Society for Ecological Restoration International

Cork Oak Woodlands on the Edge

Ecology, Adaptive Management, and Restoration

Edited by
James Aronson, João S. Pereira, and
Juli G. Pausas

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PREFACE

In the Society for Ecological Restoration International Island Press book series on ecological restoration, this book is the second to focus on cultural ecosystems but the first to consider cultural landscapes as such. Unlike *Old Fields: Dynamics and Restoration of Abandoned Farmland* (Cramer and Hobbs, editors), we focus on a particular geographic region: the western Mediterranean. As our title indicates, our subject includes restoration, amelioration, and long-term management of landscapes whose common feature is the extraordinary cork oak tree. This shared feature gives continuity and coherence to the book, but a surprisingly large range of contexts and issues will be covered, which should be of interest to a wide readership within and outside the Mediterranean region. The ancient landscapes and land use systems we present here are richly imbued with traditional and local ecological knowledge and the biophysical consequences of past human activities. In an increasingly homogeneous and globalized world, economically speaking, these landscapes and the socioeconomic systems built around cork oak seem exceptionally pertinent to study and ponder for all those searching for sustainable, equitable, and inspiring approaches to land management in rural areas with a strong cultural and natural heritage.

Genesis and Goals

Scientific research on cork oak and the ecosystems where it thrives is patchy. Results are scattered and usually limited to a single discipline, such as genetics, silviculture, or the physical properties of cork, and the few broad, interregional, multidisciplinary treatments are out of date. The present book is the result of a 4-year European Commission–funded research program (Conservation and Restoration of European Cork Oak Woodlands [CREOAK], QLKS-CT-2002-01594) that ran from 2002 to 2006. Consortium members included researchers and engineers from Portugal, Spain, France, Algeria, Morocco, and Bulgaria, experts in a wide range of fields, including ecology, economics, genetics, ecophysiology, and silviculture. In addition, foresters, scholars, land managers, and landowners from Iberia, North Africa, Italy, and Germany were asked to consult and review the group's research activities, and several of them have contributed to this book.

The general objective of CREOAK was to tackle scientific and management obstacles impeding the restoration, natural regeneration, and integrated management of cork oak woodlands and planting in new and appropriate areas of southern Europe. This is a book about ecosystems in cultural landscapes that evolved with history and economy, but it does not dwell solely on the delivery of ecosystem goods or services. The uniqueness of the consortium resides in its holistic, interdisciplinary approach, including disciplines ranging from molecular genetics, microbial ecology, and tree ecophysiology to forestry, economics, landscape ecology, conservation science, and cultural history.

As part of the CREOAK project, we have compiled a large bibliographic database on cork oak, cork oak woodlands, and cork, containing more than 1,100 items. We have also produced a precise, up-to-date digital map of cork oak distribution throughout the tree's natural distribution area. They are available on the Island Press Web site (www.islandpress.org/).

The present book provides a synthesis of the most up-to-date, practical information for anyone interested in the management of cork oak, and it is the first overview ever produced of the ecology, biogeography, and genetics of cork oak; socioeconomic settings and prospects; and restoration and active management strategies for natural cork oak woodlands and especially for the derived cultural systems. The book includes a large body of previously unpublished scientific information, with the goal of offering a timely synthesis, and novel elements to guide research programs and policy decisions concerning conservation, restoration, and sustainable landscape management.

The book is intended for a broad audience concerned with the future of cultural landscapes and low–energy input land use systems, be they for commercial, environmental, or social objectives. The book is also an example of a multidisciplinary and holistic way to study an ecosystem and manage, conserve, and restore it. We hope it can serve as guide for future studies of this kind in other socioecological systems.

Acknowledgments

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The editors and contributors also express their gratitude to the chapter reviewers: Luis Díaz Balteiro, Mario Díaz Esteban, Robin Duponnois, Helder Adegar Fonseca, Luis Gil, Lynn Huntsinger, Partap K. Khanna, José Manuel Lopes Cordeiro, Roselyne Lumaret, Manuel Madeira, Daniel Mousain, Rafael N. Navarro, Luis Ocaña Bueno, Jean Christophe Paoli, Rémy Petit, Claude Plassard, Tobias Plieninger, Fernando Pulido, Jean-Yves Puyo, Pedro Regato Pajares, Rosa Ros, Agustín Rubio, Santiago Sabaté, Alvaro Soto, Fernando Valladares, Ramon Vallejo, and Thomas Vanrensburg.

We dedicate this book to all the Mediterranean peoples and to the region itself, for the example it continues to provide that multicultural tolerance, conviviality, and cross-fertilization between cultures are possible and that cohabitation or reconciliation is possible between nonhuman and human processes, resulting in biodiversity, beauty, and productivity. Let us work together for a sustainable and desirable future.

James Aronson
João S. Pereira
Juli G. Pausas
October 2008

INTRODUCTION

When uncorking a bottle of a good wine or using any of the dozens of products made from natural cork, have you ever stopped to wonder where it comes from? If so, come with us now for a trip to the western Mediterranean, home of the cork oak (*Quercus suber*), one of the most extraordinary trees on Earth. Whether fully clothed, in its arm-thick, fissured, light gray bark, or with brick red trunks recently undressed by a once-a-decade harvest of its corky clothing, the tree has great beauty, mystery, and charm, as writers and travelers have long recounted. The landscapes where it occurs have the same charm or even more to those who know how to read them.

We travel to the western Mediterranean because today no cork oak tree grows naturally east of Tuscany, Liguria, and Sicily. And yet, four and a half millennia ago, fishing floats made of cork were used along the Nile River. Two and half millennia ago, natural cork was used throughout the eastern Mediterranean to make stoppers for earthenware jars and soles for shoes and sandals.

Theophrastus (372–285 BC) described the cork oak in detail, followed by Virgil, who had Aeneas (in *Aeneid* VII) mention that the head covering of the soldiers of ancient Latium was "stripped bark of the cork tree." Pliny the Elder (AD 23–79) also gave a detailed description of the cork tree and the use of its bark in his *Naturalis Historia* XVI. Horace (65–8 BC) wrote of wine casks being sealed with cork and Columella (AD 20–75) referred to cork used in the making of beehives. Plutarch related that Camillus used cork as a life buoy for swimming. Alexander the Great is said to have avoided drowning one day while crossing a turbulent river by clinging to a large piece of cork that happened to be nearby. From North Africa we know of very few written accounts, but it seems likely that cork oak was just as widely used, cared for, and appreciated as in southwestern Europe.

So, did the cork oak tree occur in Greece and further east millennia ago, or was cork simply imported as a product of commerce, accompanied by tales of the tree growing farther west? The second explanation is more plausible. As we shall learn in the opening chapters of this book, the natural distribution of cork oak trees in the western Mediterranean region but not in the east seems to have been constant at least since the last European ice age, which ended eleven thousand years ago.

What is the story in the western Mediterranean? What are the cork oak ecosystems, economy, and landscapes like there today? For the last few centuries, in many parts of the Iberian Peninsula, parts of France and Italy, and northwestern Africa, people have consistently protected, managed, and indeed cherished the cork oak tree, not only for its thick, useful bark but also for its shade, foliage, and wood; for its beauty, longevity, and cultural significance; and for the acorns. Some years at least, the acorns of cork oak provide a copious feast for domestic livestock, wildlife, and, in some areas in North Africa and Spain, for people. The associated flora and fauna are also valuable to people.

It is no wonder that the trees have impressed so many travelers, painters, and poets. For example, Cervantes mentioned the cork oak tree at least seventeen times, and Don Quixote often shelters in the hollow of a large cork oak tree. In many places, the local name of the tree was applied to towns and rural sites of note. In parts of southwestern Europe and northwestern Africa, the cork oak became emblematic of entire microregions. The Maamora *woodland* of northern Morocco is the largest single stand of cork oak found anywhere, but the Iberian Peninsula harbors the most cork oak woodlands, and Portugal is the country with the highest cork production in the world, followed by Spain. Cork oak management persists in Tunisia and Algeria. But what are the prospects for the future?

Our subject in this book is not only the tree but the forests, woodlands, and managed agroforestry systems of which cork oak is the major or one of the major components. Naturally, cork oak can occur in mixed forests, sharing the arboreal stratum with other evergreens and deciduous oaks, with pines and other conifers, and with a few other hardwoods. The cultural derivatives, which are open woodlands or parklands—sometimes called pseudosavannas or anthropogenic savannas—usually have just one or a few kinds of trees selectively maintained and carefully cultivated. These agroforestry systems are widely known by the generic Spanish term *dehesas*, but many other names exist. Some of them (e.g., the *montados* of Portugal and some of the *azaghar* in parts of Morocco) were specifically structured around cork oak. The trees spread over vast plains and hills and have been tended, pruned, selected, shaped, and sculpted by people for generations. Together these forests and woodlands form a certain type of landscape that has evolved over centuries as a special mix of nature and nurture that is the very heart and soul of the Mediterranean region. Indeed, the sheer beauty, mystery, and profound cultural significance of the cork oak and cork oak landscapes must not be overlooked at any point in our journey. For reasons related to past climate change and, especially, to the recolonization of territories after the quaternary glaciations, cork oak woodlands today are entirely limited to the western Mediterranean region, where they harbor remarkably high biodiversity, including many rare and endangered species. Like the olive tree (*Olea europaea*), they are emblematic of this region. Furthermore, all western Mediterranean landscapes involving the cork oak reflect a dynamic, co-evolutionary relationship between people and nature that is literally priceless but also extremely valuable as humanity seeks ways toward sustainable and desirable futures in a very crowded world.

Yet something has gone awry. Cultural cork oak woodlands are in trouble, as are many other cultural and natural ecosystems and traditional rural cultures and land uses around the world. Cork oak is not in any danger of extinction, but many of the ancient Mediterranean cultural landscapes dominated by this species may disappear unless something happens soon.

Over the millennia, cork oak woodlands have undergone numerous changes and fluctuations in land use type and intensity. The Middle Ages saw the regression of organized Roman agriculture; historians note the growing importance of agroforestry systems during this period and afterward, in both southern Europe and North Africa. In Iberia, for example, a driving force for this trend, especially in the fifteenth and sixteenth centuries, was the fact that the wool-based economy of long-distance *transhumance* gradually gave way to swine herding (Grove and Rackham 2001).

Moreover, although there was continuity and abundant cork oak in many places, such as the Alentejo (southern Portugal), as described by the German botanist and traveler H. F. Link at the end of the eighteenth century (Grove and Rackham 2001), and cork was an asset in Portuguese exports in medieval reports, most modern *montados* and *dehesas* are less than 150 years old. After the Peninsular War (1808–1814) and the ensuing political instability in Portugal and Spain, agriculture was so disorganized that it took until after the mid-nineteenth century to reconstitute the system (Picão 1903; Grove and Rackham 2001). But whereas the holm oak (*Quercus ilex*) *dehesa* systems may be one of the diehard survivors of the old European oak acorn swine-herding tradition, cork oak expanded more in the context of the emerging cork industrialization, first in Catalonia and then in Portugal.

At present, cork oak forests and open woodlands are undergoing an unprecedented rate of change. Many are aging and are unable to regenerate because of overgrazing. There is an ethical and philosophical question at issue. Modern societies change much faster than trees grow and develop. So does climate. Caring for trees is in part caring for an intergenerational legacy, and this is not very popular today. At the other extreme, a fast-growing population and clearly unsustainable increases in livestock numbers on the southern shores of the Mediterranean push North Africa to a new cycle of deforestation, leading to what can be called ecosystem and landscape collapse over large areas. Tragically, those areas include vast landscapes that were formerly diverse, productive, and beautiful, where people—in smaller numbers than live there today, of course—prospered in the shade of cork oak woodlands and other sustainable multipurpose, multiuser landscapes.

Although cork oak is well adapted to fire, bark stripping increases its susceptibility to wildfires, which are increasing in the Mediterranean region. Periodic plowing to eliminate shrub encroachment, reduce fire hazard, and facilitate grazing or cropping became widespread. The heavier machinery used in the second half of the twentieth century, as opposed to the mule- or horse-drawn plow of the past, has had equally disastrous results in terms of tree regeneration. Cork oak trees are also becoming increasingly vulnerable to pathogens and parasites, and plowing helps spread these pests. In sum, changing climate and biotic stress, changing land use patterns coupled to socioeconomic and demographic changes, and changing practices in the wine industry, where most fine cork is used as bottle stoppers—all place cork oak–dominated landscapes at high risk of socioecological collapse.

Since 1993, fluctuating and often inconsistent European Union agricultural policies have favored tree planting in the Euro-Mediterranean region but do not provide adequate measures to nurture or sustain the industries and landscapes based on those plantations. Managed ecosystems last as long as their products—tangible or intangible—are valued by society. In Europe, funding and subsidies for farming and forestry will almost certainly decline drastically in the very near future, with dramatic consequences for land use and occupation. The replanting of cork oak that occurred in the late twentieth century in the Iberian Peninsula does not amount to much in the context of the whole geographic range of the species, and very little has been done in terms of restoration or updating of management techniques in the face of changing climate and socioeconomic conditions.

In conclusion, cork oak woodlands can be viewed as a system on the edge of radical change and at clear risk of collapse, driven by rapid and turbulent socioeconomic and climatic changes. Cork production is still profitable in many places and motivates some protection, if not investment, in new stands. Furthermore, cork extraction barely interferes with ecosystem services delivered by the woodlands. As we shall see, tools and strategies are available to guide the conservation, restoration, and sustainable economic management of cork oak woodlands. But to do so intelligently, clear goals, strategies, tools, and criteria for evaluation of adaptive management will be needed. We hope that this book will contribute to efforts to define all of those and thus to ensure a sustainable and desirable future for cork oak woodlands.

What the Reader Will Find in This Book

In Part I we set the scene from ecological, genetic, ecological, and historical perspectives. In Part II we present the scientific state of the art for restoration, active management, and improvement of cork oak woodlands. In a short Part III we present a suite of restoration and management techniques related to best nursery and field practices. In Part IV we devote four chapters to a detailed examination of the recent past and current economic situations of these various systems and their prospects for the near future. In today's competitive, market-driven world, economics cannot be neglected or underestimated in the evaluation, management, conservation, restoration, and long-term planning for any kind of human-dominated system. However, adopting the approach of *total economic value*, we shall fully consider both nonmonetary and monetary values of the heritage landscapes and land use systems based on cork oak. It should be noted that throughout this book, monetary values are given in euros. At the time this book was ready to go to press (January 2009), the conversion rate was 1 euro = 1.3 U.S. dollars. In Part V we conclude the book with an overview of global drivers of change, including climate change, and some models and alternative future scenarios to help decision makers and resource and land managers in planning and constructing environmental and land management programs in western Mediterranean woodlands. There is also a chapter devoted to perspectives for and obstacles to cork oak woodland biodiversity conservation and the intimately related topic of ecosystem services, both in southwestern Europe and northwestern Africa.

We also include ten site profiles at various places throughout the book. They are invited pieces by local experts and are intended to provide a more in-depth vision of the range of cork oak woodland sites across the broad spectrum of biophysical, historical, and cultural contexts in the western Mediterranean. We hope students, managers, land owners, and decision makers will ponder and compare them in the search for integrated conservation, management, and restoration.

Moreover, sixteen color plates in the middle of the book illustrate the tree, the agro-silvopastoral systems, the different products, some of the resident biodiversity, and more.

Finally, at the end of the book we provide a glossary of terms that appear in italics the first time they appear in the text and a species index, with scientific and common names, as well as the general index.

We hope that this book will be of practical use to people in the western Mediterranean seeking ways to conserve, revitalize, rehabilitate, reinvigorate, and restore cork oak woodlands. What's more, it may be of use and interest elsewhere. The discussions, techniques, and examples provided throughout the book are applicable or relevant everywhere on the planet where traditionally managed landscapes and production systems are on the edge, under siege from land use changes driven by global climate change and related socioeconomic and political drivers in this tumultuous century.

PART I

Cork Oak Trees and Woodlands

In the first part of this book we set the scene as the first step in showing why, when, where, and how to better manage and restore natural and socioecological cork oak systems. These five chapters will give the reader insight into the origins of these systems as we review the main characteristics and origins of the tree and the systems in which it grows and prevails. Oaks live much longer than human beings. Therefore, each human generation inherits a series of landscapes whose origin and history may be lost at any turn in the trajectory of human societies. For example, the rapid urbanization of the late twentieth century changed the public perception of woodlands and the management of forests and agroforestry systems.

In Chapter 1 we address key questions about the tree, such as how it is equipped to survive the hot, dry summers of the Mediterranean climate and what may be the ecological importance of a thick, corky bark in such an environment. The trees we see today result from a long process of reiteration and ongoing adaptation of a genetic blueprint that determines form and function. The environment modulates the final result. For several millennia, people have also had a hand in selecting and modifying the result. It is a three-way process, involving plants, environment, and people, in which survival is a key point. The physiological and morphological characteristics of cork oak discussed in this chapter are essential to our understanding of adaptability and its limits. Note that in Parts II and III we further explore how cork oak copes with adversity (i.e., biotic and abiotic stresses) and review and compare available techniques for restoration and management presented in other parts of the book. Reproduction is left for these more specialized parts of the book (see Chapter 10).

In addition to knowing something about the cork oak tree—form and function—it is important to trace its phylogenetic origins. In Chapter 2, using a panoply of techniques, the authors present the biogeographic structure of the genetic variation of cork oak. We know today that individuals from the western and eastern parts of the Iberian Peninsula geographic range are genetically distinct. Different populations also differ in the likelihood of occurrence of cytoplasmic *introgression* by the evergreen holm oak, as revealed by the occurrence of *ilex–coccifera* DNA lineages in cork oak. This has ramifications for managers and restorationists, as will be discussed later in the book. Intriguingly, the role of introgression in the evolutionary history of cork oak is still unknown.

Cork oak woodlands have been remarkable components of Mediterranean landscapes for centuries. This is a result not only of the longevity and size of the trees but also of their usefulness to humans: from cork and firewood to a framework tree for agroforestry and silvopastoral systems. In the absence of human influence, in many cases, these woodlands would tend to be multispecies forests, mixed with other evergreen and deciduous oaks and pines. Especially important are the Iberian *montado* or *dehesa* and related land use systems in Italy, France, and North Africa, which are described in detail in Chapter 3 in a broad bioregional and historical fashion that has not been previously attempted to the best of our knowledge.

