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Chapter 8

Soil Properties Constraining Cork Oak Distribution

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Soils provide physical and mechanical support for plant establishment and water, oxygen, and nutrients for their growth and maintenance. Each plant species has its own range of soil requirements and constraints that determine its geographic distribution, in conjunction with climatic, historical, and evolutionary factors and the interactions with other organisms. Furthermore, some plants can strongly modify soil properties, improving their habitat conditions by generating positive feedback loops between plant and soil compartments (Ehrenfeld et al. 2005).

As mentioned in Chapter 1, cork oak woodlands generally occur in soils developed from siliceous substrates, and therefore it is commonly considered acidophilous (acid loving) and calcifugous or lime intolerant (Montoya 1980; Montero 1988). However, long-term human activities may have modified natural cork oak distribution (Pereira and Fonseca 2003), so manipulative studies are needed to accurately identify soil constraints for this species. Knowledge of species requirements and constraints can be used to promote conservation and restoration efforts or to expand its current distribution limits in view of the current climate and land use changes.

In this chapter we discuss constraints on cork oak establishment related to soil features. We first review the range of soil characteristics in the tree's main distribution area through published sources, focusing on its acidophilous and calcifugous character because soil pH seems to be critical for cork oak. Then we summarize a series of studies specifically designed to investigate soil–cork oak relationships in soils outside the main distribution area of the tree to elucidate processes limiting the species' establishment. These include a field study involving a population of cork oak growing on soils developed over *carbonate* rock and a *lysimeter* experiment examining the response of cork oak seedlings planted in soils with varying pH and carbonate content. We conclude by describing current knowledge on the ways soils constrain cork oak establishment and discuss the ways managers can promote expansion of this species.

Soil Characteristics

The main soil attributes affecting plants are physical properties, which drive water and air dynamics, and chemical and biogeochemical properties interacting with plants. Physical and chemical properties are conditioned by soil type and bedrock substrate, which we will now consider in detail.

Bedrock and Soil Types

The present distribution of cork oak is almost entirely restricted to soils derived from siliceous rocks, including siliceous sandstone, granite, granodiorite, gneiss, schist, shale, slate, quartzite, basalt, and sand. To a lesser extent, the tree can also be found on *decalcified* soils developed on carbonate rock, such as *dolomite*, dolomitic sandstones, or *limestone* (Montoya 1980; Ruiz de la Torre 2001; Sánchez-Palomares et al. 2007). The main types of soil associated with this species are leptosols, regosols, cambisols, and luvisols (FAO 2006b). This represents a range of soil types, from very shallow soils overlying hard rock to deep soils with high clay content in the B horizon and high *base saturation*. To a lesser extent, cork oak forests have also been reported on strongly acid soils, such as podzols, planosols, acrisols, and alisols, on sands (arenosols), and on soils developed from volcanic bedrock (andosols) (Montoya 1980).

Soil Physical Properties: Soil Depth, Texture, and Aeration

As is true of most oaks, cork oak is a deep-rooting species with a taproot depth of a meter or more (e.g., 13 meters; Kurz-Besson et al. 2006). The early development of a taproot appears to be an important trait in the tree's ecological life history strategy, especially in relation to drought (see Chapters 1 and 6). In fact, during summer droughts, cork oak may be able to escape moisture-depleted surface soil horizons, extracting water progressively from shallow to deeper soil layers (see Chapter 6 for details).

Cork oak generally thrives in well-aerated soils, avoiding compacted and permanently flooded soils. In fact, the most abundant soil texture where the species occurs is loamy (74 percent of studied cases), followed by sandy (14 percent), and within the loamy texture group about 30 percent are sandy loam, 28 percent loam, and 16 percent silty loam (Montero 1988).

Soil Chemical Properties: Soil Reaction and Buffering Capacity

Most cork oak woodlands occur on moderately acidic to slightly acidic soils, with pH generally in the range of 4.7 to 6.5 and, more rarely, 3.4 to 7.8 (Table 8.1). Most of these soils present a *cation exchange* complex medium to low base saturation, that is, soils poor in basic cations (Ca^{2+}, Mg^{2+}, K^+). The pH is controlled by different buffering processes capable of neutralizing soil acidity in an increasing acidity gradient (Meiwes et al. 1986; Table 8.1): The carbonate buffer provides a high acid neutralizing capacity, hampering *acidification* through dissolution of Ca and Mg carbonates; the silicate buffer dominates in carbonate-free soils, with the weathering of primary silicates as the main acid neutralizing reaction; and in the exchanger buffer, cation exchange reactions on clay minerals and soil organic matter are responsible for the *buffering capacity*. Most cork oak woodlands thrive in the silicate and exchanger pH buffers. To a lesser extent, they also occur in the carbonate buffer (Table 8.1) and in the extremely acid soils under the aluminum buffer, where the nutrient supplying capacity of the soil is low and soluble aluminum in the plant root zone is potentially toxic.

