Cork Oak

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Introduction

The cork oak (*Quercus suber*) is an evergreen oak that spreads in the countries of the western Mediterranean basin, over a total area of 2 million ha. It extends in the western coastal Mediterranean and adjoining Atlantic areas between 34° and 45° N latitude.

The species has a particular characteristic that sets it apart from other evergreen oaks: its ability to produce a thick bark with a continuous layer of cork tissue on the outside, with a thickness and properties that make it a valuable raw material for industry. Whenever the outer cork bark is removed, the tree has the capacity to form a new cork bark by adding new layers of cork every year, and this may be repeated throughout the tree's lifetime.

Cork oak forests nowadays cover considerable areas in Portugal (*c.* 725 000 ha) and Spain (*c.* 475 000 ha), and also in Algeria, France, Italy, Morocco, and Tunisia. The annual world production of cork totals about 370 000 tonnes, mostly from the cork oaks of Portugal and Spain, which produce respectively 51% and 23% of the total.

The Cork Oak Tree

Cork oaks are low spreading trees with a short stem and thick branches (**Figure 1**). The trees do not attain heights greater than 14–16 m but open-grown trees may have very large crown dimensions, e.g., 500 m^2 of crown projection in some mature trees 150–200 years old. The circumference at breast height of these 'monument' trees can be as large as 9 m. When growing in dense stands, the shape of the tree is strongly influenced by competition, giving rise to trees with narrower crowns and higher stems.

Figure 1 Cork oak trees under cork production.

The root system is characterized by a strong and long taproot with thick lateral ramifications that in open-grown trees may show a large horizontal expansion with many superficial roots. The association of the root system with different micorrhyzae is quite frequent.

Cork oak is a monoic species with flowers emerging between April and June; the flowering period may sometimes be longer, with flowers emerging in autumn. Due to the long flowering period, the acorns do not ripen at the same time. The amount of acorns varies widely from year to year, with 2–3 years of high fruit production out of 10 years. Flowering and fructification begin at around 15–20 years of age.

Tree diameter and cork growth are concentrated in spring and the beginning of the summer and are highly controlled by annual weather variations, namely by the precipitation in the previous winter and spring.

The cork oak is a semitolerant species, well adapted to mild climates, like Mediterranean climates with Atlantic influence, with mild winters but hot and dry summers. It grows well with mean annual precipitation of 600–800 mm, even surviving with 400 mm of precipitation. The optimum mean annual temperature is in the range 13–16°C but it survives up to 19°C. Mean temperature of the coldest month should not be below 4–5°C and the absolute minimum survival temperature is −12°C. The optimum growth occurs at 300–600 m of altitude, although the species can be found at higher altitudes (up to 1300 m).

The species prefers deep and well-drained soils, however, it is very soil tolerant and will grow on poor and shallow soil sites. It grows poorly on calcareous or excessively sandy soils.

Cork Biology

Cork Formation

In the cork oak the phellogen is formed as a continuous layer surrounding the stem and branches and producing an external layer of cork cells with an appreciable thickness. Unlike most species, where the phellogen only lives for some years, in the cork oak it may be active as long as the tree.

The phellogen differentiates in the young plants during the first year of growth in the cell layer immediately under the epidermis after the formation of the vascular cambium and the initiation of its activity. Several layers of suberized phellem (cork) cells are produced to the outside by the meristematic division of the phellogen mother-cells during each growth season (**Figure 2**). In the very young stages, the phellem cells are tannin-filled and tangentially stretched due to growth stress, but after approximately 7 years they acquire the characteristics of adult cork cells with empty lumina, thin suberized walls, and a regular arrangement.

Cork Structure and Composition

Cork is a cellular material made up of a regular structure of closed, thin-walled, hollow cells. The cells may be described as hexagonal prisms, packed base-to-base in columns oriented parallel to the tree radial direction. There are no cell-to-cell communication channels (i.e., pits) nor intercellular voids, with the exception of the natural occurrence of lenticular channels.

The structure of cork is anisotropic. In the tangential section (perpendicular to the radial direction), cork cells have a honeycomb-type arrangement and are seen as polygons, mostly with five to seven faces and with areas of $4\text{–}6 \times 10^{-6}\,\mathrm{cm}^2$. The radial and transverse sections (perpendicular, respectively, to the tangential and axial directions) are similar and show a brick-layered-type arrangement with the cells aligned in radial oriented rows and with a rectangular form of 30–40 μm length.