In Chapter 4 the history of the *montado* or *dehesa* is discussed at a finer resolution, based on a case study in a specific region, Evora, in southern Portugal. Clearly, Holocene history and humans have left a layered imprint on the structure and functioning of agroforestry systems, such as the *montados* or *dehesas*: How did they arise; in which socioeconomic contexts were they formed; and how did management practices change over time? All these factors condition contemporary ecosystem function and stability.

Finally, in Chapter 5, the unique physical and chemical properties that make cork an outstanding material for industry and as wine bottle stoppers are described, together with the corresponding biological and physical explanations. After characterizing cork as a material, the authors explain how it emerged as a major asset in regional economies in the past. Indeed, most cork oak woodlands would not exist if not for the economic value of cork. Used and traded for centuries, today it is the second most important nontimber forest product in the western Mediterranean. Chapter 16, in Part IV, is devoted to the cork industry and trade today and the prospects for the future.

After reading these chapters, which provide baseline knowledge of the cork oak tree and pertinent woodland systems, the reader will be ready to dig further into the conflicts, constraints, and options available so as to better understand the ancient woodlands that are now in a risky transition, all around the western Mediterranean, moving toward a very uncertain future.

João S. Pereira, Juli G. Pausas, and James Aronson

Chapter 1

The Tree

Juli G. Pausas, João S. Pereira, and James Aronson

To understand and appreciate it properly, we should first recognize that cork oak is in many ways a typical Mediterranean tree. It can survive adverse conditions of both human and nonhuman origin. It resists cutting, grazing, prolonged drought, and fire but not extreme cold. On suitable, deep soils and with adequate rainfall, the tree may reach up to 20 meters tall and live for several centuries. However, it has one feature that is extremely rare throughout the plant kingdom: an outer coat of insulation consisting of corky bark of continuous layers of *suberized* cells (see Chapter 5), up to 20 centimeters thick, that may have evolved as an adaptation to fire (see Color Plates 1a, 1b). What is more, the tree survives and grows new bark when the original bark on its trunk has been removed.

Like other evergreen Mediterranean oaks, cork oaks survive drought, thanks in part to their extensive and deep root systems. During a drought, the tree may protect crucial organs and tissues from dehydration by closing stomata on leaves, restricting water loss, and the tree's deep roots may tap water from the deeper soil or subsoil (Pereira et al. 2006). The deep root system of cork oak helps the tree maintain water status and xylem conductance above lethal levels throughout the summer drought period (see Chapter 6). In some cases, under severe drought, the tree may shed its leaves and resprout when the drought is over (in spring). During the early stages of plant life, there is a clear priority for root growth (Maroco et al. 2002). This early investment in roots, rather than in stems and foliage, may contribute to survival in the first years in drought-prone environments because seedling survival cannot be guaranteed before roots reach a soil depth that holds available water in summer. Symbiosis with *mycorrhizae* that live in or on the roots is also an important aid to cork oak seedlings in resisting drought, as described in Chapter 7.

Once aboveground parts begin to develop, cork oak has a unique leafing *phenology*. For an evergreen tree, it has short-lived foliage and a late flushing pattern (Pereira et al. 1987; Escudero et al. 1992). In fact, the average leaf life expectancy is only about 1 year, much shorter than in other evergreen oaks, such as Iberian holm oak (*Quercus rotundifolia* = *Q. ilex* subsp. *ballota*), whose leaves last 1–3 years, or the kermes oak (*Q. coccifera*), whose leaves can last 5–6 years. Leaf phenology is under strong genetic control, and the beginning of shoot flushing of populations belonging to different provenances but cultivated together can vary by as much as 4 weeks, from late March to late April.

Cork oak leaves themselves are also well designed to cope with an unpredictable climate. They are *sclerophyllous*, which means they are stiff, thick, and waxy (see Color Plate 1d). This is typical of many trees and shrubs that grow in regions with strong seasonal water deficits, such as the Mediterranean. They are also small, which allows efficient heat dissipation, thus partly avoiding overheating in the hot summer. In cork oak, as in many kinds of trees whose roots tap water from deep in the soil, supplementary cooling is often achieved through transpiration, as stomata open for some time on long summer days. Harmful leaf tissue dehydration is prevented by the highly efficient gradual closure of stomata (see Chapter 6, where other adaptations to drought are discussed in more detail).

Sclerophylly is often considered an adaptive trait of woody plants in seasonally dry climates, but it does not automatically confer greater tolerance to drought, and it may have evolved because it provides protection from many different types of stress (Read and Stokes 2006), such as poor mineral nutrition or attacks by defoliators (Salleo and Nardini 2000). In fact, sclerophylly implies a long leaf development time and fairly high ratio of carbon to nitrogen, both of which traits make the foliage undesirable to herbivores. Thus, most defoliators attacking cork oak feed on the young, tender leaves, before sclerophylly fully develops. This, in turn, conditions the nature of the web of organisms dependent on cork oak leaves.

Biogeography

Cork oak occurs in regions with average annual precipitation above 600 millimeters and average temperature near 15°C (Blanco et al. 1997). In Europe, it is low winter temperatures that appear to set the geographic distribution limits and most cork oak stands are located in areas below 800 meters in altitude. Cork oak leaves are less tolerant to frost (Larcher 2000; Garcia-Mozo et al. 2001) and to drought than those of the more widespread holm oak. In addition, whereas holm oak is indifferent to soil types, cork oak usually grows in acidic soils on granite, schist, or sandy substrates or, more rarely, in limestone-derived soils or in neutral soils overlying dolomitic bedrocks (Chapter 8).

Today cork oak occurs only in the western Mediterranean (Figure 1.1), from Morocco and the Iberian Peninsula to the western rim of the Italian peninsula. It also flourishes on all the large islands between the Iberian and Italian peninsulas, and in scattered parts of southern France and some coastal plains and hilly regions of Morocco, Algeria, and Tunisia. Total area today adds up more than 1.5 million hectares in Europe and about 1 million hectares in North Africa (Figure 1.2).

Figure 1.1 shows clearly that cork oak's current distribution is very patchy and disjunct, which suggests that much of what we see today is relictual. It is also possible that, over past centuries, humans intentionally introduced the tree to some islands and disjunct continental areas where it did not naturally occur. However, in Europe and especially in North Africa, cork oak areas have diminished in size and vitality because of overgrazing, which limits regeneration, and the expansion of plow agriculture in managed woodlands (see Chapter 3), the replacement of cork oak by pine and eucalyptus, imprudent cork stripping, and the extraction of tannins, which kills the tree. Wildfires may also be an important source of cork oak mortality, but mainly after cork extraction, when the lack of protection makes the tree susceptible to fire. In southwestern Spain and Portugal, however, the area of cork oak stands has increased in the last 200 years (Figure 1.2), despite some episodes of decline, such as that in the mid-twentieth century (see Chapter 20).

Phylogenetically, cork oak is considered to be closely related to three Asian species of oak, all of which are deciduous. These are the turkey oak (*Q. cerris*) of southwestern Asia, sawtooth oak (*Q. acutissima*) of eastern Asia, and Chinese cork oak (*Q. variabilis*) (Manos and Stanford 2001). Moreover, recent genetic studies suggest that the evolutionary origin of cork oak was quite a bit east of its current distribution area (Lumaret et al. 2005; see Chapter 2). Indeed, fossils of the ancestors of cork oak, in the *Q. sosnowsky* group, have been found in France, Poland, Romania, Bulgaria, Turkey, and Georgia (Bellarosa 2000). However, the origin of cork oak is still under debate (Magri et al. 2007).

In the last century, cork oak was artificially introduced in several countries outside the Mediterranean region, as an ornamental shade tree and botanical oddity or in hopes of generating local cork production. Reasonably good acclimatization has been attained in Bulgaria (Petrov and Genov 2004), New Zealand (Macarthur 1994), southern Australia, Chile, and California. However, none of these places has successfully developed a cork industry, even

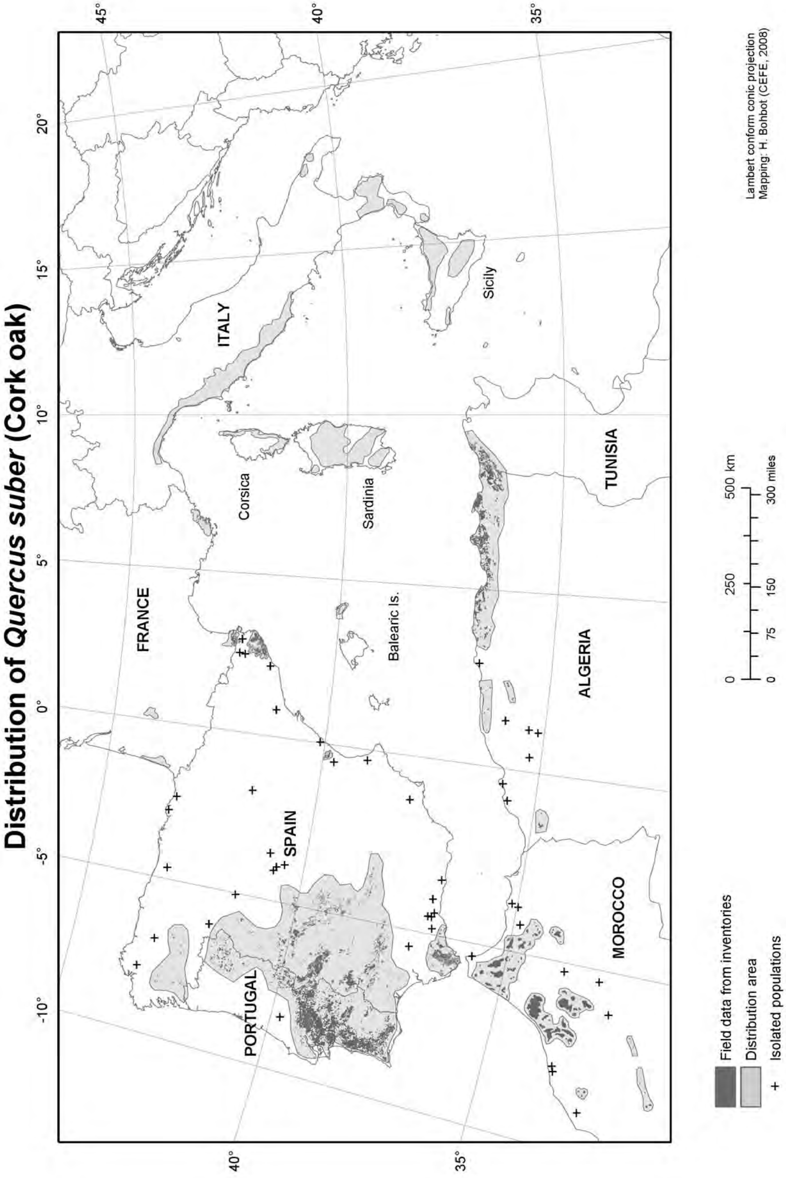


Figure 1.1. Current distribution of cork oak. (Algeria: Gaussen and Vernet 1958; Barry et al. 1974; Alcaraz 1977; Italy: modified from Bellarosa et al. 2003b; Morocco: Sbay et al. 2004; Portugal: DGF 2001; Spain: after www.inia.es, 2006; Tunisia: Khaldi 2004, after IFPN-DGF 1995)

though the tree grows reasonably well on appropriate soils. At present, despite ongoing tree decline, Portugal remains by far the largest producer of cork and has the largest industry, followed by Morocco, Italy (especially Sardinia), and Spain (see Chapter 5).

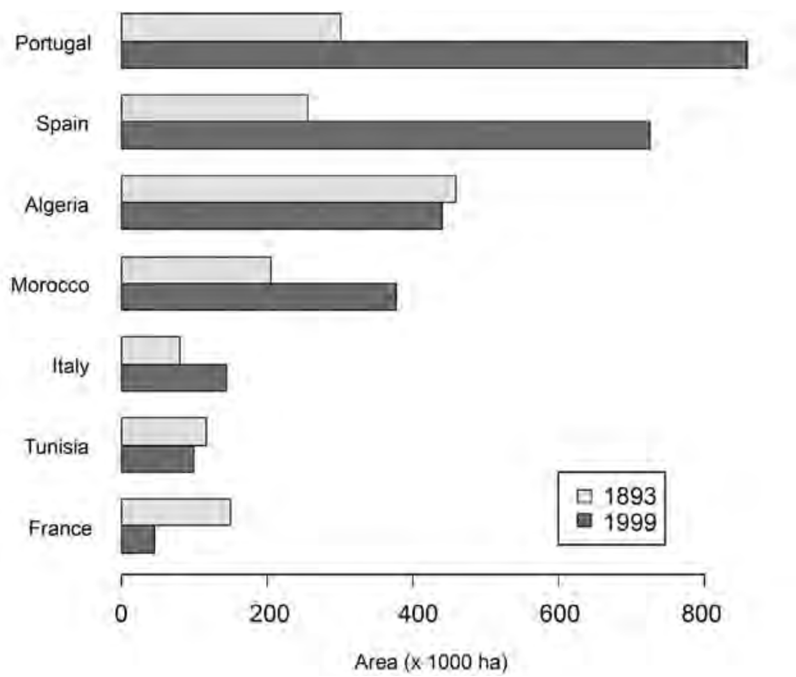


FIGURE 1.2. Areas covered by cork oak in different periods and countries. Light bars refer to areas covered in 1893 (Lamey 1893), except for that of Morocco, which refers to 1917 (Boissière 2005); dark bars indicate the area covered in 1999 (Instituto del Corcho, la Madera y el Carbón, Mérida, Spain).

Flowers and Fruits: The Ecological Role of Acorns

Like all other oaks, cork oak produces male and female (unisexual) flowers in different inflorescences on the same individual (monoecy). Staminate (male) flowers are born in catkins (see Color Plate 1e), whereas pistillate (female) flowers grow in small groups, generally no more than eight. Most trees have flowers of both sexes, with a high degree of self-incompatibility. The development of male and female flowers is asynchronous in each tree. The vector for pollination is wind, and the ovaries of fertilized flowers mature into acorns (i.e., dry fruits with a single seed).

Cork oaks produce both annual and biennial acorns. Annual acorns mature the same year as the flowers that produced them, whereas biennial acorns grow and mature in the autumn of the next year. The proportion of annual and biennial acorns varies spatially and temporally in response to environmental factors and meteorological conditions (Elena-Roselló et al. 1993; Díaz-Fernandez et al. 2004). This pattern contrasts with those of other closely related species, such as the turkey oak and the sawtooth oak, which exhibit consistently biennial fruit maturation (Schwarz 1964; Borgard and Nixon 2003), or the co-occurring holm oak, which offers annual acorns only. A biennial cycle appears to be related to short plant growth periods, limited by cold or drought.

Overall, cork oak acorn production is also quite variable in space and time. There is interannual variation in population-level reproduction, with occasional years of exceptional production followed by years with little or no production. In addition, within a population, in any given year, there can be very high variability of acorn production between individual trees for no obvious reason. In some cases, variations result from the different dominance of male or female flowers among trees. Other partial explanation can be found in tree density and relative aspect: Trees in high-density stands or on north-facing slopes tend to produce fewer acorns than isolated trees or trees located on south-facing slopes. Indeed, fruit production usually is favored in well-lit crowns because of the warmer temperatures and abundance of photosynthetic assimilates. Spring frosts also reduce acorn production.

Cork oak acorns are large (1.5 to 3 centimeters long; see Color Plates 1c, 1d), and dispersal is mediated mainly by birds, although squirrels and other animals may also play an important role (Pons and Pausas 2007a, 2007b, 2007c; see Chapter 10). Mice are major acorn predators, although they may also contribute to short-distance dispersal. Some insects, mainly weevils and moths, are also very important predispersal predators of acorn. In fact, acorns are important components of food webs in oak landscapes because they are a highly digestible, high-energy (lipids), low-protein food for many wildlife species, although secondary metabolites, such as tannins and phenolic compounds, may deter consumption by some animals.

Cork Harvest: Nature's Gift and Weakened Trees?

Each year, cork oak trees produce a new layer of suberized cells. This corky bark is not shed naturally, forming annual rings, as happens in wood. When enough cork has accumulated (e.g., up to 3 centimeters of cork in 9–12 years) harvesting may take place, as people learned thousands of years ago (see

Color Plate 2a). Cork stripping must be done when the *phellogen*, or cork cambium, is active, in late spring and early summer. If performed when the cork cambium is inactive (i.e., winter or autumn), stripping may kill the stem because the inner bark is removed through the vascular (woody) cambium. Unlike the phellogen, the vascular cambium does not regenerate once exposed.

Cork harvesting has attracted a lot of interest and inspired much admiration and curiosity. It is commonly believed that cork harvesting weakens the trees. However, this is not the result of the loss of the plant tissue per se; the trees can and do cope with such a loss of biomass, which usually amounts to only a few percent of the total biomass production by the tree on a yearly basis. In the short term, cork stripping may cause the tree water stress (Correia et al. 1992; Werner and Correia 1996), but it recovers rapidly. A major negative consequence of cork stripping may be the exposure of the unprotected surface area of the trunk to invasion by pathogens (e.g., *Hypoxylon mediterraneum*; see Chapter 9) and the temporary reduction of protection from fire damage.

Surviving Fire: The Ecological Role of Cork

Fire has exerted a selective evolutionary pressure on flora and vegetation in all Mediterranean climate regions worldwide, and many species have evolved strategies to survive periodic fires (Pausas et al. 2004b; Pausas and Verdú 2005). Indeed, cork oak is an excellent example. If not harvested, the cork layer on the tree becomes very thick and constitutes a protective barrier against fire, as cork is a good insulating material protecting stem tissues from scorching and burning (Pausas 1997).