Calcifugous Plants in Calcareous Soils?

As mentioned earlier, in some cases cork oak does thrive on decalcified soils, on moderately alkaline soils with high base saturation in the low range of the carbonate buffer, which is not common for acidophilous or calcifugous species. In general, calcifugous plants are absent from *calcareous soils* because of inadequate P and Fe uptake (Zohlen and Tyler 2000, 2004). In these soils, P is largely unavailable to plants, and iron is present as insoluble ferric forms (Fe^{3+}), which results in nutrient deficiency that limits cork oak establishment and growth. Notably, when iron supply is limited, cork oak roots exhibit a greater capacity to reduce soil Fe^{3+} through net excretion of protons (Gogorcena et al. 2001), promoting P and Fe acquisition in these soils. Consequently, the production of acidity by the plant in response to iron deficiency is an adaptive ability important to the species, but it also can contribute to soil acidification when soil buffering capacity is low.

Furthermore, it is likely that in Mg-rich soils, such as soils developed on dolomites, P nutrition could be improved because Mg uptake is higher than Ca uptake, favoring P solubility and transport in plant tissues (Kinzel 1983).

TABLE 8.1.

Topsoil pH values (mean, standard deviation, minimum, and maximum) under cork oak forests and woodlands, arranged by the different buffering ranges.

pH						
Mean (*SD*)	Minimum–maximum	Depth (cm)	Number of profiles	Rock type or soil	Reference	Site
			Carbonate buffer, 8.6 > pH > 6.2			
6.8		0–5	1	Metamorphic	1	Sulcis-Iglesiente, Sardinia, Italy
6.6		0–10	16		2	Sierra Morena, Andalucía, Spain
6.4		0–10	1		2	Sierra Morena, Andalucía, Spain
6.3		0–10	13		2	Tierras Llanas, Andalucía, Spain
6.3		0–10	15		2	Jerez Caballeros, Extremadura, Spain
6.4 (0.5)		0–2	17	Granite	3	Les Gavarres, Catalonia, Spain
6.4 (0.3)		0–2	16	Schist	3	Les Gavarres, Catalonia, Spain
6.3		0–10	18		2	El Vallès, Catalonia, Spain
6.6 (0.4)	5.6–7.8	0–10	105	Dolomites	4	Pinet, Valencia, Spain
	5.5–6.5	0–20	4	Cambisol	5	Algarve, Portugal
			Silicate buffer, pH > 5 ($CaCO_3$ free)			
5.7 (0.4)		0–15	3	Granite	1	Sulcis, Sardinia, Italy
5.6 (0.4)	5.3–6.0	0–20	3	Metamorphic	1	Sulcis-Iglesiente, Sardinia, Italy
5.4 (0.6)	4.8–6.4	0–10	12	Granite	6	Gallura, Sardinia, Italy
5.1 (0.8)	4.1–6.5		24		7	Sardinia, Italy
5.3 (0.4)	4.6–6.3	0–25	33	Siliceous sandstones	8	Los Alcornocales NP, Andalucía, Spain
5.6 (0.8)	4.4–7.3	0–25	42		9	Sierra Morena, Andalucía, Spain
5.6		0–10	9		2	Siberia Extremeña, Extremadura, Spain
5.1		0–10	30		2	Sierra de San Pedro, Extremadura, Spain

TABLE 8.1.