Corrugation of cork cells is an important characteristic of their prism lateral faces. Late cork cells show little or no wall corrugation, in contrast to the first spring early cells that are often heavily corrugated due to radial compression resulting from growth stresses.

One conspicuous macroscopic feature of cork is the presence of lenticular channels that cross the planks radially from the external surface to the phellogen; these are usually referred to as cork pores. In a tangential section the lenticular channels appear in cross-section with a more or less circular form, mostly elongated in the tree's vertical direction. There is a very large variation on the number and dimensions of lenticular channels, probably related to tree genetics. The porosity of cork is directly in relation to cork quality. In a good-quality cork, the porosity represents in general less than 4% of the area.

The chemical structure of cork cells is dominated by the presence of suberin as the main component (around 40%). Suberin is an insoluble tridimensional cell-wall polymer with an ester-linked glyceridic framework of long-chain fatty acids and alcohols. The supramolecular structure of this component is still a matter of investigation, regarding its connection to other cell-wall components. Cork cells also contain lignin to a considerable extent, as well as extraneous compounds such as fats and waxes and phenolics. Cellulose and hemicelluloses are also present but their role is much less important when compared to wood cells.

The summative chemical composition of cork is, on average: ash <1%, extractives 14%, suberin 40%, lignin 23%, cellulose 9%, hemicelluloses 11%. Variability of chemical composition has been found between corks of different trees.

Silviculture

Cork oaks can be managed according to two different silvicultural systems:

1. In most cases, cork oak stands have a relatively small number of trees per hectare (sparse forest) and are associated with agricultural crops or pasture for cattle grazing (**Figure 3**); this system is called montado in Portugal and dehesa in Spain.

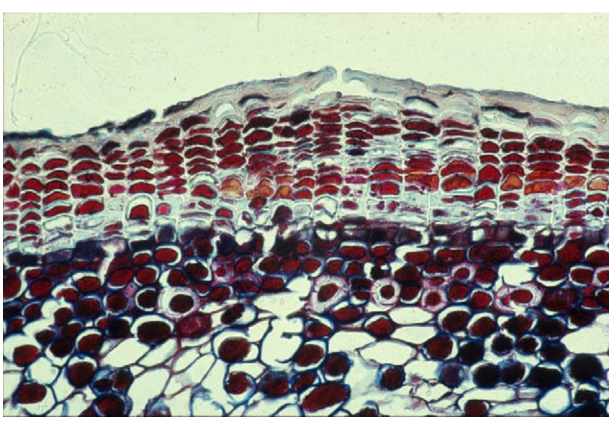


Figure 2 Phellem (cork) cells produced by the tree phellogen during its first year.

Figure 3 A montado in Portugal.

2. In some cases, in mountainous regions, cork oaks are grown in denser stands which do not permit the practice of agriculture underneath the trees.

Both systems are frequently associated with hunting, mushroom picking, and bee-keeping.

Most of the present mature cork oak stands resulted from the management of naturally regenerated stands by generations of landowners or, in some cases, through artificial seeding complemented by natural regeneration. As a result, a large percentage of the stands is characterized by a heterogeneous spatial distribution, and some can be classified as uneven-aged.

Harvesting of cork oaks usually occurs only for sanitary purposes and the present mature stands include a large percentage of old trees. The decision on the best management option or silvicultural system towards the rejuvenation and maintenance of these stands may consider:

- clearcutting the stand (as a whole or in small plots), followed by natural or artificial establishment of a new stand (even-aged silviculture)
- the gradual transformation of the stand towards continuous-cover forestry (continuous-cover silviculture)
- the use of successive regeneration fellings.

In several countries of the Mediterranean region, afforestation with cork oak has been emphasized in the last two decades and even-aged silviculture has been the option for these new stands.

Even-Aged Silviculture of Cork Oak Stands

Stand regeneration Artificial regeneration of cork oak stands is relatively recent but was greatly increased as a consequence of EU policy for the afforestation of agricultural lands. Either plantation or direct seeding by placement of two to three acorns in small holes is used. Acorns are very attractive to small rodents, and the use of repellents is recommended.