Most oak species have the capacity to resprout after severe disturbances, including fire, and most of them resprout from basal buds. However, the thick and insulating bark of cork oak protects almost all the *epicormic* or stem-borne buds, permitting them to resprout quickly and effectively from stem and crown buds (Pausas 1997; see Color Plates 12a–12d). Therefore, after a fire has burned a cork oak forest, most trees will survive. Some young trees may suffer stem death from fire because the bark is still too thin to provide thermal protection for stem buds (Figure 1.3a), although individuals may survive because they resprout from basal buds. Trees with trunk diameters larger than about 12 centimeters often survive a fire and resprout from crown epicormic buds. In these cases, the larger the cork oak tree, the quicker it will regenerate, and for a given trunk diameter, the thicker the bark, the quicker the tree will recover (Figure 1.3b). However, old trees may fail to resprout and thus die after

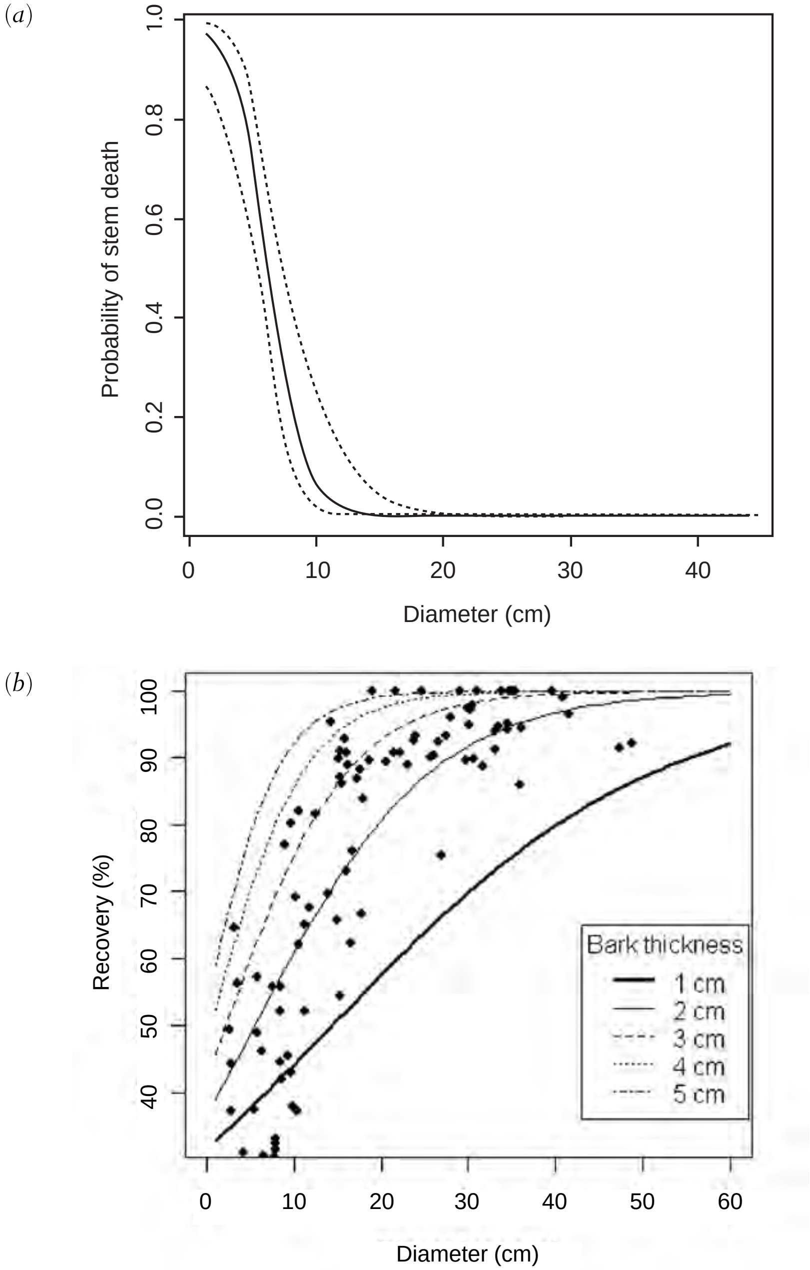


FIGURE 1.3. *(a)* Probability of postfire stem death mortality and *(b)* postfire height recovery from stem resprouts in cork oak. Height recovery is expressed as the percentage recovery from prefire height 1 year after the fire, in relation to stem diameter and bark thickness. (From Pausas 1997)

fire. Variations in bark thickness result not only from tree size or age but also from the number of years since the last bark stripping for cork production; indeed, when the bark has never been stripped (trees with virgin bark), the resprouting capacity tends to be higher (Moreira et al. 2007). Because bark thickness is a determining factor in postfire recovery, bark-stripping may reduce the ability of trees to recover from fires by reducing bud protection and thus increasing tree susceptibility to fire. Thus, recently harvested trees that have burnt resprout not from stem buds but rather from basal buds.

The evolution of an insulating corky bark is not exclusive to the cork oak; it also occurs in a few other trees growing in fire-prone ecosystems. For example, in southern Africa, the broad-leaved coral tree (*Erythrina latissima*, Fabaceae) and the spiked cabbage tree (*Cussonia spicata*, Araliaceae) both have thick, orange-colored corky barks. Also, the Australian forest she-oak (*Casuarina torulosa*, Casuarinaceae) has a vertically oriented corky bark. In these four unrelated species, as in the case of cork oak, the corky bark appears to be an adaptation for reducing fire damage. Thus, this unusual adaptation occurs in very different lineages and continents and could be considered a case of *convergent evolution*. Other trees living in fire-prone environments have also evolved thick barks composed of insulating structures different from cork, such as the thick bark of some *Pinus*, *Banksia*, or *Uapaca* species, or the thick peeling bark of some *Eucalyptus* and *Melaleuca* species from Australia. Nevertheless, there are some species with corky bark that do not occur in highly fire-prone ecosystems, at least currently, and their evolutionary history deserves further study. Examples of this group are found in the genus *Phellodendron* (from the Greek *phellos* = cork and *dendron* = tree; Rutaceae) and also include the so-called Chinese cork oak, both occurring in parts of Asia. The Chinese cork oak is related to the Mediterranean cork oak (Manos and Stanford 2001); its bark has been used for a variety of products (e.g., roofing), although the cork quality is much lower than that of cork oak.

Cork oak is undoubtedly one of the woody species best adapted to persist in recurrently burned ecosystems, and the postfire regeneration of cork oak–dominated landscapes is remarkably quick (Pausas 1997). It is the only European tree with the capacity to resprout from epicormic buds, high on the tree, a feature shared with many *Eucalyptus* species and the Canary Island pine (*Pinus canariensis*) but otherwise rare. The fact that cork oak can regenerate after fire from stem buds gives this species a competitive advantage over coexisting woody plants. For instance, a mixed cork oak and pine forest (see Chapter 13) may gradually be converted to cork oak woodland after repeated fires. Together with its socioeconomic importance and cultural significance (Chapters 13–16), this extraordinary resprouting capacity makes the cork oak a very good candidate for reforestation programs in fire-prone areas (Pausas et al. 2004a; Vallejo et al. 2006).

Framework Tree of Natural Ecosystems and Cultural Derivatives

Although we assume that cork oak is often favored by fire, most contemporary, monospecific cork oak stands clearly owe their existence to land use history and management decisions made by people. It seems likely that people have transported not only cork but also the live acorns of cork oak around the Mediterranean since prehistoric times. In its current range—the western half of the Mediterranean—we know that cork oak has been artificially protected, favored, and conserved not only for cork production but also for the valuable framework it provides in different agro-silvopastoral systems. Perhaps the best known and most extensive of these systems is the *dehesa* or *montado*, also known by other local names in different parts of southern Europe and Africa (see Chapter 3). This is an anthropogenic open woodland, used for grazing, sometimes cropped (e.g., cereals), but also used to obtain cork and acorns, as will be discussed at length in Chapters 3 and 4 (see Color Plates 4–7). In English, the term *oakery* is also used, as is *savanna*. But we prefer the simpler *woodland* or *open woodland* in this book, intended for a wide international, multilingual audience. It should be clear that *dehesas* or *montados* are different from most oak woodlands and savannas in that the structure and, to a large extent, the composition are maintained by a strong human input. In other parts of the world, people (e.g., Aborigines in Australia, Native Indians in America) also maintained other kinds of open woodlands and savannas, especially by periodically burning the understory (Jones 1969). But the intensity of the human input in *dehesas* or *montados* is much stronger than in most other woodlands and savannas.

Seminatural woodlands that are gradually becoming forests dominated by cork oak (as opposed to the *dehesa* or *montado* open woodlands) also occur and are used for cork extraction and for recreation (see Color Plate 8). Good examples occur in the Los Alcornocales Natural Park (see Site Profile 17.1) and in smaller patches of cork oak–dominated woodlands along the northeastern coast of the Iberian Peninsula (Pausas et al. 2006; Site Profile 8.1).

In Chapter 10 we discuss the implications of these two systems (*dehesa*-type open woodlands and forests) for oak regeneration. Another traditional system is the combination of cork oak with pines, found in Portugal, providing cork, acorns, and wood (in the case of maritime pine, *Pinus pinaster*), or all of these plus edible pine nuts when stone pine (*Pinus pinea*) is used.

Chapter 13, in Part IV of the book, is devoted to a discussion of this system from an economic perspective.

As mentioned at the outset of this chapter, the unique features of cork oak are adaptive traits that evolved in the context of Mediterranean climate and have progressively been put to use by people. In that sense, cork oak can be considered not only an emblematic but also an archetypal Mediterranean plant. Along with the holm oak and the olive tree it is also an ecologically and economically emblematic tree for Mediterranean landscapes, where people and nature have interacted for millennia.

The contribution of cork oak to sciences extends far beyond the Mediterranean basin. For example, the term *cell* was coined by Robert Hooke (1665) as part of his anatomical investigations of cork. We argue that it, and the landscapes in which it forms an important part of the framework, can also contribute greatly to environmental science and the practice of adaptive ecosystem and landscape management in today's rapidly changing world.

Having presented a brief profile of the tree itself and the biophysical and socioeconomic matrix in which it lives, we shall explore the current state of knowledge and the art relevant to cork oak woodlands. Today, cork oak woodlands are threatened by multiple stresses, both anthropogenic and natural, and a study of its alternative future will help us understand—and perhaps influence—the future of the entire Mediterranean basin. That study should also provide food for thought for students throughout the world. As the next step in setting the scene, Chapter 2 presents an up-to-date overview of the origin and genetic variability of cork oak, resulting from nature and nurture.

SITE PROFILE 1.1

Akfadou, Algeria

This first site profile, of the ten presented in this book, is just one example among many of the cork oak woodlands to be found in the western Mediterranean, resulting from the three-way interaction of plants, environment, and people. It is illustrative of the menace hanging over these woodlands, especially those that enjoy no conservation status or protection by the national government.

Geographic and biophysical description

Akfadou is located about 160 km east of Algiers and 20 km inland from the Mediterranean Sea, on the border between the departments of Tizi-ouzou and Bejaia (36°41′N; 04°27′E), in the Kabylie region (Site Profile Figure 1.1). The woodland here covers about 11,000 ha, which represents 18% of Algeria's total deciduous oak woodlands. This formation occurs from 800 to 1,646 m above sea level, on rugged mountain slopes. The climate is humid, with a maritime influence, and annual rainfall is 1,000–1,600 mm/year. It is a mixed oak woodland with Algerian oak (*Quercus canariensis*) (45%), afares oak (*Q. afares*) (15%), and cork oak (15%), as well as alder (*Alnus glutinosa*), yew (*Taxus baccata*), holly (*Ilex aquifolium*), Bosnian maple (*Acer obtusatum*), mountain ash (*Sorbus torminalis*), wild cherry (*Cerasus avium*), and many shrubs and herbaceous species.

Physiognomic description of cork oak woodlands and their landscapes, including woodland dynamics

Open and degraded formations are found on northeast- and southwest-facing slopes of 15–45° inclination. Aleppo pine (*Pinus halepensis*) progressively colonizes degraded oak stands. Associated vegetation in degraded facies includes strawberry tree (*Arbutus unedo*), spiny broom (*Calycotome spinosa*), sage-leaved rockrose (*Cistus salviifolius*), and elm leaf blackberry (*Rubus ulmifolius*), as well as the perennial bromegrass *Brachypodium sylvaticum*.

History of land uses, land tenure (and socioeconomic drivers), and current land uses, economic activities, and context

Extensive exploitation occurred after French colonization in 1870, especially during World War II. Timber exploitation, mainly of Algerian oak and afares oak, was estimated at 800–1,500 trees/ha, which gives some idea of the former density of these woodlands. Some native and exotic species were introduced from 1890 to 1948, including Atlas cedar (*Cedrus atlantica*), Algerian fir (*Abies numidica*), and European chestnut (*Castanea sativa*). Grazing is the major land use, and in recent years there has been intensive tree cutting.

Disturbance regime (fires, pests, overgrazing)	High human pressure is present and has increased in the last two decades (e.g., fires, grazing, tree cutting). Decline in cork oak due to bark beetle (*Platypus cylindrus*) has also increased.
Constraints and conflicts, protective measures, restoration actions, land use regulations, and relevant policies	No protection measure exists for cork oak or other oak woodlands in Algeria. Intense tree cutting has occurred in recent years. Reforestation, restoration, and adaptive management projects are absent to date but sorely needed.
Current trends and prospects for the future	Although resprouting is observed in some burned cork oak stands, overall degradation is the trend. To initiate protection measures, steps are under way to classify the Akfadou State Forest as a regional nature park.
Source	Mahand Messaoudène, Forest Research Unit of the National Institute of Forest Research, Yakouren, Algeria, and Hachemi Merouani, Faculty of Agronomy (Instituto Superior de Agronomia) of the Technical University of Lisbon, Portugal

Site Profile Figure 1.1. Akfadou, Department of Tizi-ouzou.

Chapter 2

Origin and Genetic Variability

Roselyne Lumaret, Unai López de Heredia, and Alvaro Soto

Having described the tree, we may now ask, where does it come from? And how did evolutionary forces and past climate changes forge this unique tree from the matrix of the genus *Quercus*? Today's molecular genetics gives us the tools to unravel this puzzle.

Variation and Introgression

Cork oak is a strictly western Mediterranean oak species (Figure 1.1). Its geographic genetic structure has been studied by using molecular markers, mainly *isozymes* (encoded by the nuclear genome) and chloroplast DNA (cpDNA). Range-wide isozyme studies have been conducted in order to assess the overall diversity of the species and how it is structured geographically. Differences in isozyme patterns allowed Toumi and Lumaret (1998) to distinguish two *population* groups. The first was made up mostly of populations from the Iberian Peninsula and part of France (Landes and Roussillon). The second area included populations from Provence (southeastern France), continental Italy, Corsica, Sardinia, Sicily, North Africa, and, more strikingly, one population from Galicia (northwestern Spain), very distant geographically from the others. Low genetic differentiation was observed between populations within each area. The extensive analysis of central and marginal cork oak populations of Iberia (Jiménez et al. 1999) shows that the highest values of genetic diversity and *heterozygosity* corresponded to populations located in southwestern Spain, whereas the lowest values were observed in marginal populations from eastern Iberia.

The use of other nuclear markers with a more complete coverage of the genome, such as *amplified fragment length polymorphism* (AFLP), revealed three groups of related populations, located mostly in distinct geographic areas: western Iberia, Morocco and eastern Iberia, and Italy and Provence (Lopes and Parker 2000). Although the eastern Spanish populations were underrepresented, they showed contributions from Portuguese and Moroccan cork oaks, interpreted by the authors as the product of postglacial recolonization. Alternatively, this pattern could be the product of intense contemporary gene flow between populations in each geographic area. Consistently, in their very recent wide-ranging analysis of AFLP variation in cork oak, López de Heredia et al. (2007b) obtained approximately the same three geographic groups of individuals. These groups were markedly differentiated genetically.

In addition to the analysis of nuclear genetic variation, several independent and complementary studies on cpDNA variation were conducted and revealed a clear geographic pattern for cork oak populations (Figure 2.1). Variants of cpDNA (*chlorotypes*), belonging to two very distant lineages, have been identified (Belahbib et al. 2001; Jiménez et al. 2004; Lumaret et al. 2005; López de Heredia et al. 2007a, 2007b). Lineage *suber* is the most widely distributed, and it is composed of four to eight chlorotypes depending on the technique used (Jiménez et al. 2004; Lumaret et al. 2005). Con-

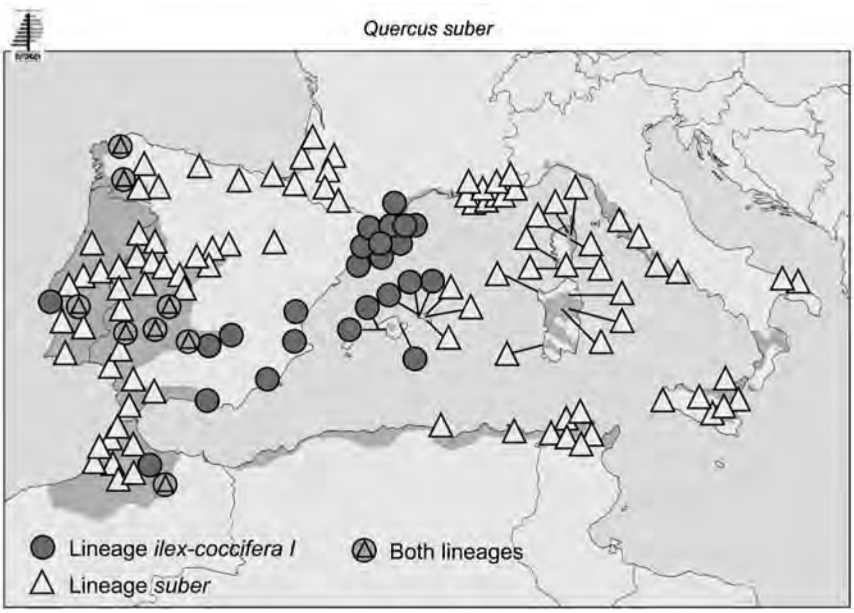


FIGURE 2.1. Distribution of lineages based on cpDNA in cork oak populations. (Distribution map of cork oak, European Forest Genetic Resources Programme, 2004, www.euforgen.org.)

versely, nineteen chlorotypes belong to a very different lineage called *ilex–coccifera*. A large majority of holm oaks and kermes oaks from Morocco, Iberia, the Balearic Islands, and southern France are also characterized by haplotypes of this lineage, hence its name.

