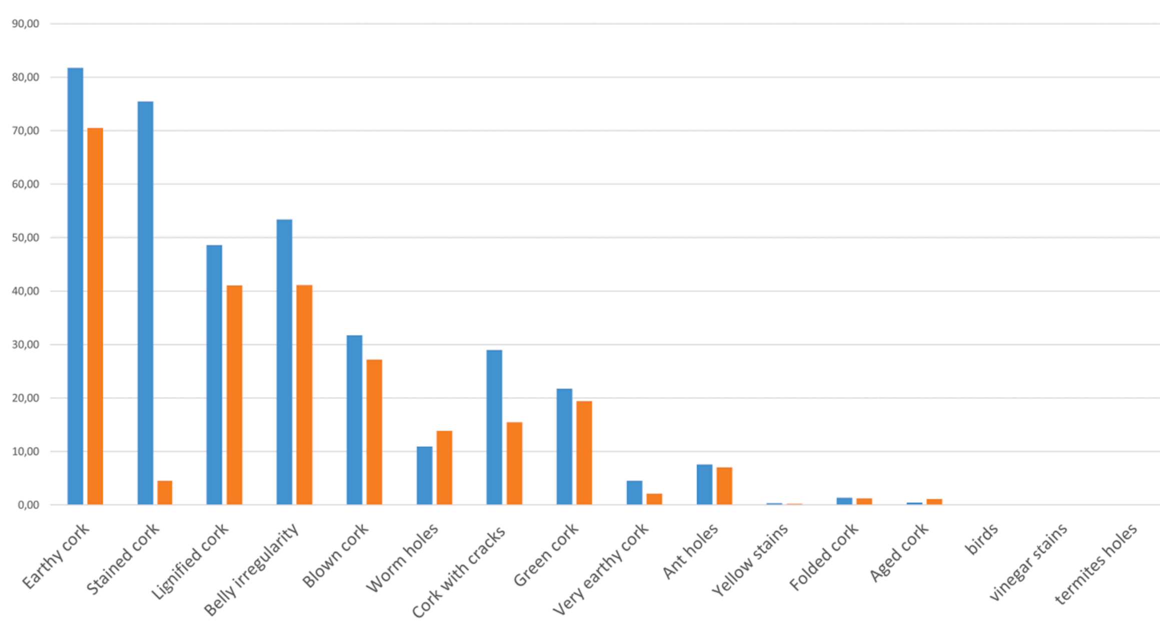

Fig. 9. Comparison of the distribution of cork sampling units (in percentage) by studied anomalies collected under the Extremadura Sampling Plan: in the 10 stands studied in this work and sampled in the period 1985–2012 (orange bars), and in the 56 stands studied by Lanzo et al (2013) and sampled in the period 2010–2012 (blue bars). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the best and aspect 7 always corresponds to raw cork waste and is in the range of thin cork for the manufacture of colmated stoppers. This Q_VIS value is consistent with the fact that the most frequent defects identified in the sampled stands were those that worsen the cork's appearance most. According to the correspondence analysis, the anomalies that most affect the visual appearance of the cork (Q_VIS) were, in this order: blown cork (Q_BLOWN), belly irregularities (Q_BELLY), galleries caused by *Coraebus undatus* larvae (Q_WORM), excessively thin cork (Q_THIN), ant holes (Q_ANT), earthy cork (Q_EARTH) and the presence of irregularities and cracks in the back (Q_CRACK). While the Q index (Q_Q) was influenced by the same anomalies except for earthy cork (Q_EARTH), which could be due to the fact that earthy cork was present in many of the cork sampling units analyzed but in an isolated form (i.e., some discontinuous pores filled with powdery materials). Chorana et al. (2019) found a similar result when analyzing 600 cork sampling units from eight cork oak stands in Algeria, none of which showed the presence of a severe grade of earthy cork. This defect prevents the cork from being used for the manufacture of cork stoppers only when it is extreme and covers large areas of the plank, which is considered a specific defect (Q_PASM) known as "pasmo" in Spain and "barrenta" in Portugal (ISO-633, 2019; Santiago Beltrán et al., 2020).