In both cases, correct site preparation is essential for the success of the new stand. This includes weeding, usually by disk-harrowing, and the improvement of soil characteristics for the development of the root system. Soil preparation depends on soil type and slope: it may include ripping or subsoiling to 60–80 cm depth, especially in soils overlying hard rock, or plowing and mounding along the contours followed by deep plowing and/or disk harrowing. Site preparation may cover the whole area or be concentrated on the planting line. Starter NPK fertilization is usually applied at 40–100 g per plant.

Plantation and/or seeding can occur either in spring or autumn. The number of trees per hectare at planting is not as high as in other species planted for wood production, and common spacings range from 4×4 m (625 trees ha^{-1}) to 8×4 m (312 trees ha^{-1}).

Operations in the regeneration stage The success of plantations with cork oaks is not guaranteed and mortality during the first years may be very high. The operation of beating-up is very common. The protection of young seedlings with individual tree shelters is considered to be beneficial against browsing and for stimulating initial height growth. However, in regions with high temperatures, this technique has caused higher mortality rates. Whenever spring and summer precipitation is too low, irrigation should be applied two to three times during periods of higher stress. During the first years after planting, weeding is highly recommended around each seedling or on the whole area. Suppression of cattle grazing during the regeneration stage is a precondition for the success of the plantation.

Operations in the juvenile stand The juvenile phase of a cork oak stand refers to the period until the beginning of cork extraction. Young cork oak trees show abundant ramifications without a leading shoot and pruning is therefore an important operation to obtain trees with a clear stem height of at least 2.5–3 m. Depending on site productivity, the first pruning occurs between 3 and 6 years of age and eliminates all the branches in the first two-thirds of the tree. A second pruning is made between the ages of 12 and 15 years. Depending on stand density at planting, this operation may be complemented by a first thinning to reduce stand density to 400–600 trees ha^{-1}. The last pruning is usually made immediately after first debarking. The first debarking for cork extraction is regulated in most countries by legislation. In Portugal only trees with a circumference at breast height ≥ 70 cm can be debarked. Depending on site productivity and stand density at planting, this operation is possible between 25 and 40 years of age.

During the juvenile stage of a cork oak stand, weeding may be undertaken. If the landowner aims at grazing underneath the future stand, the establishment of pasture may occur from the age of 10–15 years.

Operations in mature stands The most important silvicultural operations in mature stands are thinning and, naturally, cork debarking. Some managers sometimes consider applying fertilizers and tree pruning. Weed control, depending on the type of cultivation underneath, may also be needed. It is highly recommended that the method used to control weeds – usually mechanical weeding – does not damage the superficial root system.

Stand density after the first debarking is usually controlled according to a preselected spacing factor. The spacing factor is defined as the quotient between mean distance between trees and mean tree crown diameter:

$$\text{Spacing factor} = \frac{\text{mean tree distance}}{\text{mean crown diameter}}$$

It is usually assumed, even if there is not enough experimental data to confirm this empirical rule, that cork production is affected when intertree competition is too high. The use of a spacing factor that gives each tree enough space to develop its crown without substantial restrictions is recommended. The space between trees should be at least half of its mean crown radius. This rule is equivalent to the maintenance of a spacing factor of around 1.2.

After the first cork debarking, the rotation of cork extractions is also regulated in most countries. In Portugal and Spain, the minimum period allowed between successive extractions is 9 years. The cork extraction of a stand may be done either simultaneously in all the trees – even-aged cork – or in only a selection of the trees, therefore cork age is not the same for trees in the same stand – uneven-aged cork. In uneven-aged cork stands two cork-debarking rotations should be defined: (1) tree cork-debarking rotation, which is usually 9 years; (2) stand cork debarking, depending on how many different cork ages are present in the stand.

In an even-aged cork stand, thinning should occur after cork debarking, so that the landowner can profit from the cork income from the trees that will be thinned and also be able to use cork quality as an additional criterion to select trees to be thinned.