Cork oak populations from the current main range (western Iberia and Morocco) show a chlorotype from lineage *suber*, massively distributed in that area (Belahbib et al. 2001; Jiménez et al. 2004; Lumaret et al. 2005; López de Heredia et al. 2007a). The eastern range of the species is occupied by groups of chlorotypes from lineage *suber* but distinct from those of the western range (Jiménez et al. 2004; López de Heredia et al. 2005; Lumaret et al. 2005). The disjunct eastern area that comprises Algeria, Tunisia, Sicily, continental Italy, Provence, Sardinia, and Corsica presents higher cpDNA diversity than the western area (Morocco, Iberia, and southwestern France).

The occurrence of *ilex–coccifera* lineage in cork oak has been explained as a result of cytoplasmic introgression from holm oak. Introgression is defined as gene exchange between species mediated by hybridization and backcrossing to a parental species (Rieseberg and Carney 1998). Interspecific barriers to gene flow are diffuse in oaks, promoting natural hybridization events. Actually, hybrid and morphologically intermediate individuals between evergreen oak species occur sympatrically in several areas. Therefore, cork oak is able to hybridize with holm oak (Camus 1938) but also with Turkey oak (Bellarosa et al. 1996) and, in North Africa, with Algerian oak (*Quercus canariensis*) (Mir et al. 2006).

The prevalent direction of hybridization with holm oak is for cork oak to act preferentially as a pollen donor (Boavida et al. 2001). In angiosperms, chloroplasts are mostly maternally inherited; accordingly, cork oak–holm oak hybrids almost always carry an *ilex* (holm oak) chloroplast. Through subsequent backcrosses of the fertile hybrids with cork oak, the *ilex* cpDNA would become fixed in the population within a few generations. However, hybridization events seem to be infrequent because phenological overlapping does not occur or is reduced between the species (Elena-Roselló et al. 1992). An ancient hybridization of cork oak in the central area may explain the complete displacement of the *suber* lineage (López de Heredia et al. 2005; Lumaret et al. 2005). Moreover, even if cork oak shares the same lineage with holm oak in sympatric populations, the chlorotype is not necessarily the same in both species, suggesting the occurrence of distinct mutation events in the cpDNA of each species or of independent posthybridization migration processes.

The question arises whether this cytoplasmic introgression is reflected somehow in the nuclear DNA. If the hypothesis of ancient hybridizations is correct, then nuclear contribution of holm oak into cork oak may be diluted by successive backcrossing. By using diagnostic *allozymes* in mixed stands, Toumi and Lumaret (1998) identified very limited introgression. Further analysis, based on the use of *microsatellite* markers, may clarify the role of introgression in the evolutionary history of cork oak.

Origins and Migration Routes

In recent decades, the geographic location of the center of origin of cork oak has been the subject of controversy. Some authors have suggested that cork oak may have originated in the Iberian Peninsula, where the species has its present main range. This assessment was based on various different arguments, including geobotanical studies (Sauvage 1961), and on allozyme variation in the whole cork oak range, which revealed a substantially higher genetic diversity in the Iberian populations than in those from North Africa, Italy, and Provence (France) (Toumi and Lumaret 1998). More recently, Magri et al. (2007) defended this same position concerning geographic origins of cork oak, based on the partial matching of chloroplast microsatellite variation and the paleogeographic history of the western Mediterranean.

However, fossil records from oak species of subgenus *Cerris*, dating to the Tertiary, were found on the Balkan Peninsula, and several other authors consider that cork oak probably first appeared either on the Balkan Peninsula or in the Caucasus region (Palamarev 1989; Bellarosa 2000; Bellarosa et al. 2005 and references therein). According to this hypothesis, cork oak would have expanded westward during the late Miocene to become widespread throughout the Mediterranean Basin during the Pliocene, along with several other Mediterranean oak species of subgenus *Cerris*. But how did Pleistocene glacial periods affect cork oak's current distribution and genetic diversity? Glacial periods of extreme cold and arid conditions forced the tree species to search for refugia in areas of softer climate, and they expanded their range in the warmer interglacial periods (Huntley and Birks 1983). The Mediterranean islands and some continental areas at midaltitudes could have served as refugia for cork oak since the Pliocene (Carrión et al. 2000; López de Heredia et al. 2005). Decisive evidence about cork oak's origin was obtained recently through analysis of range-wide cpDNA variation in *suber* lineage populations and in several closely related oak species of the *cerris* group, more particularly the Turkey oak and Macedonian oak (*Quercus trojana*) (Lumaret et al. 2005). *Phylogeographic* surveys were used to reconstruct the evolutionary history of cork oak. Results showed a clear phylogeographic pattern of three groups, corresponding to potential glacial refugia located in Italy, North Africa, and Iberia (Figure 2.2). Examination of present geographic distribution of chlorotypes showed that those most closely related to the other oak species (and which are therefore considered ancestral molecular patterns) were found exclusively in the eastern part of the present cork oak distribution. In addition, the main clusters of chlorotypes, which were differentiated successively from these ancestral patterns, were identified in geographic areas distributed from east to west (i.e., continental and insular Italy, the eastern and central parts of North Africa, the western part of North Africa, and the Iberian Peninsula), suggesting that migration and genetic differentiation occurred initially in that direction. Moreover, substantial genetic differentiation was observed between the chlorotype clusters, which is consistent with the existence of distinct ice age refugia in southern Italian Peninsula, North

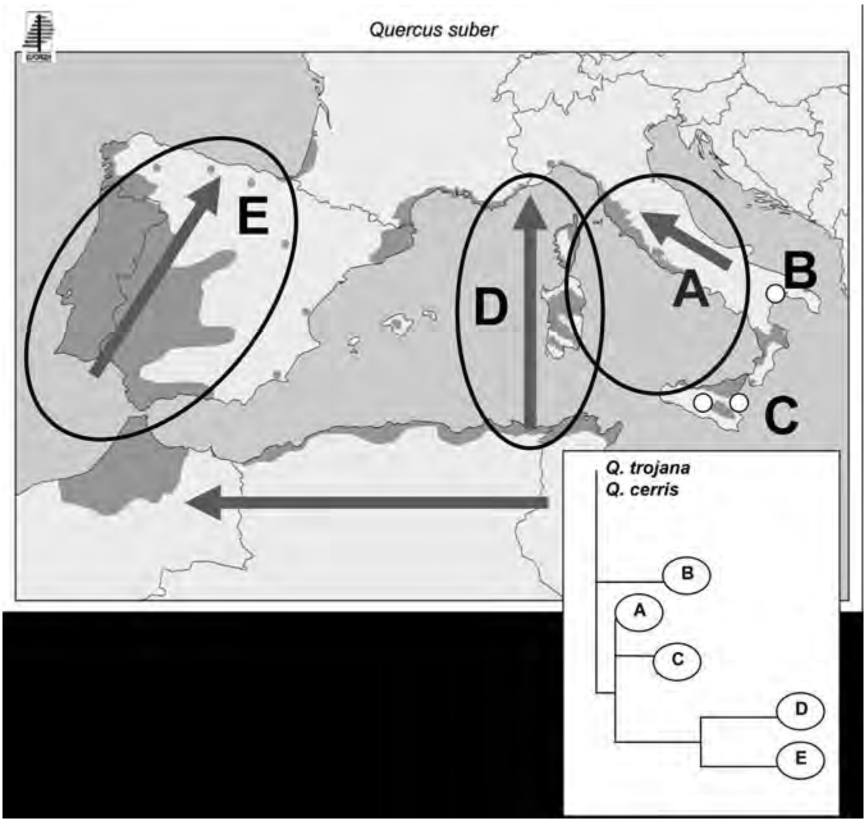


FIGURE 2.2. Geographic distribution and phylogeny of the 5 *suber* lineage chlorotypes identified in cork oak using a polymerase chain reaction–restriction fragment length polymorphism analysis over 7 chloroplast DNA fragments. (Distribution map of cork oak, European Forest Genetic Resources Programme, 2004, www.euforgen.org.

Africa, and southwestern and eastern Iberian Peninsula. These results constitute additional evidence of an eastern origin for cork oak, with the Iberian Peninsula as a secondary center of dispersal for the species. An additional striking point is that the unique chlorotype observed in Tunisia and Algeria was also identified in Sardinia, Corsica, and Provence, suggesting a successful contribution of a North African refugium to the recolonization of this part of Europe after the last glaciations, in opposition to what was reported for holm oak, which was shown to possess specific chlorotypes in North Africa (Lumaret et al. 2002). Interestingly, all the populations analyzed from southwestern France possess the same chlorotype as that identified in the western part of Iberia. This result clearly indicates a western Iberian origin for that French material, which is also characterized by an exclusive biennial maturation type cycle and which was originally described as a distinct species, *Quercus occidentalis* (Gay 1857). On the basis of several genetic studies (Toumi and Lumaret 1998; Lumaret et al. 2005) and as suggested previously by Bellarosa (2000), it should rather be considered as an ecotype of cork oak growing at the northern, coolest limits of the species' distribution range. Moreover, the chlorotype observed predominantly in continental Italy and in Sicily was identified in a few populations located in Sardinia and Corsica. This situation might reflect the occurrence of rare natural events of long-distance dispersal from several geographic sources localized in close islands or continental areas. López de Heredia et al. (2005) suggested the possibility of long-distance dispersal events to explain the sharing of several chlorotypes by populations located in eastern Spain and in the Balearic Islands, and of a rare chlorotype by cork oak populations located in Minorca and Sardinia, respectively. In addition to paleogeographic and climatic events and to animal transport, the possibility of intentional acorn transport by people to extend cork oak areas for economic purposes cannot be ruled out, and its impact on the geographic patterns of cork oak genetic variation should not be underestimated.

Unresolved Questions

Overall, as compared with the other Mediterranean oak species analyzed over their entire range with the same genetic nuclear and cytoplasmic markers, cork oak possesses low genetic diversity. Regarding allozyme variation, very few rare or local alleles were observed in cork oak populations. According to some authors, this result should be attributed to bottleneck and genetic drift effects, amplified by selection and propagation by humans, in conjunction with the production of cork (Toumi and Lumaret 1998). However, and taking into account that the main expansion of cork use took place as late as eighteenth and nineteenth centuries, other authors considered that the low nuclear genetic diversity of cork oak simply reflected recent expansion from glacial refugia and the short time available for differentiation to have taken place subsequently (Jiménez et al. 1999). In fact, both outward expansion from refugia and human selection may have simultaneously contributed to low genetic diversity. However, several other hypotheses, related to the distinct *autecology* and reproductive behavior of these oak species (Soto et al. 2007), cannot be ruled out.

An additional point of interest is the absence of cork oak populations possessing *ilex–coccifera* chlorotypes in the eastern range of the species, even though some interspecific hybrids and a few introgressed individuals were observed locally in that area (López de Heredia et al. 2005; Bellarosa et al. 2005; Lumaret et al. 2005). The possibility that backcrosses occur preferentially with holm oak has been suggested to explain the current situation (Lumaret et al. 2005). As already stated, extensive population genetic surveys with appropriate markers (e.g., highly polymorphic nuclear microsatellites) would help in assessing the importance and geographic distribution of holm oak genome introgression into cork oak. In addition, the putative functional effects of nuclear genetic introgression should be determined by combining genetic and physiological analysis in the same plant material, as was tested recently in a preliminary study based on *isoprenoid* emissions in mixed stands compared for genetic introgression between cork oak and holm oak (Staudt et al. 2004).

Implications for Conservation of Cork Oak Genetic Resources

In recent years, delimitation of cork oak provenance regions has been assessed to comply with European legislation. This process is based on a combination of genetic variation for adaptive traits, mostly morphology and phenology, which are related to climate characteristics, and of more neutral genetic characters, either nuclear (allozymes and microsatellites) or cytoplasmic (e.g., cpDNA). In addition, genetic information about the several distinct postglacial colonizing routes and the precise geographic distribution of cytoplasmically introgressed cork oak populations was used to refine provenance region arrangement. This delimitation of provenance regions should favor genetic resource conservation by preventing inappropriate cork oak material (acorn) exchange between regions. More generally, material replacement should occur only between genetically related populations, whatever their original country, rather than from more distant populations from the same country, which may derive from distinct phylogenetic origins and therefore may have very inappropriate adaptive abilities. Such a recommendation assumes that conservation strategies are established at the European level. In addition, as was reported for Spain by Jiménez and Gil (2000) and for France by Lumaret (2003), to favor appropriate use of genetic resources in the several European countries involved in cork oak management, stands selected for acorn collection have been identified in each provenance region. A catalogue of selected stands was established on the basis of ecological and genetic information and is updated periodically.

To sum up, the origin and early migration routes of cork oak are now clarified, and the results based on molecular genetic variation support Bellarosa et al.'s (2003a, 2005) assessment. In the near future, a better evaluation of cork oak nuclear introgression by the holm oak genome is expected. This should help clarify the functional effect of this introgression. However, recent improvements in scientific knowledge on cork oak genetic structure and phylogeography already constitute very useful tools to develop appropriate conservation and management strategies. The next chapter introduces the wide spectrum of cork oak woodlands and the major types of silvopastoral systems that people have crafted over the centuries.

Chapter 3

Open Woodlands: A Diversity of Uses (and Overuses)

Miguel Bugalho, Tobias Plieninger, James Aronson, Mohammed Ellatifi, and David Gomes Crespo

In the two preceding chapters, we learned how the cork oak tree has been evolutionarily shaped by the Mediterranean climate, periodic fires, and long-distance migration over long periods of time. Most ecosystems where cork oak occurs today are in fact agro-silvopastoral systems, where people have manipulated the genetics and the habitat of the tree through artificial selection and simplified the original plant communities to generate greater supplies and a wider range of goods and services. Thus, in addition to the dense mixed oak woodlands, wherein cork and other natural products are exploited without major structural modification, there are also artificially opened cork oak woodlands, where all but the most valuable trees have been removed. There, cork oak appears as part of managed, cultural land use systems, wherein a diversity of uses and sometimes overuses (e.g., overgrazing, overharvesting of acorns, wood cutting, and uncontrolled cork harvesting) occur.

In this chapter we introduce the major types of silvopastoral systems that people have developed around cork oak, mentioning some regional and historical differences. We also describe a worrisome trend: Although these systems represent an important cultural heritage and traditionally provided a plethora of goods and services in a difficult and unpredictable bioclimatic region, today their future looks grim. Almost universally, natural regeneration in these managed systems is failing because of overuses of the system, and the market outlets are decreasing, a problem we will learn about in more detail in Chapters 4 and 5.

A System with Different Names

Open cork oak woodlands, structurally similar to savannas, occur in Sardinia, Sicily, Corsica, Mallorca, Morocco, Tunisia, and Algeria and especially, throughout southwestern Spain and southern Portugal. They are also found in northeastern Spain, southern France, and parts of continental Italy until the mid-twentieth century. But in those regions, they are now mostly abandoned and are reverting to dense woodlands. In northwestern Africa, there has also been a marked loss of open woodlands over the past half century (Charco 1999), mainly because of overuse, which also prevents natural regeneration.

The best-known examples of the surviving managed open cork oak woodlands are found on the Iberian Peninsula, where they are known as *montados* in Portugal and *dehesas* in Spain. These agro-silvopastoral or silvopastoral systems are characterized by a number of adult trees ranging from twenty (or less, in degraded areas) to sixty (in younger stands) trees per hectare, with a mean number of forty adult trees per hectare (see Color Plates 4–6 and 7a). Similar land use systems occur in Morocco, Algeria, and Tunisia, involving cork oak, other oaks, various conifers at higher altitudes, and various fruit trees, such as pear (*Pyrus communis*), often grafted onto wild pear (*Pyrus bourgaeana*), carob (*Ceratonia siliqua*), olive and, formerly, in northeastern Morocco, argan (*Argania spinosa*) (see Color Plate 7b). In Sardinia, these systems are known as *pascolo arbolato* (meaning "wooded grasslands," in Italian), and other regional names are used in Corsica, Mallorca, and Minorca to describe variants of the same general system. In some parts of North Africa, they are known by the Berber term *azaghar*, which we will discuss in more detail. In general, the various terms are used interchangeably to refer to either the silvopastoral system or the resulting savanna-like landscape characterized by scattered holm and cork oak stands and an understory of grassland of value to livestock, occasional cereal crops, and open shrublands (Díaz et al. 1997) (Box 3.1).

According to several sources, the *dehesa* originates in the late Latin word *deffensa* (Cabo Alonso 1978; García-Martín 1992), which, in the context of the Castilian medieval transhumance (thirteenth century), referred to an enclosed pasture protected from grazing by migratory sheep flocks (Klein 1920) and also maintained for feeding and resting of laboring cattle (Langston 1998). Other sources report that the word *dehesa* may come from the Arabic word *dehsa* (pl. *Ad'has*) (Arabic Language Dictionary 2000), designating a landscape that is dominated by neither the dark green color of a dense forest nor the brownish color of a desert (Ellatifi 2005, 2008). However, the most accepted origin of the term *dehesa* seems to be that of "private land," inde-

Box 3.1. Plant Composition

Miguel Bugalho, Tobias Plieninger, James Aronson, Mohammed Ellatifi, and David Gomes Crespo

Cork oak woodlands vary in plant species composition. Both cork oak and holm oak can form homogeneous stands or occur in co-domination with other oaks, such as the Portuguese oak (*Quercus faginea*), the Pyrenean oak (*Quercus pyrenaica*), and the English oak (*Quercus robur*), or conifers, such as the stone pine or maritime pine (*Pinus pinaster*), or even wild olive trees (*Olea europaea* var. *sylvestris*). Trees such as the narrow-leaved ash (*Fraxinus angustifolia*), alder (*Alnus* spp.), willow (*Salix* spp.), or poplar (*Populus* spp.) occur mainly in riparian gallery forest, sometimes mixed with shrubs. Common shrub species include many kinds of rockrose and also, depending on soil and climate conditions, broom (*Cytisus* spp. and *Retama* spp.), lavender (*Lavandula* spp.), rosemary (*Rosmarinus* spp.), myrtle (*Myrtus* spp.), gorse (*Ulex* spp.), and others. Other tree or tall shrub species include tree heath (*Erica arborea*), hawthorn (*Crataegus monogyna*), strawberry tree(*Arbutus unedo*), laurustinus (*Viburnum tinus*), mastic (*Pistacia lentiscus*), and, in North Africa and some coastal areas in the southern Iberian Peninsula, the Mediterranean fan palm (*Chamaerops humilis*). In the Maamora forest, northwestern Morocco, there is what appears to be an endemic pear (*Pyrus bourgaeana* subsp. *mamorensis*), part of the interesting and complex wild pear that is widespread but now quite rare in southern Iberia and northwestern Africa. Grassland patches include a great diversity of species of grasses (Poaceae), as well as Asteraceae, Fabaceae, Geraniaceae, Brassicaceae, Plantaginaceae, Apiaceae, Liliaceae, Ranunculaceae, Boraginaceae, and other families. More than 135 herb and grass species per 0.1-hectare plot have been recorded in grasslands of a Spanish cork oak woodland (Díaz-Villa et al. 2003).

pendent of vegetation type (Vicente and Alés 2006). This is in agreement with the Portuguese term *montado*, which refers to the medieval tax called *montaticum* in Latin, *montatus* in low Latin, *montadigo* or *montadêgo* in ancient Portuguese, and *montazgo* in medieval Spanish. This tax was to be paid per head of livestock for the use of a particular area for grazing in different regions of Iberian Peninsula (Coelho 2005a; see Chapter 4).