Continued

pH						
Mean (*SD*)	Minimum–maximum	Depth (cm)	Number of profiles	Rock type or soil	Reference	Site
6.0 (0.5)		0–2	16	Granodiorite	3	Les Gavarres, Catalonia, Spain
5.9		0–10	21		2	La Selva, Catalonia, Spain
5.9		0–10	19		2	Agullana, Catalonia, Spain
6.0 (0.4)		0–10	4	Siliceous sandstones	10	Espadà, Valencia, Spain
5.8		0–10	4		2	Navahermosa, Castilla-La Mancha, Spain
5.7		0–10	4		2	Talavera, Castilla-La Mancha, Spain
		Cation exchange buffer, 5 > pH > 4.2				
5.0 (0.6)	4.2–6.3	0–25	30		11	Salamanca-Zamora, Castilla-León, Spain
4.7		0–10	12		2	Campo Gibraltar, Andalucía, Spain
5.0		0–2.5	1	Phillite	12	Farma Valley, Tuscany, Italy
4.4		2.5–20	1	Phillite	12	Farma Valley, Tuscany, Italy
	3.6–6.5	0–20	31	Leptosol	5	Algarve, Alentejo, Tras-os-Montes, Portugal.
	3.9–5.3	0–20	11	Cambisol	5	Alentejo, Ribatejo, Portugal
	3.4–6.0	0–20	5	Luvisol or leptosol	5	Algarve, Portugal

Sources: 1, Serra et al. (2002); 2, Montero (1988); 3, Kooijman et al. (2005); 4, Pausas et al. (2006); 5, Moreira and Martins (2005); 6, Vacca (2000); 7, Corona et al. (2005); 8, Carretero et al. (1996); 9, Núñez-Granados et al. (2003); 10, unpublished data; 11, Jovellar (2004); 12, van Wesemael et al. (1995).

Nutrient Cycling and Soil Acidification

Calcium and magnesium taken up from the rooting zone of cork oak gradually accumulate throughout the life span of tree leaves (Oliveira et al. 1996; Passarinho et al. 2006). With litterfall, basic cations build up in the forest floor and return to mineral soil through litter decomposition and *leaching* (van Wesemael et al. 1995; Madeira and Ribeiro 1995). Indeed, cork oak may accumulate as much as ten times more calcium in its litter layer than coexisting pines (Noble et al. 1999). Nitrogen mineralization in the forest floor consumes H^+ for ammonium production and thus decreases acidity. In most cork oak soils, there is a decreasing vertical pattern of pH, calcium, and base saturation along the soil profile (van Wesemael et al. 1995; Noble and Randall 1999; Vacca 2000). Nutrient uptake (especially of calcium) and allocation to biomass may be the main causes for these changes (Dijkstra and Smits 2002; Jobbágy and Jackson 2004), in addition to leaching of basic cations. During plant growth, ammonium and basic cations are taken up, whereas protons are excreted by the roots. The deep rooting systems of cork oak trees act as biological pumps, assimilating basic cations from deep soil, and bring alkalinity back to the soil surface through litterfall and decomposition. This vertical decoupling between mineralization and root uptake is a source of acidity in the rooting zone (Meiwes et al. 1986; van Wesemael et al. 1995; Ehrenfeld et al. 2005) that could be neutralized by the soil buffering systems (i.e., rock weathering), or it can lead to acidification when soil acid neutralizing capacity is low.

Evidence of soil acidification under cork oak has been widely reported in the literature, including plant uptake and enhanced leaching, dissolution of clay minerals, and Fe and Al organic complexation (Madeira and Ribeiro 1995; van Wesemael et al. 1995; Noble and Randall 1999; Noble et al. 1999). As mentioned earlier, the degree of soil acidification depends on the intensity of proton input and production and on the soil's buffering capacity. Soil acidification may be detrimental for plant growth in poorly buffered, cation-poor soils, but it is less so in soils where roots have access to a base-rich horizon or in carbonate rocks. In the following section we present relevant results from a field study of cork oak woodland growing in soils developed over carbonate rocks; the purpose of the study was to elucidate how soil features control or influence the highest pH thresholds known within the species' natural area of distribution.

Cork Oak on Soils Developed over Carbonate Rocks: The Case of Pinet

Cork oak woodlands growing on soils developed over carbonate rocks cover only a minor area of their total geographic distribution. An example is the small (about 70-hectare) cork oak forest in Pinet (Valencia, eastern Spain; see Site Profile 8.1) that grows on luvisols over dolomite, which is a calcium–magnesium carbonate rock. Soils are partly decalcified, and most topsoil layers (10 centimeters) present less than 1 percent carbonate content in fine earth, but some present higher values, up to 11 percent. Topsoil pH ranges from moderately acidic to alkaline (5.7 to 7.8), but most of the soils are close to neutral, with base saturation around 90 percent (Pausas et al. 2006).