As expected, both the visual appearance (Q_VIS) and thickness (Q_THICK) of the cork were correlated with the Q index (Q_Q). However, in addition to the sign, the strength of this correlation changes, with the visual appearance of the cork (-0.8) showing a stronger relationship than cork thickness (0.3). This may be due to the fact that the variation in cork thickness at each stand in the three cork stripping cycles does not follow a clear pattern. In some stands, the mean thickness increases, in others it decreases and in others it remains constant (Table 2). As for the relationship with the stripping cycle, the expected correlation between mean cork thickness and stripping cycle was not found. This might be due to the small difference in the duration of the stripping cycles, which was nine years in seven stands and ten years in three stands, with a maximum variation of one year that is not reflected in the mean cork thickness. Another factor to consider is that different trees were sampled in the three successive cork stripping cycles and to properly evaluate the evolution of cork thickness it would be necessary to sample the same trees under the Sampling Plan.

4.2. Cork oak health and stripping damage

The mean health status of the stands (P_GGS = 2.65) is good and close to the optimum value of 3. The damage caused by *Cerambycidae* (P_CBX) and *Coraebus undatus* (P_COR) is noteworthy in practically all the stands, indicating the prevalent nature of these pests. *Coraebus undatus* has also been reported to be prevalent in other regions of Spain such as Andalusia (Jimenez et al., 2012) and Catalonia (Fürstenau et al., 2015). Martin et al. (2005) reported attacks by *Cerambyx* beetles in Extremadura, and several authors have identified some species as a determining factor in the decline of cork oaks in south-western Spain (Sallé et al., 2014; Tiberi et al., 2016; Torres-Vila et al., 2017). However, although these species were present in the stands studied, they do not pose a threat to the survival of the cork oaks. Stand 3 (see Fig. 3), for example, shows the maximum symptoms of different pests and diseases (P_WHITE, P_CRE, P_DEN, P_PLT, P_DEF, P_BISC) and others that were also present but to a lesser extent (P_CBX, P_COR, P_PHYT, P_OTHER); however, 93 % of the trees belong to the P_GGS3 class (P_GGS = 3). Since we only have data on the symptoms of disease and pests in the trees sampled in the last stripping, we cannot know whether this is a recent situation or has been sustained over time. This stand may be on the verge of general decline, since compared to the rest of the stands sampled, this one has by far suffered the most damage due to *Phytophthora* (P_PHYT), *Platypus cylindrus* (P_PLT), defoliating insects (P_DEF) and ants (P_CRE). These pests and diseases are associated with Iberian oak decline that affects both cork and holm oaks (Tiberi et al., 2016). In particular, the presence of *Phytophthora cinnamomi* Rands. is considered the principle cause of the Iberian oak decline (Brasier, 1996; Cardillo et al., 2021; de Sampaio e Paiva Camilo-Alves et al., 2013). However, if the incidence of pests and diseases in this stand were sustained over time, it could be interpreted that, if the stand is in good condition and the populations are kept in balance, the presence of these diseases and pests will not reduce tree vigor and the trees will remain in good health state.

Table 3 shows the comparison of means for the main dendrometric, phytosanitary and stripping damage variables used in this study and in one conducted by (Lanzo et al., 2013). The mean values of the dendrometric variables are very similar as well as the percentages of trees with different types of damage due to stripping. The most extensive stripping damage is associated with axe cuts in the cork-generating layer (D_AX) and the extraction of wedges (D_WEDGE) and necks (D_NECK). As for the variables that indicate the presence of diseases and pests, the trees in our study were significantly more affected by ant damage (P_CRE), defoliating insects (P_DEF) and *Coraebus undatus* (P_COR) and less affected by *Cerambycidae* attacks (P_CBX) than the mean for the 56 stands spread throughout and sampled in the period 2010–2012.

In this work, three types of diseases were studied as they occur most frequently in cork oak forests (Moricca et al., 2016): *Biscogniauxia mediterranea* (P_BISC), species of the genus *Phytophthora* (P_PHYT) and fungi of the family *Botryosphaeriaceae* (P_BOTR). A significant and positive relationship (0.14) was only found between the first two. Several relationships between the insect pests studied and these diseases have been found, some of which have been reported previously, such as the case of *Cerambyx* sp. with *Biscogniauxia mediterranea* (0.15) (Martin et al., 2005) and with pathogens of the family *Botryosphaeriaceae* (Sánchez et al., 2003; Panzavolta et al., 2017). These relationships are explained by the fact that cerambycids, although considered secondary pests, cause damage to trunks that can serve as an entry point for fungal infections (Soria et al., 1994; Martin et al., 2005). To the best of our knowledge, other relationships found in our study have not yet been reported. This is the case of the positive relationship between ants and *Biscogniauxia mediterranea* and pathogens of the genus *Phytophthora* and the negative relationship (-0.20) with pathogens of the family *Botryosphaeriaceae*. In Portugal, Inácio et al. (2011) found that *Platypus cylindrus* acts as a vector of *Biscogniauxia mediterranea* and pathogens of the *Botryosphaeriaceae family*. However, we only found a significant and positive relationship with the genus *Phytophthora* (Fig. 7) mainly in Stand 3 (Fig. 3). As seen above, this stand differs from the rest in terms of the incidence of pests and diseases, so it would be interesting to conduct further studies on this stand to improve our knowledge of Iberian oak decline and help to combat this problem.