One important parameter of cork debarking is the so-called debarking coefficient, which defines the height in the stem to which cork can be stripped off (debarking height). The debarking coefficient is defined as the quotient between the debarking height and the perimeter at breast height over cork (pbh_{overcork}):

$$\text{Debarking coefficient} = \frac{\text{debarking height}}{pbh_{\text{overcork}}}$$

In some countries the debarking coefficient is also regulated by legislation. For instance, in Portugal, maximum legal debarking coefficient depends on the stage of development of the tree: 2.0 for the first cork debarking, 2.5 for the second cork debarking, and 3.0 for subsequent debarkings.

The application of fertilizers during the period between cork extractions is often made by landowners to improve cork quality. However, the few experimental results available do not show its effect on cork growth and quality.

The acorns of cork oaks were an economically important product in past years and the trees were pruned to increase fruit yield. This practice is still used by some farmers who associate pruning with tree vigor and cork yield, a fact that has never been experimentally proved.

Rotation period Cork oak trees may attain 250–350 years of age. The trees maintain their ability to produce cork but cork thickness decreases as trees age and 150–200 years seem to be the limit for an industrially useful cork production. Rotation periods between 100 and 150 years are usually assumed in most management plans.

Continuous-Cover Silviculture

Continuous-cover silviculture is a very interesting alternative to even-aged silviculture for the management of the existing mature stands, even if at present there are no examples of the use of continuous-cover silviculture in cork oak stands. Some tentative studies using growth and yield models have compared cork yield under this type of silviculture. The main conclusion is that the total production of cork in a continuous-cover silviculture strongly depends on the selected target diameter distribution. It is possible to find options that in the long term will originate cork yields comparable to those obtained with even-aged silviculture.

Three main consequences of using continuous cover forestry are: (1) the proportion of virgin cork – of low commercial value – is higher than in even-aged silviculture due to the continuous maintenance of a large number of young trees in the stand; (2) cork yield is highly dependent on one or two large trees, and if one of these dies, there is a strong negative impact on cork yield during the next period; (3) it is difficult to make this silvicultural system compatible with underneath grazing or game browsing.

Cork Extraction

The first cork taken from the tree is called virgin cork (**Figure 4**). It has deep fractures due to tissue failure upon the tangential stresses of tree radial growth and is of low commercial value. The second cork obtained in the following extraction is more homogeneous in

Figure 4 A young cork oak tree with virgin cork and second cork, respectively, in the upper and lower part of the stem.

Figure 5 Cork extraction from cork oak trees.

Figure 6 Field storage of raw cork planks.

thickness but still has numerous longitudinal running cracks (**Figure 4**). It is only from the third extraction that the cork planks show a continuous and uniform thickness that will allow their full utilization by the industry. The cork layer is removed from the tree as large planks by manually cutting with an ax along vertical and horizontal lines on the stem and thick branches and subsequent stripping-off (**Figure 5**). This operation is made in spring and early summer when the tree is physiologically active and allows easy separation of the outer bark.

The raw cork planks have variable dimensions, depending on the tree size and operational conditions at the tree debarking. They are rectangular with dimensions usually falling in the range of 1–1.8 m height and 0.4–0.8 m width. The cork planks are piled up in the field while waiting for transport to the industrial premises (**Figure 6**).

A distinctive feature of cork planks is the presence of a thin layer of lignous materials to the outside of the cork tissues, named the 'back' of the cork planks. The trees under cork production show on the stem and branches the characteristic dark grayish-brown color due to weathering of the back of cork planks and numerous fissures resulting from the radial tree growth. The inside surface of the cork planks corresponding to the tree inner side is industrially named the 'belly.'

Growth and Yield

Tree Growth

Cork oak is a slow-growing species. The SUBER model, the only published growth and yield model for the species based on data from Portugal, expresses site productivity as the number of years that dominant trees take to attain diameter at breast height (dbh) level. In this model this index is assumed to vary in the range 5–9.

Figure 7 shows the dbh growth of individual trees obtained in tree disks collected at dbh-level as well as the corresponding growth curves used in the SUBER model. As can be seen, dbh growth is very slow but trees can attain very large dimensions as a consequence of the large rotation period.