By contrast, the Berber word *azaghar* probably derives from the verb *zaghara*, meaning "withdraw" or "take out." In the case of *azaghar*, the term refers to an area of land "taken out" from a closed forest, to be managed and used as a silvopastoral system, and whose size was determined on the basis of the number of livestock held in the region (Ellatifi 2005, 2008; see Site Profile 3.1 at the end of this chapter). For convenience and simplicity, and unless otherwise specified, we will use the term "open cork oak woodlands" in this chapter to refer to all these anthropogenic savannas and, by extension, to the landscapes of which they form the major part.

One System, Multiple Land Uses

Open cork oak woodlands are diverse, heterogeneous, and well adapted to the unpredictability of Mediterranean climate. Never highly productive, the system was managed for multiple goods and services, including pasture and browse for livestock, cereal cropping, firewood, charcoal, fruits, oils, berries, mushrooms, and, especially in the last two centuries, cork. Wild animals of many kinds provided game for food and recreational hunting. Given that these are cultural, anthropogenic systems, the socioeconomic aspects are a vital part of the story related to conservation, management, and restoration. In this section we describe the multiple uses of the system.

Pastures and Livestock

Natural pastures under the oak trees, tree and shrub foliage, cereal stubble after crop harvest, and, of course, acorns all are foodstuffs for livestock grazing in open cork oak woodlands. The relative importance of each of these feed stocks varies from place to place, over the course of the year and through history. In northwestern Africa, for instance, fodder is still one of the most important economic products of the system, and ruminants may get approximately 90 percent of their food intake from pasture, acorns, and woody plant foliage during their autumn to winter stay in open cork oak woodlands. Sheep, goats, and cows are the main beneficiaries in North Africa, and pigs are mostly absent. In Iberia and the western Mediterranean islands, livestock include sheep, goats, and pigs and, more recently, cattle (see Color Plate 6). Sheep and goats produce meat, fiber, skins, and milk, which is used mainly for making high-priced cheeses. In Iberia, hardy, indigenous livestock breeds, such as the merino sheep, whose ancestors may have been introduced from Morocco in medieval times, traditionally grazed the system, producing valuable wool. Today, little wool is produced anywhere in Europe because cheaper imports are available from Oceania, southern South America, and elsewhere.

Until five decades ago, it was common to associate grazing of oak woodlands with the seminomadic movement of livestock, called transhumance.

This involved moving sheep and goats to high mountain pastures in summer, when the rainfall stopped lower down, and back down to lower pastures in midautumn, when the open oak woodlands once again became green (see Site Profiles 3.1 and 4.1). Today, this practice has been almost completely abandoned, except in a very few areas of Spain (Manzano and Malo 2006), southern France (J. Aronson, personal observation, 2004), and Morocco (El-latifi 2008).

Cattle were not common in the traditional system and their main use was as draft animals, but more recently they have gradually replaced sheep and goats and increased in numbers in the Iberian Peninsula because of the higher incentives given by the Common Agricultural Policies (CAP) per head of cattle than for smaller ruminants. (The CAP is a system of European Union [EU] agricultural subsidies and programs. It represents between a third and a half of the EU's budget at present, but this may change in the near future.) Despite the partial removal of subsidies during the 2003 CAP reform, preference for cattle has persisted because cattle have lower management requirements and beef is still greatly in demand on global markets. The breeding of black bulls in open cork and holm oak woodlands is also widespread in Iberia, in conjunction with bullfighting, one of the most common Iberian sports and festivities.

In Iberia, free-ranging pigs also commonly graze the pasture under cork oaks and are fattened in the winter season of acorn production, October to February. Iberian pigs fed with acorns generate world-famous culinary products, such as the Iberian ham exported from Spain to Japan, the United States, and elsewhere, and are a mainstay of cultural tourism in Iberia. Apart from a period of crisis in the 1960s and 1970s, caused by the African swine pest, fattening of pigs in cork and holm oak woodlands is an ancient and unbroken tradition. Indeed, Pliny the Elder (23–79 AD) noted in *Naturalis Historiae* that Iberian pigs raised on acorns were appreciated by the finest Roman chefs and gourmets. Similar traditions exist in Corsica and Sardinia to this day.

Historically, open cork oak woodlands have been managed with different grazing regimes, varying in type and number over the centuries, although small ruminants have always been dominant in the system (Figure 3.1.). The importance of grazing led to much work in the 1960s and 1970s on the improvement of Iberian pastures. This was done mainly through the introduction of new varieties of nitrogen-fixing legumes, such as medics (*Medicago* spp.) and subterranean clover (*Trifolium* spp.). More recently, carefully assembled mixtures of legumes are being used to improve grazing resources and to increase soil fertility, halt shrub encroachment, and provide firebreaks

(Crespo et al. 2004). However, unless it is well managed, grazing may adversely affect tree regeneration and limit the sustainability of open cork oak woodlands.

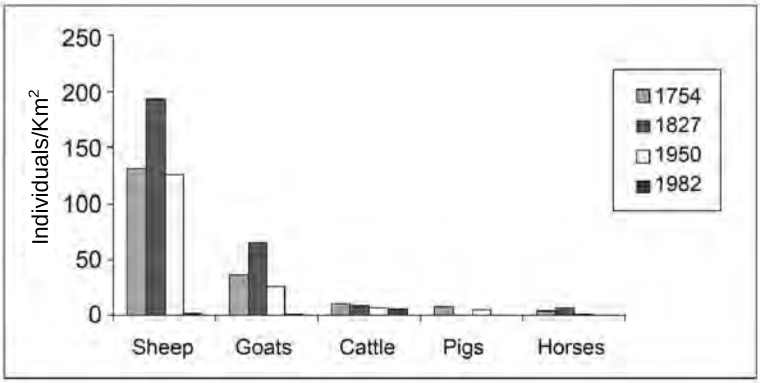


Figure 3.1. Variation of livestock density (individuals per square kilometer) in an oak *dehesa* of central Spain between 1754 and 1982. (Adapted from Pardo and Gil 2005)

Grazing as a Limiting Factor

Livestock grazing in open cork oak woodlands faces seasonal changes in the quality and quantity of plant food available. In spring and early summer, there is plenty of green, nutritious pasture. But as early as June, lack of moisture in the soil and high ambient temperatures bring vegetation growth to a halt. Within a few weeks, most annual herb species—grasses, legumes, and forbs—set seed and die back until the first autumn rains (Bugalho and Milne 2003). The nutritive value of perennial grasses and herbs also drops drastically, and, in their place, browse from trees and shrubs becomes a crucially important source of food for livestock, particularly ruminants (Le Houérou 1980). Negative effects of herbivores on tree regeneration and establishment of open cork oak woodlands therefore are more likely to occur toward the end of summer (Bugalho et al. 2006), although in winter, shrub and tree foliage are also browsed by animals because of the low quantity of pasture available.

Ensuring or promoting tree regeneration despite the presence of grazing ruminants is a major challenge for managers of open cork oak woodlands and, indeed, most silvopastoral systems (see Chapter 10). Using individual tree shelters to protect young saplings from grazing is a common practice, particularly for establishing new cork oak stands (see Chapter 12). Rotational grazing has been less favored because it requires a minimum property size to be implemented. However, the harsh summer conditions of the Mediterranean region may be as important as grazing in limiting tree seedling survival in open cork oak woodlands. For example, a study conducted in Alentejo, southern Portugal, showed that the mortality of cork oak seedlings toward the end of summer was similar between fenced plots protected from grazing and unfenced plots where grazing was allowed (Bugalho et al. 2006). Season, number, and type of grazing animals (cattle may be particularly harmful to young trees) must be considered carefully if regeneration of the system is to be maintained.

Cereal Crops

Apart from animal products, open cork oak woodlands traditionally provided grain cereals. In the typical system of the Iberian Peninsula (Montero et al. 1998), plowing was used for the cultivation of wheat, barley, oats, and rye, in rotation with leguminous fodder crops, especially common vetch (*Vicia sativa*) (see Color Plate 5). Cultivation traditionally occurred in long rotation cycles of four to seven years. Cereal crops were produced in soils that were often deficient in organic matter and nutrients (particularly phosphorus), usually yielding 400–1,200 kilograms per hectare for wheat, for example, a mere 7 to 20 percent of the average yields achieved in the twenty-five countries of the European Union in 2005 (http://epp.eurostat.ec.europa.eu). These crops were regarded mainly as a source of staple food (wheat) and fodder for livestock (oats, rye, stubble, and straw). In recent decades, cereal cropping has decreased in southwestern Europe and northwestern Africa, but shrub cleaning without cultivation, traditionally conducted manually but done mechanically nowadays, is still a common practice to halt shrub encroachment and prevent wildfires.

Tree and Shrub Products

The trees and shrubs of managed cork oak systems directly or indirectly generate different products. For instance, fruits and natural oils can be obtained from various shrubs occurring in open cork oak woodlands. The strawberry tree, a common shrub of many open cork oak woodlands, produces a fruit distilled for spirits. In Tunisia, for example, collection of myrtle (*Myrtus communis*) or rosemary (*Rosmarinus officinalis*) is common for small-scale production of essential oils (Daly-Hassen and Massoura 2005; Berrahmouni et al. 2007). As mentioned earlier, the domestic pear was grafted onto wild pear, and other fruit trees were grafted onto appropriate wild or cultivated stock. Beekeeping and honey production are also common in open cork oak woodlands, where flowering is abundant (Ellatifi 2005). Edible mushrooms are also very common and occasionally abundant, depending on how much organic matter and leaf litter are allowed to accumulate under the trees. Foliage and acorns are palatable and attractive to livestock, but if the animals are allowed free access, this can reduce overall productivity and natural regeneration by seedlings. Firewood and charcoal, resulting from tree pruning, are also important products of the system, particularly in North African countries, where firewood is still the main source of cooking and heating fuel in many rural areas. At present, cork is by far the most valuable product generated by the system (see Chapter 5 and Color Plate 2).

Wild Game

Open cork oak woodland systems are prime habitats for a variety of big and small game species, such as red deer (*Cervus elaphus*), fallow deer (*Dama dama*), wild boar (*Sus scrofa*), hares (*Lepus granatensis* and *L. capensis*), red-legged partridge (*Alectoris rufa*), gambra partridge (*Alectoris barbara*), and wild rabbit (*Oryctolagus cuniculus*). Hunting, particularly of big game such as red deer, is a large source of income in many *montados* and *dehesas* of the Iberian Peninsula, often complementing otherwise marginal agricultural production. Revenues generated from hunting—either directly, through selling of hunting day permits and trophies, or more indirectly, through renting of land to hunting associations—allow landowners to maintain large areas of open cork oak woodlands, particularly in countries such as Portugal and Spain, where hunting has a long historical tradition. In northwestern Africa, where most open cork oak woodlands belong to the state, hunting generates income for the government, mainly through payments of taxes and licenses by tourist or local hunters to the Forest Administration (Daly-Hassen and Massoura 2005). In Morocco, many open cork oak woodland hunting estates belong to the king and are used only by a small number of royal visitors.

Recent Trends of Transformation and Degradation

The development of farm mechanization in the twentieth century led to the general use of wide plows, disc harrows, and scarifiers, particularly in Iberia. Unlike the traditional narrow, shallow plow, pulled by animals, this heavy machinery unselectively destroys young trees and may damage roots and weaken established trees. Indeed, in dry sites or during droughts, trees become more dependent on their extensive superficial root system to survive (Joffre et al. 1999; see also Chapters 6 and 18) and thus become more susceptible to the effects of heavy farm machinery. Tree weakness, in turn, may induce pests and fungal diseases that have attacked open cork oak woodlands and related systems in the last twenty years (see Chapter 9 and Color Plate 11).

In Iberia, where most open cork oak woodlands are private, changes in rural socioeconomic conditions, induced in part by the CAP, have led to abandonment of some open cork oak woodlands, where invasive shrubs, particularly rockrose (*Cistus* spp.), grow freely and represent a serious fire hazard. Recent changes in the CAP have converted direct aid to cereal areas and to some grazing animals into single payments to farmers, which are decoupled from production. This, together with the decrease in cereal and animal prices, has also increased the difficulties of maintaining the traditional system. The replacement of the cropping phase may contribute to degradation through the disappearance of stubble and straw and the loss of pasture caused by shrub encroachment. Landowners have tended to eliminate the cropping phase and to replace sheep and goats with cattle, even though this may severely affect oak tree regeneration (see also Chapter 10).

In northwestern Africa, open cork oak woodlands are state owned, although local people are allowed to used them. There, the main driver of open cork oak woodland degradation is related to overgrazing (Box 3.2), overcollection of acorns and firewood, and excessive crop cultivation in marginal rainfall areas. Uncontrolled and excessive out-of-season bark harvesting is also a major problem in some parts of northwestern Africa. Overuse of the system there results primarily from high demographic pressure and increasing demands for consumer products. Rural human populations have quadrupled in Morocco, Algeria, and Tunisia over the last fifty years, and per capita consumption of energy, meat, and industrial goods has increased rapidly.

Throughout the region of cork oak distribution, market changes are leading to devaluation of cork. In particular, the partial replacement of cork bottle stoppers with synthetic ones has decreased the income formerly derived from open cork oak woodlands, reducing the economic incentive of landowners to preserve these systems for cork production (see Chapters 5, 13, and 16 for more details and discussion of public and private interests).

Box 3.2. Livestock Grazing in Dehesas: A Self-Destruct Mechanism?

Tobias Plieninger and Fernando Pulido

The long-term persistence of oak stands in *dehesas* is a subject of serious concern among both the public and the scientific community. Given the even-agedness of many holm and cork oak stands, some question the sustainability of the *dehesa* system and predict that insufficient regeneration might lead to the conversion of *dehesas* into grasslands (Elena-Roselló et al. 1987). The difficulties of combining grazing, brush clearing, and plowing with oak regeneration in *dehesas* have been described for a long time (Rupérez 1957). This box reports on a series of studies on the impact of livestock on regeneration in holm oak *dehesas*, which largely share the same problems as cork oak *dehesas* and have been far better studied and documented.

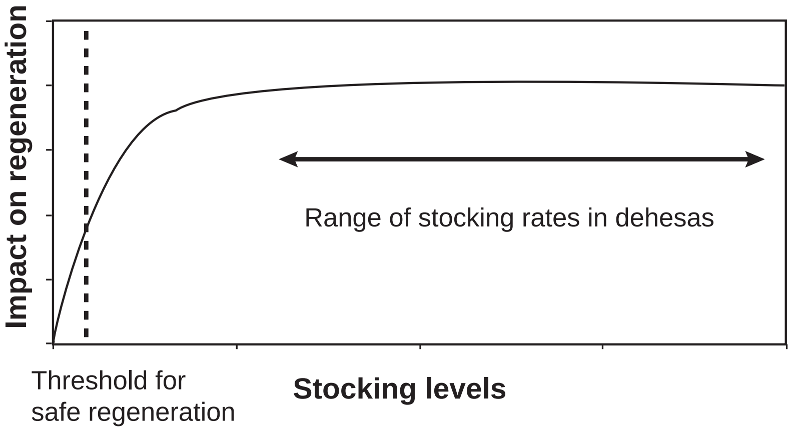
A regeneration inventory of holm oak stands in Cáceres province (Spain) has shown that most *dehesas* almost completely lack juvenile age classes (Plieninger et al. 2004). Moreover, it was demonstrated that *dehesa* age (the time elapsed since the establishment of a *dehesa*) and the current mean age of stands were correlated, which means that historically older *dehesas* possess older trees, whereas more recent *dehesas* comprise a younger cohort of oaks (Plieninger et al. 2003). The bell-shaped size distributions of the oak stands indicated single-cohort, single-age stands with few saplings entering mature tree size classes and a gradual mortality of large trees (Ashton et al. 2000). This means that the forest cycle has been disrupted in most *dehesas* and that regeneration failure is an inherent problem in *dehesas*, that is, it occurs whenever a *dehesa* starts to be formed out of the dense Mediterranean hardwood forest (Pulido et al. 2001).

A study of between-habitat differences in holm oak recruitment demonstrated the mechanisms of regeneration failure: Flower-to-sapling recruitment rates were seventy-five times as high in well-preserved, ungrazed holm oak forests as in *dehesas* (0.00150 and 0.00002, respectively). This whole-cycle disparity was the result of differences in the conversion rate from viable fruits to newly emerged seedlings. The inability to direct acorns to safe (shaded) sites, by means of efficient dispersers, was shown to be the main recruitment limitation (Pulido and Díaz 2005b). As expected, studies on within-farm *dehesa* management have shown that shrub encroachment predictably results in higher recruitment rates than grazing or cropping (Plieninger et al. 2004; García Lopez 2005).