Table 3
Comparison of means for the dendrometric, phytosanitary and stripping damage variables used in the current study and in the one conducted by Lanzo et al., (2013) in 56 stands spread throughout and sampled in the period 2010–2012.

GROUP	VARIABLE	CURRENT STUDY	CORK SAMPLING PLAN
Dendrometric variables	T_PBH	162,6	172,1
	T_DH	275,6	299,3
	T_NB	1,22	1,48
Debarking damages	D_AX	0,67	0,62
	D_WOUND	0,27	0,29
	D_FRAG	0,08	0,1
	D_NECK	0,49	0,41
	D_WEDGE	0,39	0,36
Phytosanitary	P_CBX	0,34	0,43
	P_COR	0,27	0,2
	P_WHITE	0,25	0,14
	P_CRE	0,1	0,01
	P_PLT	0,06	0,04
	P_DEF	0,05	0,005
	P_BOTR	0,28	0,34

4.3. Relationships between cork quality, tree health and cork damage

The correlation analysis between cork quality and cork oak health showed a relationship between the presence of stained cork (Q_STAIN) and tree health status (P_GGS). This cork anomaly was only found in Stand 2 (Fig. 3) and increased considerably in the last stripping (the cork sampling units with stained cork increased from 28 to 43). Moreover, stand 2 had the lowest percentage of sampled cork oaks in an optimal health state (23 %), while this percentage ranged from 40 to 95 % in the rest of the stands. The presence of widespread fungal stains could indicate a decline in the health status of the stand. To establish a conclusive relationship, it would be advisable to monitor the cork produced at tree level. The cork sampling units analyzed in this work were collected from the same stands over three consecutive stripping cycles but were not obtained from the same trees. As mentioned above, it would be advisable to collect all or at least some of the cork sampling units from the same trees and stands.

Another expected relationship is the association between variables indicating the presence of *Coraebus undatus* in the cork (Q_WORM) and in the cork trees (P_COR and P_WHITE). In the sampling units analyzed, Q_WORM indicates the presence of galleries caused by larvae. Tree infestation is manifested in traces left by *Coraebus undatus* galleries in the trunk of the tree (P_COR) and white spots that indicate the presence of these galleries in the cork (P_WHITE). Gallardo et al. (2012) found a similar result when studying the external symptoms of *Coraebus undatus* attacks. In our study we found a significant and positive relationship between the presence of white spots (P_WHITE) and ants (P_CRE), while Gallardo et al. (2012) found that trees infested by *Crematogaster scutellaris* had a lower value on the index of damage caused *Coraebus undatus*. In our study, no distinction was made between different ant species, although *Crematogaster scutellaris* is usually the most abundant species (Verdinelli et al., 2017). The relationship found in our study is mainly due to the trees sampled in Stand 3 (Fig. 3), as almost all of the trees had white spots and ants and no other external symptoms of *Coraebus undatus* (P_COR).

As for the relationship between the presence of *Coraebus undatus* and the health status of the tree, a slight positive relationship (0.2) was found between the P_GGS value and the damage these larvae cause in the cork (Q_WORM) and symptoms in the tree related to this pest (P_COR and P_WHITE), which seems to indicate that *Coraebus undatus* prefer trees in a good health state. In addition, significant positive relationships were found between the presence of symptoms caused by different pests, indicating that ants, beetles, defoliating insects and bark beetles coexist in cork oak stands (Tiberi et al., 2016). These relationships are due to the fact that several pests can simultaneously attack cork oak trees, even those in a weakened state, and to the predator–prey relationship, as in the case of *Crematogaster* spp., which is a predator of defoliating insects. The presence of these insects makes it difficult to extract the cork and, in the case of ants, can even hinder the work of operators since these insects are aggressive biters. Negative relationships were also found between the poor execution of necks (D_NECK) and extraction of wedges (D_WEDGE) in the presence of ants. This is an expected result because although ant colonies are destroyed when the cork is harvested, part of the nest can remain in both areas of the virgin cork and colonize the reproduction cork (Suñer and Abós, 1992).