Cork oak trees in Pinet are present throughout the whole woodland area, but the cork oak basal area is higher on sites with low soil pH and low carbonate content (Figure 8.1). Low pH values in soils with carbonates below 1 percent indicate that those consist of low-reactive dolomite associated with the sand fraction. We postulate that topsoil layers are in transition between the carbonate buffer and silicate buffer ranges, depending on the degree of decalcification and spatial heterogeneity of bedrock.

This case study illustrates that soils developed over strongly decalcified dolomites, with pH nearly neutral, can provide suitable conditions for cork oak and that a sort of feedback occurs between cork oak trees and this soil. Indeed, cork oak trees influence soil pH by increasing its acidity, which probably has positive effects on P and Fe uptake and assimilation. However, the soils at the Pinet site may represent a particular case in the current distribution of cork oak. In order to evaluate the response of this species to other soils within and beyond its current distribution, in the next section we describe an experiment in which cork oak seedlings were planted in a range of contrasted soils.

Cork Oak Establishment in Contrasted Soils: A Lysimeter Experiment

We evaluated the performance of cork oak seedlings in different types of soils and precipitation regimes. Seedlings were planted in lysimeters (simulating plantation hole size: 40 cubic centimeters), filled with four contrasted soil types under low (500-millimeter) and high (800-millimeter) simulated annual precipitation regimes for this species. The four soil types are two carbonate-free soils, one derived from siliceous sandstone (SA) and another from dolomite (DO), and two carbonate soils (about 5 percent $CaCO_3$ equivalent) developed from dolomitic limestones (DL1 and DL2). These four soils represent a variety of physical (texture and aeration) and chemical (pH, $CaCO_3$, and Ca:Mg ratio) properties within and at the edge of the current values for soils in the present cork oak distribution, and therefore the results may help clarify which soil factors most strongly constrain cork oak establishment and its interaction with rainfall.

One year after planting, soil pH was significantly lower in the rhizosphere than in the bulk soil, regardless of soil type, with differences ranging from 0.5