Cork Growth

The production of new cork is more intense in the years immediately after debarking and decreases from then on. Cork thickness after 4 years is around 75% of the thickness at 9 years of age. When analyzing cork growth, which can be done after cork harvest by measuring cork growth rings, one can show that the first cork growth ring, located adjacent to the cork back, is usually smaller than the subsequent rings. This ring corresponds to the growth of cork in the growing season during which cork was extracted, after debarking. Therefore it is not a complete growth ring and is usually called the first half-ring. Similarly, the last cork growth ring also corresponds to a partial growing period and is called the last half-ring. Cork growth capacity of a tree can be expressed by the accumulated thickness of the first 8 complete years. This index, the cork growth index (CGI), is used in the SUBER model.

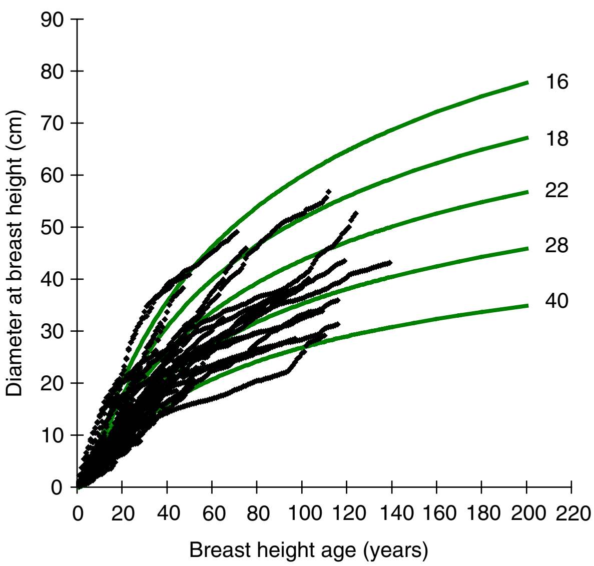


Figure 7 Diameter at breast height (dbh) growth obtained from stem disks at dbh-level as well as simulated dbh growth curves used in the SUBER model.

Stand Development

Stand development depends on site characteristics and on forest management. **Table 1** gives an example of the predicted development of a cork oak stand in a site of mean productivity, managed as an even-aged cork stand, maintaining a spacing factor close to 1.2, and following the maximum legal debarking coefficients. As can be seen, number of trees per hectare, in comparison with other species that are planted for wood production, is quite low, leading to low values of stand basal area. **Figure 8** shows cork yield and stand characteristics in four different stands with a percent crown cover of approximately 58%.

Cork Processing and Products

Cork is a light material, with a density ranging from 0.2 to 0.3. It is rather impermeable to water and other liquids. It is a very durable material, being stable as regards weathering and biotic attacks. On compression, cork behaves as a viscoelastic material, allowing large deformations without fracture and appreciable dimensional recovery. It is an insulation material, with low conductivity. Cork is also a sound and vibrational insulator.