Bird damage (P_DEN) is primarily caused by woodpeckers (*Dendrocopus* spp.) foraging for wood and cork borer larvae (Ceia and Ramos, 2016), thus explaining the correlation between white spots caused by *Coraebus undatus* (P_WHITE) and ant damage (P_CRE). A relationship has also been found with symptoms due to *Biscogniauxia mediterranea* attacks, which is explained by the relationship between coleoptera and fungi, the former acting either as vectors or as facilitators of fungal infections. Finally, wounds due to poorly executed cork stripping (D_WOUND) lead to more damage by birds. This is logical since, as we have seen, wounds increase the presence of cerambycids. However, given that none of the analyzed cork sampling units exhibited bore holes produced by birds (Q_BIRD), the situation is not very serious since the incidence of bark damaged by birds is low.

In all the sampled stands, stripping was performed in the traditional manner using axes. The results show a positive and expected relationship between the presence of axe damage on the surface of the cork-generating layer (D_AX) and wound damage (D_WOUND), but also that axe damage is more pronounced in trees with smaller cork thickness at the end of the cycle (Q_THICK), thus highlighting the importance of careful stripping in these trees. The correspondence analysis shows a relationship between damage and the stands where the sampled trees were located, indicating that not all cork strippers had the same expertise. Although we have not assessed the expertise of the cork strippers here, this relationship may be due to this decisive factor and indicates the need for experienced cork strippers to ensure that these operations are carried out properly.

4.4. Relationship with climate

Precipitation and temperatures during the stripping cycle influence the quality of the cork produced (Figs. 5 and 6). In our study, the mean monthly precipitation and temperature values were calculated at different levels: the complete stripping cycle, years of the cycle, seasons of the year and mean monthly values. As expected, the mean values of precipitation and temperature of the complete stripping cycles explain a lower percentage of variability than the monthly, seasonal or annual mean values, which were the values that show significant correlations with some variables that define the quality of the cork.

Cork thickness at the end of the cycle was found to be positively related to some temperatures, mainly fall and winter temperatures, particularly higher maximum temperatures in October and December and the mean temperature in October. This indicates that the cork growth period could be extended when temperatures are moderate (Caritat et al., 2000; Costa et al., 2016). The correlations between cork thickness and temperature were weak, thus confirming that temperature has a smaller effect on cork growth than precipitation (Costa et al., 2001; Costa et al., 2022). However, the analyses showed no significant correlations between cork thickness at the end of the cycle and mean precipitation at any of the levels analyzed. This is due to the high variability in the mean monthly precipitation values compared to the mean monthly temperature values (Figure SM7, Table SM4), indicating that the effect on growth is lost when mean precipitation values are considered (Figure SM7, Table SM4) (Sánchez-González et al., 2007). A CCorA conducted with data from the third stripping cycle only (Fig. 5) clearly showed the influence of precipitation on cork thickness, especially in June. Therefore, dendrochronological analyses of yearly growth are the best way to detect the influence of climatological variables on cork growth. Although we have not performed an analysis of this type here, dendrochronological analyses could be performed using the cork sampling units from the Sampling Plan, which would contribute to our knowledge of how precipitation and temperature influence cork growth and hence the final thickness of the cork produced at the end of the cycle.

The CCorAs showed a clear relationship between climate variables and the variables defining cork quality. To determine if the dendrometric variables can explain greater variability, a CCorA was performed using data only from the third cork stripping cycle, including variables defining cork quality, climate variables and dendrometric variables. In this cycle, data were collected on the trees from which the cork sampling units were obtained, the perimeter at breast height over cork (T_PBH), the total stripping height (T_DH) and the number of stripped branches (T_NB). The inclusion of these variables in the analysis does not significantly improve the explained variability (from 58.17 to 58.37), thus indicating that tree size and stripping intensity have little influence on the cork anomalies and final thickness of the sampling units analyzed in this study. This is in line with Costa and Cherubini (2021), who found that tree size does not affect cork thickness and concluded that tree size influences wood growth but not cork growth.