Current browsing intensity did not correlate with current juvenile or sapling densities in several farms studied (Plieninger et al. 2004). This sug-

Box 3.2. Continued

gests that the regeneration failure of holm oak does not vary across prevalent grazing regimes. Thus, impacts on regeneration occur even at livestock stocking levels lower than the stocking rates measured in this study (Figure 1). However, study of the long-term impact of grazing is difficult, and regeneration and stand structure might be influenced by past grazing regimes acting over decades.



Box 3.2 Figure 1. Model of livestock stocking rate and regeneration impacts in *dehesas*. Current stocking rates in most *dehesas* are clearly higher than what would be compatible with regeneration.

In Spain, it has been shown that *dehesa* degradation, caused by lack of tree replacement, can be reversed through livestock exclusion and subsequent natural regeneration (Plieninger et al. 2003). In addition, the function relating regeneration status and time elapsed after grazing reduction has been fitted for a regional dataset in central Spain (Ramírez and Díaz 2008). Although more effort should be devoted to investigate local effects on this relationship, it is clear that a *dehesa* should be managed as a temporal sequence of a set of plots (grazed and encroached) integrated in a rotational cycle (Moreno and Pulido 2008).

The central dilemma of the *dehesas* is that the land use pattern that has created a wide array of environmental amenities also appears to endanger the long-term stability of the system. The *dehesa* system does not permit a sustained oak stocking level for more than a few hundred years, and this

Box 3.2. Continued

duration is likely to be shortened by oak diseases and periods of overexploitation. In fact, the system could be understood as very long-term shifting cultivation, where primeval land is developed, cultivated, and later abandoned in a treeless, degraded state. The speed and scope of this process are determined by social, economic, and political incentives. A *dehesa* is not constructed to last forever; grazing and cultivation do not seem to be compatible with regeneration, yet they are the rationale for the existence of the *dehesa* (Figure 2). Modifications to the *dehesa* land use system are needed that provide sufficient oak regeneration to be sustainable in the long term, but also maintain the productivity, biodiversity, and beauty of the traditional *dehesa*.

Figure 2. Livestock grazing can both enhance and endanger a *dehesa*. (Photo: Matthias Meißner; Rio Almonte valley, Cáceres province, Spain, November 2005)

Conclusions

Many authors have considered silvopastoral systems derived from open cork oak woodlands as an archetype of a stable, adapted, and economically viable agro-ecosystem that meets the interests of both biodiversity conservation and agricultural production (Bignal and McCracken 1996). However, the long-term viability of the system may well be in jeopardy, both in Africa and in Europe, because of mismanagement, overuse, and global factors. Indeed, different authors suggest that regeneration rates may be not sufficient to ensure the sustainability of the system. For instance, after an anticipated period of widespread oak cutting in Extremadura, Spain, Elena-Roselló et al. (1987) predicted that the last open cork oak woodlands could vanish altogether by 2069. Indeed, it seems that without direct public or private efforts to promote and assist oak seedling regeneration, many or most Iberian open cork oak woodlands could become treeless (Pulido et al. 2001). The same thing is occurring in northwestern Africa. In sharp contrast, land abandonment is occurring at high rates in northeastern Spain, Portugal, France, and Italy, which is also jeopardizing the survival of the system. Although it can contribute to oak regeneration and long-term self-regeneration of species-rich Mediterranean forests, land abandonment first induces shrub encroachment and greatly increases the risk of wildfire, not to mention endangering the viability and sustainability of a cultural landscape system of recognized patrimonial value.

Like any other human-made system, open cork oak woodlands need investment of labor and financial capital in order to be maintained. Both in southwestern Europe and in northwestern Africa, the system needs enough oak regeneration to ensure viability of the tree stands but also must adapt to novel socioeconomic contexts and needs. Direct commodities complementing cork production, such as interplanted crops (e.g., vineyards or olives), and providing regular income during the long period (nine to twelve years) between cork harvests deserve consideration. Seeking and developing alternative activities (e.g., hunting and ecotourism) that generate additional income may provide incentives to conserve these systems. In addition to direct services and commodities, extending concepts such as payment for environmental services (e.g., biodiversity maintenance, regulation of the hydrologic cycle, soil conservation) could ensure additional financial support and motivation to maintain the system (see Part IV and Chapter 17).

At the beginning of the twenty-first century, open cork oak woodlands show real potential to survive, but new kinds of valuation may be needed to ensure investment in conservation and restoration of the system. That will be the subject of Part IV. In the next two chapters we will review the historical evolution of oak-dominated silvopastoral systems in southern Portugal—one of the areas where they survive and flourish most strongly today—and then the historical development of the cork industry, leading up to the international scale it now enjoys, or struggles to enjoy, today.

SITE PROFILE 3.1

Aguelmous, Morocco

This communally owned Moroccan woodland is in a precarious state because of overgrazing and overharvesting of fuelwood. No protection status exists as yet. Active management and restoration are urgently needed.

Geographic and biophysical description	Aguelmous is situated in the Middle Atlas region, 45 km northwest of Khenifra (32°45′N, 4°55°W). The total area is 33,000 ha, including 2 distinct woodlands, both at altitudes of 1,300–1,620 m. The climate is semiarid to subhumid, with more humid patches. Average annual rainfall is 800 mm (range 570–1,700 mm). Average maximum temperature during the hottest month is 35°C, and average minimum temperature during the coldest month is 5°C. Topography is rugged and mountainous, on Cambrian schist or granitic substrates. Deep and fertile brown soils occur on some Cambrian schists, with abundant clay and consequently a tendency to hydromorphy in deep horizons. Vegetation is dominated by cork oak: 13,500 ha, along with holm oak (*Quercus ilex* 13,000 ha) and about 5,000 ha of shrubland. The main woody species are Mediterranean fan palm (*Chamaerops humilis*), wild olive (*Olea europaea* var. *oleaster*), mastic (*Pistacia lentiscus*), terebinth (*Pistachia terebinthus*), prickly juniper (*Juniperus oxycedrus*), and Berber thuya (*Tetraclinis articulata*); the shrubs are sage-leaved rockrose (*Cistus salviifolius*), various brooms (*Cytisus villosus*, *C. grandiflorus*, and *Teline monspessulana*), and white-flowered sun-rose (*Halimium umbellatum*).
Physiognomic description of cork oak woodlands and their landscapes, including woodland dynamics	Dense stands occur on north- and northeast-facing slopes, and less dense clumps are found on southern and southwestern slopes. Many dead cork oak stumps testify to wide spread cutting.
History of land uses, land tenure (and socioeconomic drivers), and current land uses, economic activities, and context	Up to the 1970s, these woodlands were well conserved, and natural regeneration was satisfactory. Trees are aging, and natural regeneration is very rare. In the cold season (October to March), the area serves as a stopover or *azaghar,* receiving flocks of sheep and goats on their way back from the Almou (summer pastures), in the Middle Atlas Mountains during the semiannual migration, known as transhumance.
Disturbance regime (fires, pests, overgrazing)	Tree felling is strictly forbidden in Morocco. However, this cork oak woodland, like most others in the country, is under severe pressure of overgrazing and overharvesting of fuel-

	wood. Forest fires occur from time to time but remain under control.
Constraints and conflicts, protective measures, restoration actions, land use regulations, and relevant policies	Fodder and fuelwood are the main products collected by the local communities. Because of aging trees and low quality, cork is not regularly harvested. Acorns are bitter and are grazed primarily by wild boars. Some aromatic and medicinal plants are also occasionally collected by local people.
Current trends and prospects for the future	Since the 1970s, within the framework of a prospective research and development program led by the Forest Department, several patches (in the Sidi Ahsine area), on about 10 ha, were planted with various introduced conifers. However, cork oak and holm oak are the natural tree species in the area. They should be maintained and reinforced with more efforts to assist their natural regeneration. Further introductions of exotic species should be avoided.
Source	Mohammed Ellatifi, Sylva-World, Casablanca, Morocco

Site Profile Figure 3.1. Flocks of goats during their winter stay in Aguelmous site (*azaghar*) after having left the mountain pastures (*almou*) during the hot season.

Chapter 4

Historical Perspective of Montados: *The Example of Évora*

Teresa Pinto-Correia and Ana Margarida Fonseca

In this chapter we provide a historical overview of the land use activities and products in the traditional silvopastoral *montados* (also called *dehesas*; see Chapter 3), in the region of Alentejo, southern Portugal, particularly around the ancient city of Évora. This is one region where this land use system, in which forestry and cattle production are combined, is still dominant. However, the processes described here are very similar to those used in many open cork oak woodlands, especially on the Iberian Peninsula, and thus the history of the Évora woodlands can be considered as a model for the history of most open cork oak woodlands. We start with ancient history for southern Iberia up to the fifteenth century and then discuss the fifteenth to eighteenth centuries, a formative period crucial for understanding the workings and management of the Alentejo *montado* system today. We then briefly discuss the nineteenth and twentieth centuries, but for this period, more detailed documentation is available elsewhere (Natividade 1950; Balabanian 1984; Fonseca 1996, 2005; Radich and Monteiro Alves 2000; Radich 2003; Martins 2005). We close with a discussion of perspectives for the future, the main focus of the remainder of this book.

Land Use before the Fifteenth Century

In many places in southern Iberia, around 6,000 years BP, the evergreen oak forests were converted into dense woodland or even scrubland formations (Riera-Mora 2006). The spread of Neolithic agriculture to the region, starting around 5,600 years BP (Zilhao 2001; Zapata et al. 2004), brought about further transformation through the opening of patches around the most important human settlements. The dominant farming activity was livestock raising, and the woodlands were cleared for wood harvesting and to obtain better grazing areas for livestock.

As noted in Chapter 3, *montado* and *dehesa* open cork oak woodlands developed from the mixed oak woodlands, possibly starting in Roman or even prehistoric times (Stevenson and Harrison 1992; Grove and Rackham 2001). Many references suggest that extensive use was made of Mediterranean forests and woodlands throughout the upper Middle Ages, whereby various components were astutely combined and managed under careful legislation (Castro Caldas 1994; Barata and Leite 1996; Alonso 1998; Blondel and Aronson 1999; Grove and Rackam 2001). Although detailed descriptions of land use in the Middle Ages are scarce, some revealing references do exist, such as the Visigoth Code, from the seventh century, which established rights and restrictions with regard to the use of specific tree and shrub species and to grazing lands and their uses (Vieira 1991). Subsequently, during the period of Islamic domination from the eighth to the eleventh century, there are other historical references to the introduction of a breed of sheep with high-quality wool, and to the increasing role of goat grazing and growing conflicts over cultivated areas. There are also references to the importance of oak acorns as a source of food for humans and domestic animals and of mast, or pruned foliage, used as fodder for livestock. It is also clear that during this period honey was produced in the region, and cork was harvested from the cork oak trees and sold (Grove and Rackham 2001).

With the growth of human population and a corresponding increase in livestock, the conflicts rising from grazing in cultivated areas led to the establishment of fenced grazing parcels. The fencing was often carried out by private landowners, who sold the right to use the pasture to livestock producers. As the income from this system became increasingly significant, a tax was made compulsory. The first documents referring to this type of tax are from the thirteenth century and call it *montado* in Portugal and *montazgo* in Spain. Some other authors indicate that the term *montado* was used in the Middle Ages, not as a tax but as the payment due by livestock producers to owners of the grazing land, both private, and to the municipality counties (Coelho 2005a). Thus, it did not necessarily refer to an oak savanna or woodland. Similarly, in North Africa, the term *azaghar* is quite generic, as explained in Chapter 3.

In relation to this tax, how it should be collected, and what it was for, some texts refer to the system of land use and its various components. From these texts it appears that in the thirteenth century, when the modern boundaries of continental Portugal became fixed, an increase in livestock numbers and in the income generated from selling the right to use the pastures led to the clearing of much formerly wooded land in order to increase pastures for grazing. This clearing was often initiated and maintained by intentional fires, and because cork and other oaks are more resistant to fire than many shrub species, they survived (see Chapter 1). Furthermore, the most useful trees were often protected from fire and semicultivated for the pruned foliage and acorns they provided. There are no historical references to plowing or cultivation underneath oaks. Cultivated fields were grouped near human settlements, and they were used intensively, with most or all trees being removed.

As seen in previous chapters, the cork oak tree has a large number of uses. The first references to the harvesting of cork near Évora are from 1320, mentioning its various uses (e.g., decorative objects, bee hives, construction material for small buildings) and exportation to England (Natividade 1950; Castro 1965). Gradually, regulations were approved to protect the cork oaks from excessive cork harvesting. Charcoal production was also increasing rapidly, with the result that from the fourteenth century onward, several laws were enacted to impose limitations and guidelines on the pruning and cutting of trees. Furthermore, a common practice at that time was the beating of the branches with long sticks in order to bring acorns and leafy branches to the ground, where they could be used for food and livestock fodder. Regulatory texts have been found that aimed at limiting this activity because too much, too early, or out-of-season harvesting by beating clearly damaged the trees.

Thus, by the fourteenth century there were regulations on the use of trees, grazing areas, and fields in order to protect and maintain a vegetation cover, seen as an important and vulnerable resource. Reflecting a concern for food production and the maintenance of cultivated areas, a Cultivation Act was published in Portugal: the “Lei das Sesmarias” of 1375, promoting the clearing of shrubs in fields to be used for cultivation. It should be mentioned that there are no historic references from that period to anything resembling the modern *montado* (i.e., an integrated land use system). But it does seem clear that there was an understanding among the authorities and some of the various users that a balance between trees and pasture was needed and that these should be treated with care and prudence. Notably, similar enlightened policies were introduced in other Mediterranean countries, such as Catalonia and the Republic of Venice, during the same period or shortly thereafter (Merlo and Croitoru 2005a). It also seems clear that a landscape type similar to the modern-day *montado* was probably found in patches of varying shapes and sizes in the region of Évora and in different parts of the Iberian Peninsula. We could call this a proto-*montado*.

In the fourteenth century, however, there was also a marked decrease in population throughout Europe, as a result of a period with a colder climate and, above all, the Black Plague of the 1430s, an epidemic that affected large parts of the European population. Many previously farmed areas were abandoned and underwent shrub and tree encroachment. The pressure on natural resources dropped to a very low level.

Land Use between the Fifteenth and the Eighteenth Centuries

From the fifteenth century onward, there was a relative stabilization of the Portuguese population. In Alentejo, the clearing of shrubland in order to obtain farmland was done more systematically, even if, in some areas, dispersed tree cover was kept. But the main development in the farming sector concerned livestock, mainly sheep and goats. Transhumance was very important, and many regulations concerned both the roads that could be used by the livestock and the protection of cultures, as well as the leasing out of pasture areas for grazing. The clearing of woody plants for grazing spread, and grazing areas with scattered tree covers of varying densities expanded. The existence of a tree cover in grazing areas—a so-called anthropogenic savanna—was an important advantage because of the use of the fruits, foliage, and acorns for feeding. An analysis of paintings from that period shows that direct harvesting of masts and acorns was used, and the grazing areas were mostly natural pastures, with grass and dispersed low shrub. Other sources indicate that shrubland also had other uses, mostly for the production of honey and medicinal herbs and even for charcoal production. The need to limit grazing intensity, in order to protect trees and maintain natural regeneration, was reflected in related legislation. In 1538, for instance, selling the right to use pastures to Spanish livestock producers was forbidden in order to keep the limited resources available for the national meat production. The "Lei das Árvores" (Tree Act), from 1565, recognized the importance of trees as a resource and was intended to promote the protection of existing trees and the planting of new ones. This protection was necessitated by increased grazing pressure and the increasing activity of charcoal producers. Even if the regional impact of this act was modest (Devy-Vareta 1986), it reflects the pressures on forest systems and shows the concern by public authorities. Also, the use of fire for shrub clearing was subject to control: Permission had to be obtained and a bond posted beforehand. In principle, this monetary guarantee was kept by the authorities if any trees were accidentally burned.

Concurrently, with increased public incentives for cereal cultivation, especially in previously noncultivated areas, and with the possibilities created by technological improvements, grain production in the open areas between oak trees developed. By the seventeenth century this practice had become quite common. The *montado* had become an agro-silvopastoral production system, with short-term advantages but some built-in hazards, as will be described in later chapters.

National legislation and local regulations from the sixteenth and seventeenth centuries reflect a clear desire on the part of the authorities to improve shrub clearing and cultivation techniques as well as livestock production. But they also reflect a real concern for the protection of oaks and the maintenance of existing forest and woodland areas. The result of these policies has been the development, especially in the more populated and fertile areas, of a complex land use system, highly regulated and carefully managed, including both the exploitation of trees and several kinds of production in the understory. There were many variations in the use of the various components of the *montado*, just as similar diversity in land use occurred throughout the Mediterranean region during the same period. In Portugal, these variations resulted from official government strategies, as reflected in legislation, but primarily from the irregular distribution and growth of population, the combination of different types of properties and exploitation rights, and technological development. Nevertheless, the combination of cultivation and grazing in the *montado* understory, together with exploitation of the cover of holm and cork oak, became more common during this period.

Notably, in the seventeenth and eighteenth centuries, large land holdings were linked to smaller tenant farms, and thus different users had specific rights for the use of the same area (Santos 2003). Even within types of property rights quite different from the modern latifundia system, this land use system corresponds roughly to the modern *montado*. Only the harvest and use of cork were still limited.

Land Use in the Eighteenth and Nineteenth Centuries: Emergence of the *Montado*

The regional agrarian world of the seventeenth century, where the traditional landowner owned a large property that was linked to small and medium-size tenant farms, started to change in the first half of the eighteenth century. This transition, complete by about 1870 (Santos 2003), had important impacts on the *montado* because responsibility for the production and management of one piece of land was now borne by landowners alone, bringing more coherence to system management and balance between the various components.

Some existing laws were modified. The public body that regulated transhumance was abolished, and the tax on the selling of pastures, maintained since the thirteenth century, ceased in 1739. Furthermore, land could no longer be leased out so easily. Livestock production by tenant farmers with no land and, particularly, transhumance were drastically reduced. The grazing areas within each property were integrated in the land use management of that property. Also, the previously cultivated land was returned to landowners, who in some cases chose not to keep up cereal cropping because of fluctuations in market conditions and difficulties in finding farm workers. The number of available workers decreased: Soldiers for successive wars were recruited from among the rural population, migration to the coastal area increased, and slavery was abolished in 1761 (slaves from Africa had been an important part of the farm workforce in the region of Alentejo). As a reaction, in 1787 the government ordered the forced migration to Alentejo of several thousand people from the Azores.