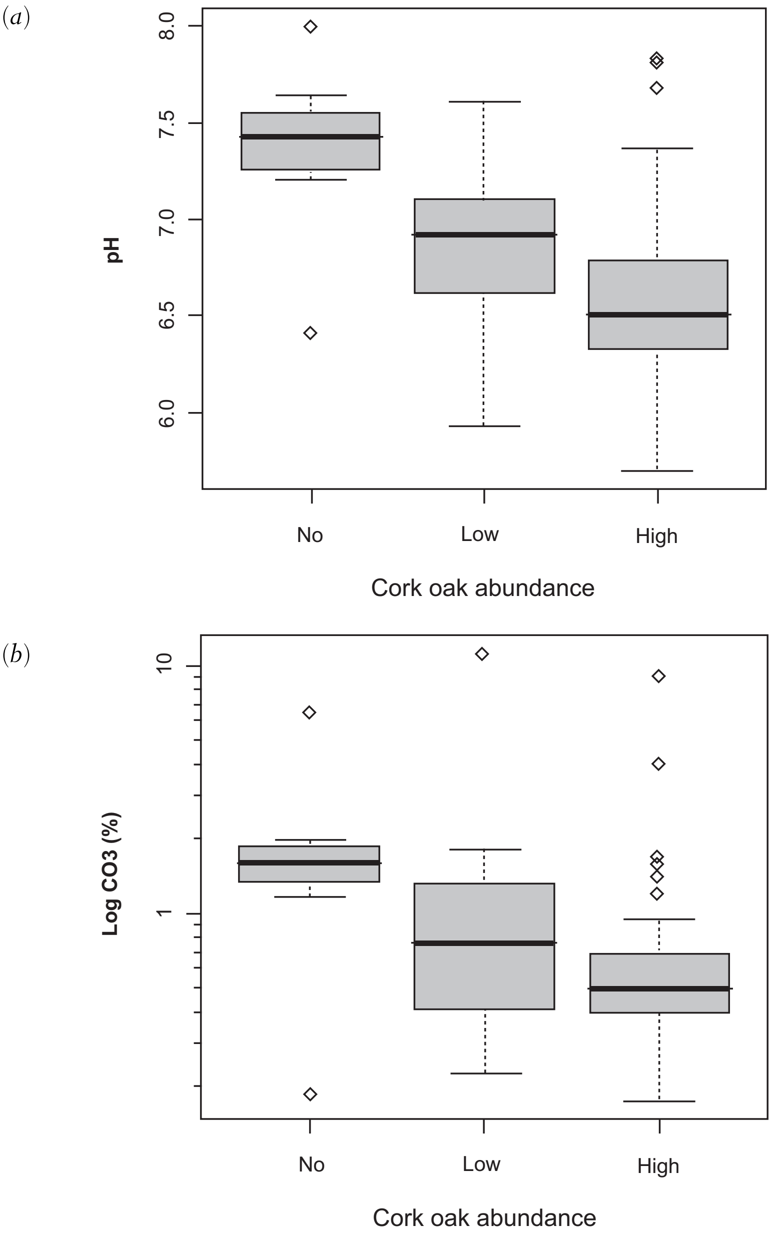

Figure 8.1. Relationships between cork oak abundance classes and *(a)* soil pH and *(b)* soil carbonate content in Pinet forest (eastern Spain; data from Pausas et al. 2006). In both cases, differences are statistically significant (one-way ANOVA, $p <$ .0001). Box plots indicate medians, quartiles *(boxes)*, 1.5 times the interquartile range *(whiskers)*, and extreme values *(dots)*. Cork oak abundance classes are *None* (absence), *Low* (basal area < 1 m^2/ha), and *High* (basal area > 1 m^2/ha).

to 1 pH units (Figure 8.2a). In the two carbonate-free soils (DO and SA), the net increase of H^+ concentration in the rhizosphere was 0.01 millimole, in contrast to only 0.001 to 0.003 millimole in carbonate soils (DL1 and DL2), because of their higher buffer capacity. Decreases in rhizosphere pH (down to pH 5.4–6.2) may have favored an increase in Fe and P availability. These results reinforce the theory that soil buffering capacity is a critical property for cork oak establishment and probably more relevant than soil pH.

As expected, the acidic soil derived from SA was the most suitable for the establishment of cork oak seedlings, as shown by the healthy state of the plants and the highest growth rates, as compared to seedlings planted on other soil types regardless of water regime (Figure 8.2b). In addition to poor growth, seedlings planted on soils containing reactive carbonates (DL1 and DL2) presented generalized iron chlorosis at the onset of summer, especially at the highest level of water availability. The poor performance of cork oak seedlings growing on soils strongly buffered by active carbonates confirms the calcifugous character of this species and, although seedlings may survive in the short term, cork oak forest expansion in areas with active carbonate in the soils seems doubtful.

Seedlings planted on the carbonate-free soil derived from dolomites (DO) also showed poor growth (Figure 8.2b), although seedlings showed no signs of iron chlorosis, and the physiological status was good. Such poor performance was unexpected because the soil was collected from a cork oak woodland (Pausas et al. 2006). We suggest that the poor fertility of this soil—low organic matter, nitrogen, phosphorus, and exchangeable bases—could be the limiting factor for growth. Critical differences between the lysimeter experiment and the field soils are that in the latter there are nutrient inputs from the forest floor (especially N and P), and deep roots have access to the base-rich bedrock surface. Therefore, the lysimeter study takes into account only the role of the bulk mineral soil on seedling nutrition. In addition, seedlings have especially high nutrient demands for growth (see Chapter 11).

Conclusions

Our experiments provide the key elements to elucidate cork oak distribution in relation to soil and bedrock type and the necessary insights to optimize cork oak plantations. Planting cork oak seedlings must take into consideration local soil characteristics, especially soil depth and aeration, soil buffering capacity and pH, and nutrient availability. Soil capacity to buffer acidic inputs seems to be the main chemical soil property governing cork oak establishment and species distribution.