Of the anomalies analyzed, a positive correlation was only found between the presence of stains (Q_STAIN) and minimum temperatures in spring and in October. This seems to indicate that relatively high minimum temperatures in the rainiest periods of the year could cause the fungi responsible for cork stain to proliferate. The CCorA using data only from the last stripping cycle showed a positive correlation between the presence of green cork (Q_GREEN) and earthy cork (Q_EARTH) and mean precipitation in June. This result explains how ambient humidity and soil moisture favor the formation of cells with abundant water and humidities of up to 400 % (Parameswaran et al., 1981; Pereira, 2007), two anomalies that are worthy of further studying.

As for the relationship between climate variables and tree health, the analysis showed that the symptoms most closely related to the climate variables were caused by ants (P_CRE), defoliating insects (P_DEF) and *Coraebus undatus* (P_WHITE). This result confirms that these pests increase with precipitation and when temperatures are not extreme (Jimenez et al., 2012; Loi et al., 2012).

Finally, a weak relationship was found between the climate and dendrometric variables and the variables related to stripping damage, thus indicating that climate is not a decisive factor for carrying out proper stripping operations in the stands.

4.5. Implications for the management of cork oak stands

Good knowledge of the factors that influence cork quality and the health of cork oak forests is essential when making decisions regarding the management of productive cork oak forests. Monitoring anomalies in cork oak forests is important not only from an economic but also an environmental viewpoint, as these defects indicate the forest's health status. Knowledge of cork anomalies can also be useful for making decisions aimed at the sustainable management of these forests. This work analyzes the anomalies present in 2049 cork sampling units obtained in three consecutive cork stripping cycles and is the first to examine cork quality based on anomalies detected in analyzed sampling units. The analysis is complemented with an additional analysis of data on diseases and pests in the trees where the cork sampling units were obtained in the third stripping cycle, as well as the damage produced in the cork oaks during stripping. The results are generally congruent and support the empirical and scientific knowledge, thus confirming what is known about cork oaks, cork quality and the practice of cork stripping and contributing new knowledge that can be used as background information for strategic and tactical cork oak forests management, to optimize the duration of cork extraction and to improve cork quality, thus helping forest managers in their task of preserving cork oak forests while using them for cork production.

The results regarding the factors that influence cork quality and its evolution over time suggest that the length of stripping cycles should be reconsidered to obtain good quality cork for stoppers. Although no relationships were found between cork thickness and stripping cycles, it is expected that adverse climatic conditions will reduce cork growth, which would lead to longer stripping cycles (Oliveira et al., 2016; Ghalem et al., 2018). However, extending these cycles would entail a higher risk of yellow stains and a higher incidence of anomalies. This finding has already led the Código Internacional de Prácticas Subericolas to recommend stripping cycles of no more than 15 years (SUBERNOVA, 2005). Both of these conflicting factors are affecting operational practices. In southern Spain, stripping cycles are being lengthened from 9 to 10–11 years. According to Leite et al. (2019), stripping cycles should be longer under drought conditions, especially in the first two years of the cycle.

Another aspect to consider is damage caused by cork stripping practices. In this regard, there are new tools and systems that have shown to reduce damage and should be used, and operators should be properly trained and specialized (Costa et al., 2010; Beira-Dávila et al., 2014). The restrictions placed on the use of these new tools, which can only be used up to shoulder height for reasons of occupational health and safety, reduce the stripping height and hence the stripping pressure, which in turn reduces tree stress, allowing the trees to recover.

The cork sampling units collected and stored in the framework of the Extremadura Sampling Plan, which began more than 35 years ago, contain valuable information. The Cork Quality Field Assessment Plan is proving to be an effective tool for assessing the quality of cork, the health status of cork oak forests and the evolution of these forests over time (Gamero Guerrero, 1993). But also, the information provide about the different sampled stands could be used to identify places worthy of further study. However, the data already collected could be complemented with information on the type of soil, which influences cork oak growth (Costa et al., 2008), and some soil characteristics related to cork thickness and porosity. Assessments on the quality of stripping after sampling are also needed, although this would entail additional changes in the data collection methodology, as this information would be obtained after the plan has been implemented. Another significant improvement would involve the monitoring and tracking of the trees from which the cork sampling units are obtained in successive cork stripping cycles as well as the use of dendrochronological techniques that allow the information in the growth rings to be "read" in order to study the influence of climate on the evolution of cork oak forests and understand its effects with a view to foreseeing changes and mitigating their effects.

5. Conclusions

This is the first study to evaluate cork quality based on anomalies in cork sampling units and link these anomalies to the health status of the trees that produced the cork taking into account climate data and damage caused during cork stripping. The results obtained are congruent and support the empirical and scientific knowledge, thus confirming what is known about cork oak, cork quality and cork stripping quality, but also contribute new knowledge that can serve to improve sampling plans and help the sustainable management of cork oak forests.