Landowners invested more in livestock, mainly in areas where tree cover had been maintained and thus where mast and acorns were available. Cereal production continued on the most fertile land, and some holdings ended all cereal production. Livestock production increased strongly, including that of the Iberian black pig, a source of pork products highly acclaimed to the present day (see Chapter 3).

The land use pattern was again changed, with some return to natural pastures and the progressive development of shrubs in the less fertile and most peripheral land, resulting in a more closed mosaic. The Parish Memories, church registries of all local activities and happenings at parish level, reflect an increased use of these shrub areas, both for the exploitation of medicinal plants and for diversified hunting. The Parish Memories from 1758 are important sources of information because of their number, local distribution, and detail. For example, they describe the distribution of the oak species in the region: the cork oak in northern Portugal and along the Atlantic littoral, the holm oak in the southern and eastern parts of the country, and also some Pyrenean oaks at higher elevations and along the valleys of the Tejo and Sado rivers. The information in the Parish Memories also makes it possible to understand what were the most important products and the most important questions or conflicts in the various parts of the region.

Beginning at the end of the seventeenth century, with the increased demand for cork for wine bottle stoppers, cork harvest also expanded significantly, and cork production started being seen as a source of income for landowners. Beginning in the early eighteenth century, the use of the term *montado* is common in Portuguese texts. By the end of the eighteenth century, partly as a result of population growth and of profound changes in property rights and new economic conditions promoting cereal production, *montado* was the dominant land use throughout the Alentejo (Santos 2003;

Coelho 2005a). Many authors argue that an agro-silvopastoral system at the farm unit level, where all components were managed under private landownership and with a single farm manager, began during this recent period (Natividade 1950; Silbert 1978; Balabanian 1984). In some regions, such as Évora, the landscapes around 1835 may have been similar to what is seen there today, if we can trust English traveler George Barrow (1907). (Site Profile 4.1, at the end of this chapter, describes a typical contemporary *montado* near Évora.)

In the second half of the nineteenth century, with technological improvements, an increased labor pool, and public incentives, population growth in Portugal led to greatly increased demand for food, such that livestock and crop production intensified in the fertile Alentejo region. The end of the nineteenth century and the beginning of the twentieth century brought the largest occupation and use of farmland in the Alentejo ever registered, including cereal production, both in open areas and under tree cover. This is the period in which the integrated management of the *montado* was most detailed and precise, including many different components and production systems and employing many specialized types of workers (Picão 1903). Tenant crop or livestock producers disappeared, and landscapes dominated by *montado* expanded, integrating various densities of tree cover and a mosaic of uses in the understory, including hunting, gathering, grazing, cultivating, and beekeeping.

Conclusions

Since the twelfth century, there has been diversified and fluctuating land use in the Alentejo region. The changes we have chronicled here are similar to those found in open cork oak woodlands of other regions of the western Mediterranean, even though the precise history of each region has its own unique features as well. Along with changes in political situations, property rights, populations, technology, and strategies by central decision makers, the progressive transformation and use of formerly natural vegetation changed in intensity and form over the succeeding centuries. The oaks and their products have always been important, however, as was domestic livestock, with a dizzying array of domesticated breeds and varieties, most of which are lost today. Cultivation appeared and expanded in some periods but always remained limited.

Looking back in history, the region has been exploited through a silvopastoral system and less often as a fully agro-silvopastoral system. Today, cultivation in the understory is justified only when it is associated directly with livestock production, for direct grazing or fodder harvesting. Intensive crop cultivation under a tree cover is not economically viable and often results in damage to the trees. In the Alentejo, at least, it may be maintained in open patches, without trees, on more fertile soils (Pinto-Correia and Mascarenhas 1999; Pinto-Correia et al. 2006; Pinto-Correia and Breman 2008).

Furthermore, the resilience of *montados* is remarkable. It is noteworthy that in Portugal this resilience has been reinforced by legislation aiming to limit excessive pressures on one or another component of the system. But to this day, in Portugal and elsewhere, there has never been legislation concerning the whole *montado* or related system as such. In many countries there is legal protection for holm and cork oaks and laws governing the extraction of cork and pruning of oaks, but there is no real regulation of grazing pressure and distribution, cleaning methods, or harvest of complementary resources, such as mushrooms, medicinal herbs, and honey.

In summary, the Alentejo *montado* is both highly multifunctional and strongly anchored in regional landscape heritage and identity. This system remains the dominant land use of the Alentejo region, despite radical changes in context in modern times. In order to keep such a rich and mixed land use system alive and well, new and more integrated forms of regulation and incentives are needed, along with creative farming and marketing developments in response to changing markets. Adaptive management and restoration also may be needed in many cases. In Chapter 5 we will learn about bottle stoppers and other products derived from cork.

SITE PROFILE 4.1

Machuqueira do Grou, Portugal

This site profile presents an example of the privately owned *montado* formations common in southern Portugal, as described in Chapters 3 and 4.

Geographic and biophysical description	The area comprises 2,500 ha and is part of a left bank tributary of the Tejo River, in the Ribatejo province, 100 km northeast of Lisbon (39.116°N, –8.352°W). The entire watershed is on deep Miocene sands. Altitudes range from 79 to 173 m, with slopes between 0% and 5% and, exceptionally, up to 35%. Mean average annual rainfall is 600 mm; mean annual temperature is 15°C. The bioclimate is considered subhumid. The main soil types include fluvisols, leptosols, and podzols.
Physiognomic description of cork oak woodlands and their landscapes, including woodland dynamics	This is a mesa-type landscape with U-shaped gullies, valleys, and occasional sandstone outcrops. With the exception of the cultivated valley floors, the area is dominated by open cork oak woodlands with an average density of 90 trees/ha, an average crown projection area of 2,600 m^2/ha, and average tree height of 7.5 m.
History of land uses, land tenure (and socioeconomic drivers), and current land uses, economic activities, and context	The *montado* at this site has been managed as an agrosilvopastoral system in roughly the same fashion since the 1940s. The main economic outputs are cork and cattle. Cork is harvested every 9 years, with an average production of 1,300 kg (dry weight) per hectare. The average cattle stocking rate is 0.16 animal units per hectare.
Disturbance regime (fires, pests, overgrazing)	No fires have been reported in the last 100 years. Some tree decline is observed, especially on podzols. The natural regeneration of the tree stand is not uniform, and they are lacking in some places because of grazing and shrub clearing for fire prevention.
Constraints and conflicts, protective measures, restoration actions, land use regulations, and relevant policies	Conflicting interests arise from the livestock grazing component that affects the natural regeneration of cork oak trees. Interventions and adjustments to promote natural regeneration and active afforestation (e.g., fencing combined with shrub clearing) have been included in the stakeholders' management plan over the last 5 years.
Current trends and prospects for the future	Most of the woodland has been managed so as to maintain or increase tree crown cover over the last 10 years. In areas where thinning occurred, due to natural mortality, active

	restoration is being pursued through improvement of conditions for natural regeneration, combining cattle management modifications and reduced soil disturbance during shrub clearing. About 20% of the area shows symptoms of tree decline, with the result that restoration activities also entail fertilization and active afforestation.
Source	Nuno de Almeida Ribeiro, University of Évora, Portugal

Site Profile Figure 4.1. Machuqueira do Grou, Ribatejo, Portugal.

Chapter 5

Cork Bottle Stoppers and Other Cork Products

Américo M. S. Carvalho Mendes
and José A. R. Graça

Basic botany texts and many other books and articles attest to the uniqueness of cork, or the outer bark of the cork oak tree. As stressed by Tudge (2005:80), "Cork is a wonderful material, it is light; it is waterproof; it helps to repel pests," and it also helps to protect the tree from fire, thanks to its thermal insulation properties (see Chapter 1 and Color Plate 1a, 1b). All this results from the combination of the cellular structure of the plant tissue and the cell wall chemical composition (Pereira 2007). Indeed, cork was the first plant tissue to be described by Robert Hooke in his book *Micrographia*, published in 1665. When he wrote about his microscope observation of thin slices of cork, he coined the word *cell*, which has been used ever since to refer to the basic unit of all living organisms.

As a type of plant tissue, cork must have evolved along with the tree; that is, it must have some value in promoting the survival to the cork oak itself, as noted in Chapter 1. But these same properties also prompted its use by people, gradually giving rise to an industry that is relevant for the economy of cork-producing countries, especially for particular regions. In this chapter we describe some major properties of cork as a material and how they influenced the development of the industry in the past. The recent past and the current situation will be treated in more detail in Chapter 16. We focus on the history of the Iberian Peninsula but make references to other countries as well.

Cork as an Industrial Material

As an industrial material, natural cork has outstanding properties. The reasons for this are found at two levels: the cellular structure of the suberized tissue and the specific chemical composition of the cell walls. Cells are small, with a

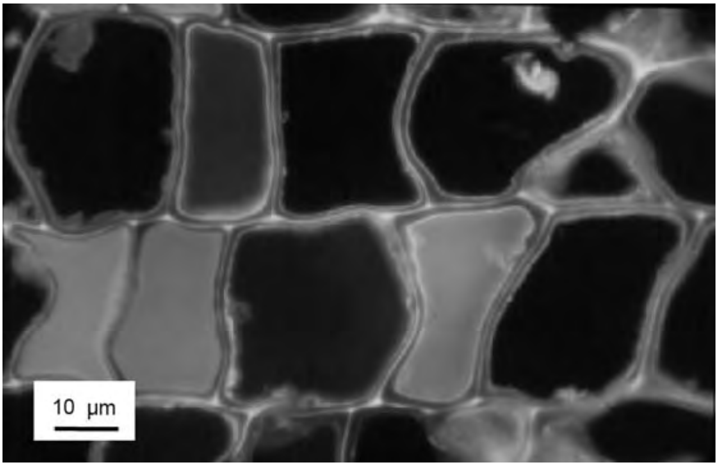


Figure 5.1. Cellular structure cork suberized tissue (cross-section).

radial length of only 30–40 microns and a width of about 15 microns in cross-section, and they are densely packed (about 50 million per cubic centimeter). The unusual honeycomb structure of the cells is depicted in Figure 5.1.

Cork cells are dead, with very thin cell walls and no cell contents. The chemical composition of their walls is dominated by a biopolymer known as suberin, which accounts for about 45 percent of cork's weight. Suberin is a polyester polymer, based on glycerol and long-chain, fatty, aliphatic acids. In the process of suberization, the walls become impermeable. Besides suberin, the chemical composition of cork cell walls includes polyphenols (25 percent), polysaccharides (15 percent), and extractives (15 percent) (Graça and Pereira 2000).

Cork is light and elastic; it can be highly compressed, with high capacity for quick recovery. It is also insulating, with low conductivity of noise, heat, and electricity, and it is highly impermeable to liquids and gases. It has good surface properties (low friction) and high chemical stability, and when dry it never rots because it is not attacked by biological agents. Therefore, it is of great use for packaging food products because its contact is harmless and leaves no aftertaste (Gibson and Ashby 1997). Cork is made of suberized tissue, with its characteristic spongy properties, and *lenticel-associated tissues*. The suberized tissues never rot, no matter how moist they get. However, with high humidity and temperature, the other tissues can easily get infected with fungus and rot. Although cork is not the best example in the world for each of these properties, it has the unique advantage of combining them all in the same material.

Because it is a natural material, cork is widely variable in its characteristics. One of the sources of variability is the presence of lenticels: channels of loosely bundled cells that cross the suberized tissue in the radial direction (Figure 5.2). Because trees cannot function well with a tight impermeable jacket, the lenticels have the important role of letting in air to the living cells of the stem. The number, size, and distribution of cork lenticels (i.e., porosity) are highly variable, and to a large extent porosity determines the industrial quality, technical performance, and economic value of cork.

As mentioned in Chapter 1, year after year the cork cambium of cork oak lays down annual layers of compact cork tissue, made of suberized cells (Figure 5.2). In most tree species, the cork cambium lives for only a few years. Periodically new cork cambia are formed on the inside, deeper in the phloem tissue. Therefore, the outer bark of most trees is made of sequentially deposited thin layers of cork, with portions of dead phloem between them, a tissue known as rithydome. In cork oak, however, the same cork cambium remains active forever, being destroyed only when exposed to air during cork extraction. As a consequence, the outer bark of the cork oak is made of continuous layers of suberized cells (Graça and Pereira 2004).

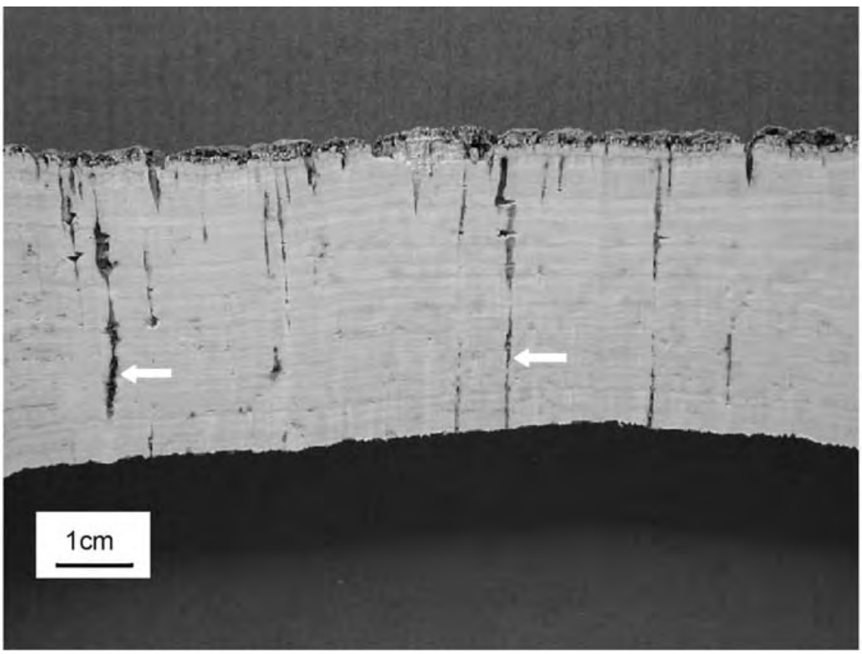


FIGURE 5.2. Cross-section of a plank of reproduction cork. Annual layers can be seen, and arrows indicate lenticels.

The resulting thick layers of cork can be stripped off easily in large planks, separating from the trunk through the fragile cell layers of the cork cambium and recently divided cork cells (see Color Plate 2). The planks are removed after longitudinal and transverse incisions are made through the cork down to the cork cambium. The process is so delicate that no machine has yet been invented to reliably strip cork mechanically without damaging the trees.

When the cork is removed from the tree, the cork cambium cell layer dies. A new cork cambium layer is formed in the nonactive part of the underlying phloem tissue. This regenerated cork cambium immediately starts the division of suberized cells, producing a new cork layer.

The cork is first harvested when the perimeter of the trunk of the tree reaches about 70 centimeters (including the cork) at breast height (1.30 meters above the soil), when the trees are twenty to thirty years old. This cork is known as virgin cork, whereas all later harvests are known as reproduction cork. On average, nine or ten years must pass between two extractions of reproduction cork. Notably, one tree may give fifteen to twenty harvests of cork over the course of two and a half centuries.

Cork bottle stoppers are the major use of cork. However, today myriad cork products are produced for diverse uses (Figure 5.3) (see Color Plate 3). Cork mixed with other polymers, such as rubber or epoxide resins, has more recently found use in the automotive and aerospace industries.

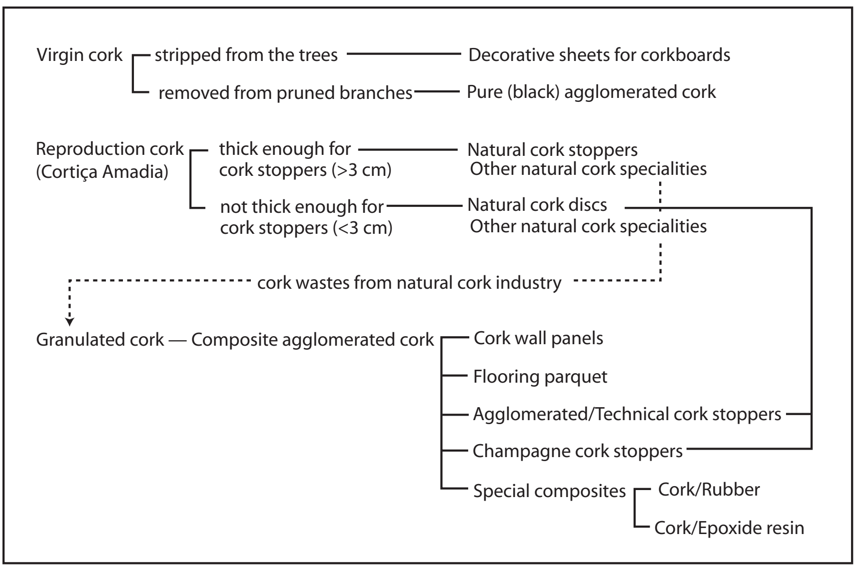


FIGURE 5.3. Major industrial products made from cork.

Economic History of the Cork Sector

Currently, cork oak is the second most important marketable nonwood forest product in the western Mediterranean, after animal products produced through extensive grazing (Table 5.1; Merlo and Croitoru 2005b; see Chapter 16 for more details). However, this has not always been the case, as we saw in the two previous chapters. Let us now review the modern emergence of cork in some detail.

The economic importance of cork was realized only after the invention of what is now the major product of cork industries: the bottle stopper. A Benedictine monk, Pierre Perignon (1638–1715), of Hautvillers Abbey in Reims, France, is often credited with having rediscovered in about 1680 the advantages of cork as a stopper for champagne bottles, as compared to the wooden and hemp stoppers that were used until that time in Europe. The cork stopper and other improvements in wine making supported a rapid expansion of the wine sector in the Champagne region, which in turn increased the demand for cork. It was in the department of Eastern Pyrenees (south of France) that the industrial manufacturing of cork stoppers was initiated, at the end of the seventeenth century, expanding later to the department of Lot-et-Garonne and to Marseille. With the beginning of this industry, a public exchange market for cork was established near Marseille, at Beaucaire.