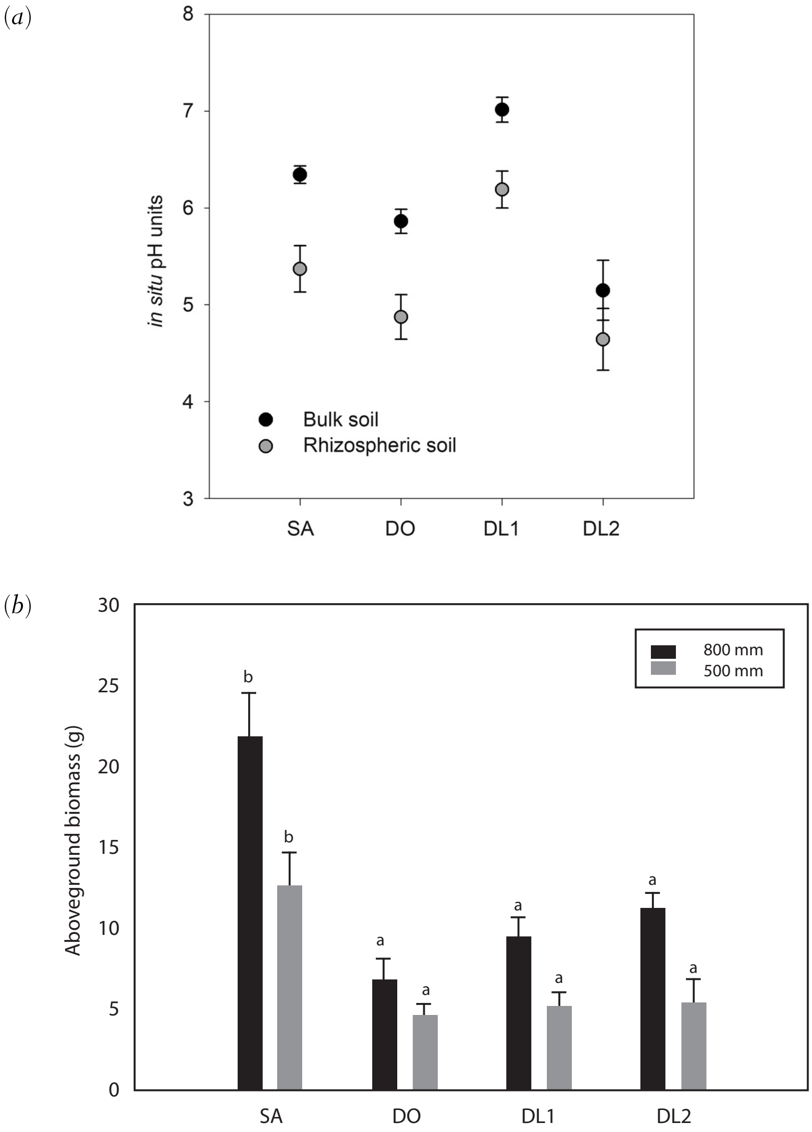

FIGURE 8.2. *(a)* In situ pH of bulk and rhizospheric soil of cork oak seedlings planted in four contrasted soil types: 2 carbonate-free soils derived from siliceous sandstone (SA) and dolomite (DO) and 2 carbonated soils developed from dolomitic limestones (DL1 and DL2). *(b)* Aboveground biomass of cork oak seedlings 11 months after planting on the 4 soil types and 2 rainfall regimes (500 and 800 mm annual rainfall). Average values and standard errors of 5 lysimeters per soil type and water regime. Different letters indicate significant differences between soil types.

Indeed, cork oak shows a strong capacity to acidify rhizospheric soil. Under strongly acidic soil conditions and low acid neutralizing capacity, increasing acidity may lower soil fertility. Therefore, conservation activities for cork oak woodlands growing in extremely poor, sandy, acidic soils should prevent further soil acidification. Indeed, sustainable nutrient management is needed in these long-term managed open woodlands, reducing nutrient losses, for example, by using shrub clearing and chipping, spreading slash on the soil surface, and avoiding intensive soil preparation and soil erosion. Soil ameliorative practices could be also considered, such as fertilizing by adding organic matter amendments and introducing legumes.

Although cork oak grows best in slightly or moderately acidic soils, it can also grow on soils overlying carbonate bedrocks, provided the soils themselves have been thoroughly decalcified and have only low to moderate buffering capacity. This is possible thanks to cork oak's unusual ability to decrease soil pH, thereby improving its ability to absorb both iron and phosphorus. However, when cork oak is planted on soils with active carbonates in the upper profile, the tree can suffer iron chlorosis and impaired growth. These facts should be taken into account before cork oak trees are planted anywhere, both within and beyond their current distribution area. As mentioned in Chapter 1, cork oak woodlands are facing severe disturbances, including pests and diseases, as will be described in Chapter 9.