A decreasing pattern is observed in the total mean values of the cork quality index and in cork thickness for all the sampled stands in each stripping cycle, while a larger number of anomalies have been detected in the successive cork stripping cycles, indicating a progressive deterioration of cork quality in the sampled cork oak stands. The most frequent anomaly found in the analized cork sampling units is earthy cork although in an isolated form (i.e., some discontinuous pores filled with powdery materials). The presence of this anomaly and of green cork is correlated the mean precipitation in June. The less frequent were pasmo, folded cork, yellow stains, other stains and aged cork, indicating: that the sampled stands have not suffered major disturbances that paralyzed tree growth in the period 1986–2012; that most of the available cork is suitable for the manufacture of wine stoppers considering only the presence of stained and folded cork; and that the cork was stripped from the tree at the appropriate time during the cycle. The analysis of the correlations between the variables used to define cork quality shows the expected correlations. According to the analysis done using data only from the last stripping cycle, tree size and stripping intensity have little influence on the cork anomalies and final thickness of the sampling units analyzed in this study.

Regarding climate variables, it was found a positive relationship between cork thickness and temperature indicating that the cork growing period could be extended when temperatures are moderate. This correlation was weak, thus confirming that temperature has a smaller effect on cork growth than precipitation. No significant correlations were found between cork thickness and mean precipitation at any of the levels analyzed. This is due to the high variability in the mean monthly precipitation values compared to the mean monthly temperature values, indicating that the effect on growth is lost when mean precipitation values are considered.

According to the cork oaks sampled in the third stripping period, the health state of the sampled stands is good. Trees were more affected by *Cerambycidae* attacks and *Coraebus undatus*. The damage caused by these pests is noteworthy in practically all the stands, indicating their prevalent nature. The presence of *Coraebus undatus* were higher in stands with good health state. A significant and positive relationship was found between the presence of white spots in trunks caused by *Coraebus undatus* and the presence of ants. Both pests jointly with the attacks of defoliating insects increase with precipitation and when temperatures are not extreme.

The most frequently diseases occurring in cork oak forests were studied: *Biscogniauxia mediterranea*, species of the genus *Phytophthora* and fungi of the family *Botryosphaeriaceae*, finding a positive correlation between the first two. Besides, it was confirmed the known relationship between *Cerambyx* sp. and *Biscogniauxia mediterranea* and *Botryosphaeria* sp. and a relationship was found between the presence of *Crematogaster scutellaris* and the three studied diseases. This last relationship has not been previously reported. The presence of these diseases in the studied stands has been determined based on the most commonly symptoms they cause. We are aware that in order to have an accurate diagnosis, it would be necessary to isolate and identify pathogens in the laboratory. Nevertheless, given the fact that the operators doing data gathering in the Cork Quality Field Assessment Plan of Extremadura are highly familiarized with these symptoms, we think that the information given is highly reliable.

The presence of ants is also associated with the poor execution of cork necks, which jointly with the poor execution of wedges and axe cuts in the cork-generating layer, caused the most damage to the trees during stripping. Stripping damage increases with smaller cork thickness so caution should be taken. The weak relationship found between the climate and dendrometric variables and the variables related to stripping damage indicates that climate is not a decisive factor for carrying out a proper stripping operations in the stands.

Although having room for improvement, the Cork Quality Field Assessment Plan is proving to be an effective tool for assessing the quality of cork, the health status of cork oak forests and the evolution of these forests over time. The information provided could be also used to identify places worthy of further study. The main recommendation for improving the Cork Quality Field Assessment Plan would be to monitor the same trees in each consecutive sampling for properly monitoring not only the evolution of cork thickness, but also the presence of defects to be used as a proxy for tree health. Another recommendation of improvement would be to include variables related to worker specialization and soil characteristics. Regarding forest management, the main recommendations would be to extend the length of stripping cycles to enhance cork production, and to use the new tools and systems for cork stripping to reduce damage.

CRediT authorship contribution statement

Mariola Sánchez-González: Investigation, Formal analysis, Writing – review & editing. **Ramón Santiago Beltrán:** Investigation, Resources, Writing – review & editing. **Raúl Lanzo Palacios:** Investigation, Resources, Writing – review & editing. **Cristina Prades:** Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2023.121012.

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