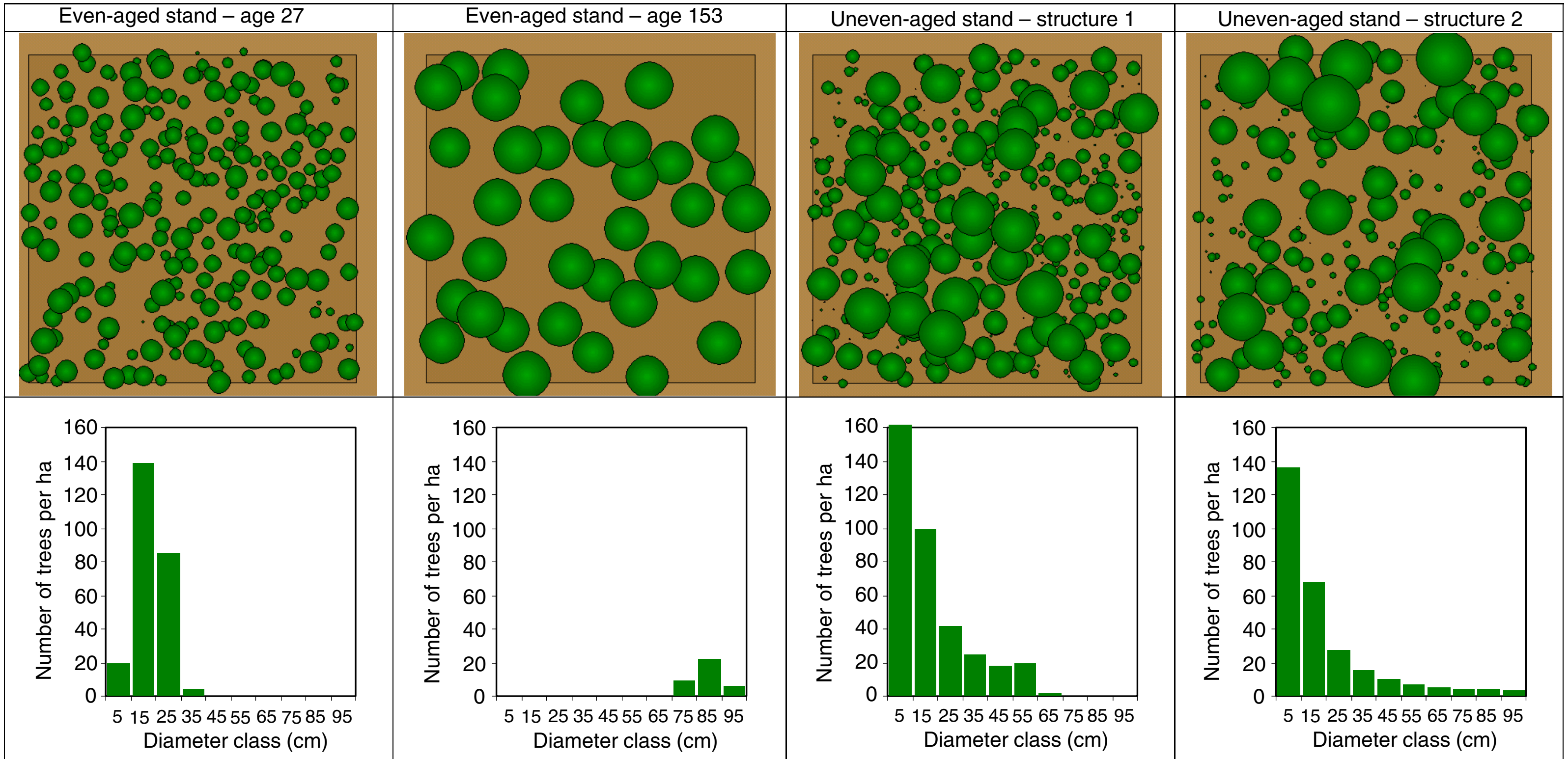
These properties led to cork being used for several purposes, some ancient, others more recent: buoys and floating material, sealants of liquid recipients (i.e., wine bottles), insulation of buildings and industrial equipment, surfacing of walking areas, surface joint sealant in engines, and antivibrational joints in structures (i.e., antiseismic construction).

At present, the cork industry produces different products with variable incorporation of cork and technological transformation. However the economic viability of the whole sector is determined by the production of stoppers of natural cork for use in the bottling of wine. Nowadays it is the suitability of the cork raw material for this production that establishes its commercial quality and the objectives for the forest manager.

Table 1 Yield table for an even-aged stand of mean site productivity managed to maintain a spacing factor of 1.2 and using the legal debarking coefficients

Age (years)	*Stand characteristics after thinning*					*Cork weight (kg ha^{-1})*	
	N *(ha^{-1})*	G *(m^2 ha^{-1})*	d_g *(cm)*	d_{crown} *(m)*	*Crown cover (%)*	*Virgin cork*	*Mature cork*
27	250	7.1	19.0	5.0	49.4	833.0	1153.1
45	114	12.0	36.7	7.8	54.4	639.1	3833.9
63	76	14.6	49.5	9.5	54.2	23.7	4656.3
81	59	16.3	59.4	10.8	53.8	42.8	4853.3
99	50	17.8	67.3	11.7	53.9	60.2	4993.7
117	44	19.0	74.1	12.5	54.0	63.1	5171.2
135	40	19.9	79.6	13.1	53.9	40.9	5293.9
153	37	20.5	84.0	13.6	53.5	38.5	5393.6

N, number of trees per ha; *G*, basal area; d_g, quadratic mean diameter; d_{crown}, crown diameter.