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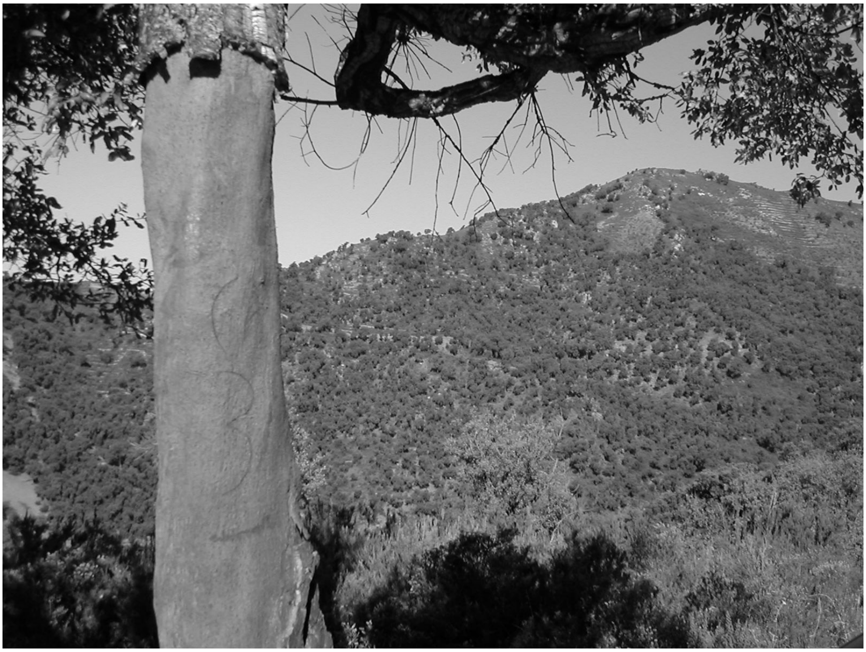
SITE PROFILE 8.1

Espadà, Calderona, and Pinet, Spain

This site profile presents several disjunct patches within a matrix of topographic and geologic features generally inappropriate for cork oak. Land abandonment is the main driving force shaping these cork oak landscapes, where most land is privately owned.

Geographic and biophysical description	Situated in eastern Spain, in the Valencia region, this profile includes Espadà (ca. 7,000 ha, Castelló), Calderona (ca. 700 ha, north Valencia), Pinet (ca. 70 ha, south Valencia), and some smaller patches. Precipitation ranges from 500 to 800 mm. The topography is rugged, and altitude ranges from 200 to 1,100 m over short distances. Substrates are red sandstones and siltstones and dolomites, with moderately acidic, sandy entisols (shallow) and xerochrepts (deeper). Accompanying vegetation includes maritime pine (*Pinus pinaster*), tree heath (*Erica arborea*), sage-leaved rockrose (*Cistus salviifolius*), holm oak (*Quercus ilex*), and many other shrubs, herbs, and vines.
Physiognomic description of cork oak woodlands and their landscapes, including woodland dynamics	Dense formations on slopes, with isolated individual trees colonizing old fields, within a matrix of shrublands and patches of maritime pine and Aleppo pine (*P. halepensis*) woodlands.
History of land uses, land tenure (and socioeconomic drivers), and current land uses, economic activities, and context	Extensive deforestation and terraced cultivation were prevalent until the 1960s, when land abandonment began and slowly progressed. Maritime pine plantations were created throughout the mid-20th century. Land holdings tend to be extremely small and are used for cork production in Espadà and, to a lesser extent, in Calderona. Espadà and Calderona are now recognized as natural parks. Pinet is in a recognized regional microreserve.
Disturbance regime (fires, pests, overgrazing)	Fires are frequent. No large herbivores are present. Human pressure is low at present.
Constraints and conflicts, protective measures, restoration actions, land use regulations, and relevant policies	Natural park protective measures for cork oak woodlands exist on paper. Small reforestation projects are undertaken, albeit with little success. Soil protection measures are applied after forest fires (Calderona). Subsidies for grazing and shrubland clearing exist, but there is little overall cohesion or integration of activities. Cork stripping takes place every 14–15 years for bottle stopper production in Espadà.

Current trends and prospects for the future	Oak populations are increasing at present by natural regeneration and colonization in Espadà and Calderona. Populations appear stable in Pinet. Cork production will persist in the future in the large patches. Recreation activities are becoming important, especially in Calderona and Espadà because of their proximity to the city of Valencia.
Source	Juli G. Pausas, Centro de Investigación sobre Desertificación of the Spanish National Research Council (CIDE, CSIC), Valencia, Spain, and V. Ramon Vallejo, Mediterranean Centre for Environmental Studies, Valencia, Spain



SITE PROFILE FIGURE 8.1. Espadà cork oak forest (eastern Spain).