Crown cover = 49%	Crown cover = 54%	Crown cover = 58%	Crown cover = 58%
Stand density = 250 trees ha^{-1}	Stand density = 37 trees ha^{-1}	Stand density = 181 trees ha^{-1}	Stand density = 143 trees ha^{-1}
Basal area = 7 m^2 ha^{-1}	Basal area = 20 m^2 ha^{-1}	Basal area = 12.5 m^2 ha^{-1}	Basal area = 15.0 m^2 ha^{-1}
Mean quadratic dbh = 19 cm	Mean quadratic dbh = 83 cm	Mean quadratic dbh = 30 cm	Mean quadratic dbh = 36 cm
Mean crown diameter = 5 m	Mean crown diameter = 14 m	Mean crown diameter = 6 m	Mean crown diameter = 7 m
Virgin cork weight = 833 kg ha^{-1}	Virgin cork weight = 40 kg ha^{-1}	Virgin cork weight = 342 kg ha^{-1}	Virgin cork weight = 274 kg ha^{-1}
Mature cork weight = 1153 kg ha^{-1}	Mature cork weight = 5394 kg ha^{-1}	Mature cork weight = 3076 kg ha^{-1}	Mature cork weight = 3760 kg ha^{-1}

Figure 8 Cork yield and stand characteristics in four different stands with a percentage crown cover of ≅58% (stands simulated with the SUBER model): 1, even-aged young stand; 2, even-aged stand close to rotation age; 3, uneven-aged stand with maximum diameter at breast height (dbh) in the class [62.5; 67.5]; 4, uneven-aged stand with maximum dbh in the class [92.5; 97.5]. dbh, diameter at breast height.

Figure 9 Cork planks after the water-boiling operation.

Figure 10 Boring of stoppers from a cork strip in the industry.

The processing of cork depends on the type of cork: virgin and second cork are directed for trituration to produce cork granules that will be used for cork agglomerates; the reproduction cork planks (from the third extraction on) are used to produce stoppers.

The cork planks undergo postharvest preparation for further industrial processing consisting of immersion in water at approximately boiling point for 1 h. The objective of this operation is to flatten the stem-curved raw planks and to soften the cork tissue for easier subsequent cutting (**Figure 9**). In boiling water the cork expands and the most important practical consequence is that the raw cork planks increase in thickness, on average by 12%. There is a high variation in thickness increase with water boiling between different cork planks, with values ranging from almost nil increase to more than one-third of the initial dimension.

Cork planks that have a thickness over 27 mm are directed for production of stoppers. For this they are cut into strips and the stoppers are bored with a hollow cutting cylinder with an inner diameter equal to the desired stopper diameter (**Figure 10**). The stoppers are dimensionally rectified, washed, bleached, dried, and classified into commercial quality classes according to the extent of the porosity shown on their surface, as given by the lenticular channels. In the stoppers the lenticular channels run parallel to the top and bottom faces.

The cork planks that have a thickness below 27 mm are directed for the production of disks. The planks are cut into bands, and laminated tangentially in the cork into 2–5-mm-thick cork sheets from which the disks will be punched out. The disks will be used glued on bodies of agglomerated cork, i.e., for champagne and sparkling wine.

The residues from the boring of stoppers and of disks (amounting to more than 75% of the initial cork plank) are triturated and agglomerated. Cork agglomerates are used to produce agglomerated stoppers and for cork boards and sheets used in various surfacing situations, i.e., flooring, paneling, joints. In a mixture with rubber, a composite material is produced for industrial and construction vibrational absorption.

A special insulation material called expanded cork agglomerate is made by high-temperature (*c.* 300°C) expansion and self-agglomeration of cork granules in autoclaves with superheated steam. The agglomerate has a dark brown color and is used for heat and sound insulation.

See also: **Temperate Ecosystems**: Fagaceae.

Resins, Latex and Palm Oil

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Introduction

Besides timber and fuelwood, many commercial products of biological origin are sourced from forests all over the world. These comprise medicinal herbs, edible plants and plant parts, aromatic oils, gums, resins, latex, fibers, flosses, and a variety of other products commonly referred to as non-wood forest products. Resins, latex, and palm oil are one such category of product which have found place in industrial, commercial, and subsistence use with