Because cork oak trees also existed in nearby Catalonia, the market of Beaucaire began to attract cork from across the Pyrenees in Spain. This source became more important as the growing stocks of cork in France were depleted. Gradually, cork manufacturing units also started to appear in Catalonia. The date of origin is still disputed among historians, but the first one apparently was established in 1750, in the village of Agullana (Gerona). There is also evidence of some manufacturing and exports of cork stoppers from Portugal beginning in the mid-eighteenth century, when industrial manufacture of cork stoppers also started in the major importing countries, especially England.

At that time the cork industry was organized in small units relying mostly on manual and family labor that could be combined with part-time farming. This type of business structure persisted until the invention, in 1820, of a type of plane (*garlopa* in Portuguese) that allowed the mechanization of cork plank cutting for the manufacture of stoppers. Labor productivity and the quality of the stoppers improved immensely as a result, and the cork manufacturing units could expand the size of their operations. Another important innovation supporting the expansion of the industry was the invention of cylindrical bottles with small bottlenecks. This was crucial for wines, such as port, that can be improved by aging in bottles closed with cork stoppers.

TABLE 5.1.

Direct use values for western Mediterranean woodlands (all types), excluding recreational value.

	Portugal	Spain	France	Italy	Morocco	Algeria	Tunisia	Total
Timber	506,321	725,000	49,000	529,475	47,724	671	2,009	1,860,200
Firewood	37,273	38,000	—	227,183	139,680	253	2,083	444,472
Cork	390,726	41,000	3,000	4,181	6,817	5,397	9,018	460,139
Grazing and acorns	112,377	203,000	—	61,811	255,485	206,550	74,704	913,927
Mushrooms, truffles, plants, and fruits	70,960	114,000	46,000	170,930	9,124	82	5,841	416,937
Honey	7,619	—	—	22,500	19,400	516	1,706	51,741
Hunting	21,383	180,000	5,800	71,250	8,924	—	1,942	289,299
Other	3,089	133,000	1,600	0	0	1,577	0	139,266

Data for 2001 (in 1,000 euros).
Source: Compiled from Merlo and Croitoru (2005b).

Most of the expansion of this industry in the nineteenth century happened in Catalonia, in connection with the important market of cava, the sparkling wine of that region. As the Catalonian stocks of cork became insufficient to supply the local industry, the Spanish regions of Extremadura and Andalusia and the Portuguese regions of Alentejo and Algarve gradually assumed the role of main suppliers of raw cork. In the nineteenth century, in southern France, cork production declined irreversibly because of the exceptionally cold winter of 1830, the expansion of planted pine forests in the Landes region, and the competition from imported cork from Spain, Portugal, and Algeria (Puyo 2008). This decline in mainland France was partially compensated by the expansion of cork production in the new French colonies of Algeria (1830), Tunisia (1881), and Morocco (1911). The colonial authorities in those territories took over the formal ownership of the forests and delegated cork harvesting to private concessionaires, but they often faced resistance from the local people, expressed in different ways, including intentional setting of forest fires. The damage caused to cork oak resources by these fires was very heavy (Puyo 2001, 2002).

In the two major cork-producing countries, Portugal and Spain, cork oak woodlands were and still are privately owned and privately managed. When cork became a commercial asset in these countries, old communitarian uses of cork oak woodlands either had already disappeared or were not very relevant anymore. Therefore, commercially oriented private initiatives could develop the potential cork supply in Portugal and Spain more intensively than in the Maghreb. This explains part of the differences in the amount of cork oak woodland and cork production in the different producing countries (Table 5.2).

The end of the nineteenth century and the first quarter of the twentieth were a time of consolidation and mergers of large international groups in the

TABLE 5.2.

Geographic distribution of cork oak woodlands and cork harvests at the beginning of the 20th century.

Countries	Area (hectares)	Production (tons)
Portugal	325,000	110,000
Spain	275,000	30,000
Italy	95,000	4,000
France	200,000	13,000
Morocco	250,000	Commercial harvests started in 1923
Tunisia	140,000	Commercial harvests started in 1892
Algeria	440,000	4,850
Total	1,725,000	

cork industries, namely in Catalonia (e.g., Manufacturas de Corcho, SA), Portugal (e.g., Mundet), and the United States (e.g., Armstrong Cork). These changes in industry structure were driven by the industrial and urban growth in Western Europe and the United States and by various technological changes that favored more capital-intensive firms. These changes had to do with the development of different kinds of cork agglomerate products, such as agglomerate stoppers and flooring and thermal and acoustic insulation products. Most of these technological changes were initiated in the United States, Germany, and other cork-importing countries, where there was more pressure to make full use of the raw product.

This was also the time when the cork industry took off in Portugal. As was said before, there is evidence of manufacturing of stoppers in this country since at least the mid-eighteenth century. Until the twentieth century, however, this activity remained scattered in small units, without reaching the international importance it gained in Catalonia.

This situation began to change, in the last quarter of the nineteenth century, with increasing industrial activity in Portugal. One reason for this later takeoff of cork industries in Portugal, compared with Spain, is that Portuguese landowners preferred to sell their harvest abroad because they were paid higher prices and in a stronger currency than locally. Also, cork manufacturing in Portugal did not benefit from public protection and support for new industries as early as in Spain. Another reason is that the regions where the cork producers and manufacturers were located did not benefit from the same degree of transport infrastructure and the dynamic entrepreneurial environment and business connections to major importing markets that existed in Catalonia. Finally, another impeding factor was the asymmetric trade policies of major cork importing countries, with high tariffs on imported processed cork and low tariffs on unprocessed cork, which Spain was more successful in managing than was Portugal.

Despite all these constraints, business connections to the primary British market, expansion of the local wine sector (particularly port wine), and substantial improvements in transport infrastructure in the second half of the nineteenth century contributed to the success of cork industries in Portugal, especially between 1870 and 1875, when processed cork as a percentage of the total value of cork exports rose from 9 to 30 percent.

The Civil War in Spain (1936–1939) was another turning point in the cork economy because it was a period when the relative positions of Portugal and Spain were reversed. Thereafter, Portugal remained the leader in cork supply and took over the leadership in cork manufacturing. Since the 1950s, in the parts of Catalonia where cork industries were important before the war, tourism started to take over as the main driver of the local economy.

During the same period, in Morocco, cork oak woodlands declined after an initial period of expansion in the first half of the century. There were several reasons for that, including the damage caused by expanding livestock production, less restrictive rules about grazing, inadequate *afforestation* techniques, lower cork prices, and substitution by eucalyptus and other trees (Puyo 2002). From 117,000 hectares at the beginning of the twentieth century, the Maamora forest was down to 55,000 hectares by the 1990s (Titolet and Villemant 1997; see Site Profile 14.1). In Morocco and Tunisia, French protectorate status did not favor the development of local cork industries because exporters of cork products to France had to pay taxes similar to the ones paid by Portuguese and Spanish cork producers (Puyo 2008). In Algeria, the situation was different because it was a French colony. This allowed the development of local cork industries strongly oriented toward the French market, but they were interrupted by the troubles resulting from the struggle for independence. Because Portugal was the only major cork-producing country to be able to preserve its cork resources during this period, it maintained its dominant role in this sector. In Sardinia, production, industrial transformation, and export of cork thrived in the nineteenth century but diminished and stagnated in the first half of the twentieth century (Ruju 2002). Only in the region of Sassari, in northern Sardinia, is there continued activity today (see Chapter 16). In the second half of the twentieth century, there was also a decline in available cork oak resources, caused by changes in agro-silvopastoral activities traditionally carried out under the cork oak canopy (Vogiatzakis et al. 2005). Since the 1950s, cattle grazing has been gradually replaced by sheep grazing, with a corresponding increase in stock number. Although both are detrimental to natural regeneration of cork oak, sheep are worse. Also, in some parts of the island, especially where private landownership prevails, cork oak woodlands have been replaced by intensive pasture and intensive farming promoted by perverse subsidies (sensu Myers and Kent 2001) from the European Union's Common Agricultural Policy. Removal of shrubs and deep plowing in areas with steep slopes has increased soil erosion and land degradation. This human pressure also contributed to more frequent fires, resulting in about one third of the area of the island burnt around 1970 (Ruju 2002). Although most cork oak trees can survive fires, when these fires recur, land quality degradation and vulnerability of the trees to pest attacks tend to increase (Sechi et al. 2002). Recent trends toward conservation policies and lower subsidies for intensive farming may counteract the decline in cork oak resources. In fact, some cork oak woodlands are now protected as natural parks or Natura 2000 sites (Vogiatzakis et al. 2005). Also, the good quality of Sardinian cork, due to its slow growth, may help sustain the future of the Sardinian cork industry at a time when quality is crucial.

In the 1940s, plastic materials made from petroleum byproducts started to gain importance and compete with agglomerated cork products. This soon proved detrimental to the large cork industrial groups in Portugal, Spain, and some cork importing countries, where agglomerates were an important part of the business. This decline contributed to the gradual concentration of cork industries in a region where cork manufacturing firms could better resist competition from synthetic substitutes. That region is an industrial district located in Feira, south of the city of Porto, in Portugal, where small cork manufacturing units have existed since the mid-nineteenth century. Those units focused on manufacturing of stoppers, relying heavily on family labor, often supplemented by part-time farming or other income-generating activities. The barriers to entry in the industry were low, so that many workers could become entrepreneurs. This type of business structure was more capable of weathering difficult times than the one established in the other major locations of the cork industry. This region, whose importance emerged only after World War II, has developed rapidly since then and now is the undisputed center of the world cork economy.

Conclusions

Wine bottle cork stoppers are more important in the economy of cork-producing countries than when there was demand for more variety of cork products. This is happening at a time when the cork industry is facing two major structural changes in the bottle stopper market:

- The emergence of new substitutes for cork stoppers, backed by aggressive sales and marketing techniques
- Increasing consolidation of large producers and bottlers in the wine industry

These structural changes were driven by the need of the wine industry to cut costs in order to be more competitive with respect to other beverage industries, at a time when wine supply is increasing worldwide, forcing prices downward. The cork industry has reacted quickly to competition from stoppers made with alternative materials by acting on several fronts:

- Substantial improvements in quality control systems, including avoidance of the bad taste caused by trichloroanisole that cork was accused of causing in bottled wines
- Implementation of certification schemes
- Vertical integration, including cork plank preparation in some cases
- Research on the interactions between cork stoppers and wine quality

The cork bottle stopper industry has improved greatly in terms of controlling the quality of its products and responding to the needs of its customers. Today, diversification in cork supply has picked up again, but mainly within the core business of cork stopper manufacturing.

One factor that prevents the industry from benefiting more fully from these improvements is the fact that it has to pay most of its costs in euros and receives part of its revenues (exports outside the European Union) in dollars, which have declined sharply in value as of this writing. This puts the industry under even more pressure to cut costs, to improve the quality of existing products, to get better prices, and to look for new, high-value products that make full use of the harvested cork. Cork has an enormous potential for new industrial uses, alone or as part of composite materials, and as a source of "green" chemicals. Furthermore, the carbon balance of cork farming may be highly positive in terms of greenhouse gas mitigation (J. S. Pereira, personal communication, 2007; cf. Part IV and Chapter 17).

To keep production costs under control, improve the entire production chain, and develop valuable uses for cork and cork oak woodlands, forest owners and cork industries must come together, overcoming the long historical split between the two sides (see Chapter 16). Only by joining forces can they improve their market power with respect to the major forces they confront: a more concentrated wine industry and substitutes for cork stoppers.

If the cork industries fail to drive the cork production economy, alternative land uses, such as subsidized livestock production or hunting, may be more appealing to landowners. The coexistence of these activities with high-quality cork production is not easy (see Chapters 3 and 10). An integrated approach is needed, through the entire production and marketing chain and on to the final consumer of cork products, in order to ensure the sustainability of the sector. This chapter ends Part I. We will now tackle the scientific bases for restoration and management.

PART II

Scientific Bases for Restoration and Management

In the first two chapters of Part I of this book, we presented the ecology, biology, and genetic geography of the cork oak tree. Next, Chapters 3 and 4 described the various formations in which cork oak is prominent, with emphasis on the development of the open woodlands or anthropogenic savannas commonly known as *dehesas* or *montados*. Finally, Chapter 5 provided a historical overview of cork and its uses, up to the present day. We now know that a general decline in cork oak woodlands is taking place. They are aging and subjected to new threats, driven by diseases and changes in land use and climate. This leads to unsustainable intensification in many areas (i.e., overgrazing, bark overexploitation, and deep plowing of soils) and to a sudden abandonment after long use in other areas.

Nevertheless, cork oak and the cultural systems formed around it are an integral part of the Mediterranean biophysical environment and many of its historical cultures. In order to preserve them in a dynamic state, we will have to actively reverse the current trends of degradation. Otherwise, there will be no socioeconomic impetus to maintain them. In other words, we need to achieve a dynamic, healthy state for these socioecological systems and cultural landscapes that is also consistent with current needs of people and constraints of market and climate.

In Part II we provide an up-to-date scientific basis for restoration and management of cork oak woodlands. We start with a description of how cork oak copes with drought (Chapter 6), a phenomenon of increasing importance in our changing world. Next come two chapters related to cork oak mineral nutrition, specifically with regard to the role of mycorrhizal relationships (Chapter 7) and soil properties as they affect nutrient uptake (Chapter 8). These chapters are relevant in the context of how and where to introduce new cork oak trees in order to reinforce declining populations. Then, we present a review of the diversity of pests and diseases affecting the different life cycle phases and physical components of the tree (e.g., acorns, seedlings, leaves, wood) (Chapter 9). Finally, we end this part by presenting the complete natural regeneration cycle of the cork oak system (i.e., from seed to seed), showing the different bottlenecks that may lead to failure in natural regeneration (Chapter 10). Understanding the points at which the regeneration process can fail will help us address restoration and management actions.

Together, these five chapters provide an integrated body of knowledge and state of the art for forest managers to learn how to address their specific problems in cork oak woodlands, including the lack of natural regeneration. In Part III we will discuss some specific seeding and planting techniques for enhancing the success of afforestation and the active restoration of cork oak woodlands.

Juli G. Pausas, João S. Pereira, and James Aronson

Chapter 6

Coping with Drought

João S. Pereira, Cathy Kurz-Besson,
and M. Manuela Chaves

Cork oak survives in its native habitats thanks to its ability to withstand the long, dry, and hot summers of the Mediterranean region, when soil and atmosphere water deficits combine with high light intensity and high temperatures to make life difficult for perennial plants (Pereira et al. 2004). Recent changes in the region's climate, such as consistent warming and a significant reduction of springtime precipitation, have increased environmental adversity and unpredictability (Pausas 2004). Moreover, the frequency of droughts has increased dramatically in the last twenty-five years in the western Mediterranean (Miranda et al. 2002), and episodes of high tree mortality occur more and more frequently, especially in severe drought years (Pereira et al. 2006). Water deficits may also be critical in generalized cork oak decline associated with root pathogens because trees infected with pathogens, such as root rot (*Phytophthora cinnamomi*), are more vulnerable to water deficit-induced damage than uninfected trees (Desprez-Loustau et al. 2006) (see Color Plate 11).

The main question we address in this chapter is how cork oak copes with drought. This is relevant not only for assessing the vulnerability of cork oak to soil degradation and climate change but also for general management and conservation programs, including the restoration and reintegration of fragmented cork oak landscapes. Indeed, increased aridity is the most likely cause for the low regeneration rates observed in cork oak (see Chapters 10 and 20). Therefore, many restoration projects based on artificial regeneration may fail because of postplanting water deficits. Similarly, postfire resprouting of trees may fail because of drought stress.

The Limits of Survival

In areas with Mediterranean-type climate, most trees avoid dehydration of their living tissues during water deficits by reducing water loss or preserving access to soil water (Walter 1973; Pereira et al. 2006). Whereas *stomatal* closure and leaf shedding may limit water losses, deep root systems provide access to water, free from the competition of coexisting plants with shallower roots. However, when water deficits prevail and both these strategies fail, the tree may die. How and when does that occur?

Without soil water replenishment, plant dehydration becomes unavoidable. As drought progresses, the resulting plant water deficits may cause the *cavitation* of some water columns in the *xylem* water transport system. If water deficits and cavitation persist, those conduits may become *embolized*, thus losing the capacity to transport water. Persistence of drought may lead to a state in which the hydraulic integrity of the tree is lost. When runaway embolism occurs in the whole trunk, severing the connection between tree roots and shoots, water is no longer delivered to the leaves and other living tissues, and eventually the entire tree dries out. In such cases, trees lose their ability to resprout, even when water becomes available once again. The limit to this catastrophic loss of xylem conductivity is set by the *xylem vulnerability* to water deficits, that is, the values of *leaf water potential* at which most xylem elements fail to function. Whereas many seedlings are eliminated by such processes in the first summer season of drought, in large trees this does not occur at once. Indeed, it may take a long time, usually long enough to allow other agents, namely pathogens or insects, to join the attack.

In other words, when a tree dies it has usually undergone a gradual period of weakening (Jenkins and Pallardy 1995). To understand and counteract this process, we need to know how to measure plant water status. The most common measure used is leaf water potential, which is denoted by the symbol (Ψ). Leaf water potential is an approximate indication of the difficulty plants experience in extracting moisture from the soil. By convention, a value near zero indicates plants that are well hydrated, whereas negative Ψ values signify that water is held by soil matrix forces in a way that is not easily taken up by plants. When measured at dawn or predawn (pd) (Ψ_{pd}), this assay indicates whether there is an abundance of water in the soil (values near 0) or water is scarce near the roots (negative values). The lowest Ψ_{pd} values usually occur at the end of the summer and depend on the annual precipitation amount (Figure 6.1). In general, leaf water potential near –4 MPa corresponds to the minima measured in healthy cork oak trees in the field (David et al. 2007; Figure 6.1).

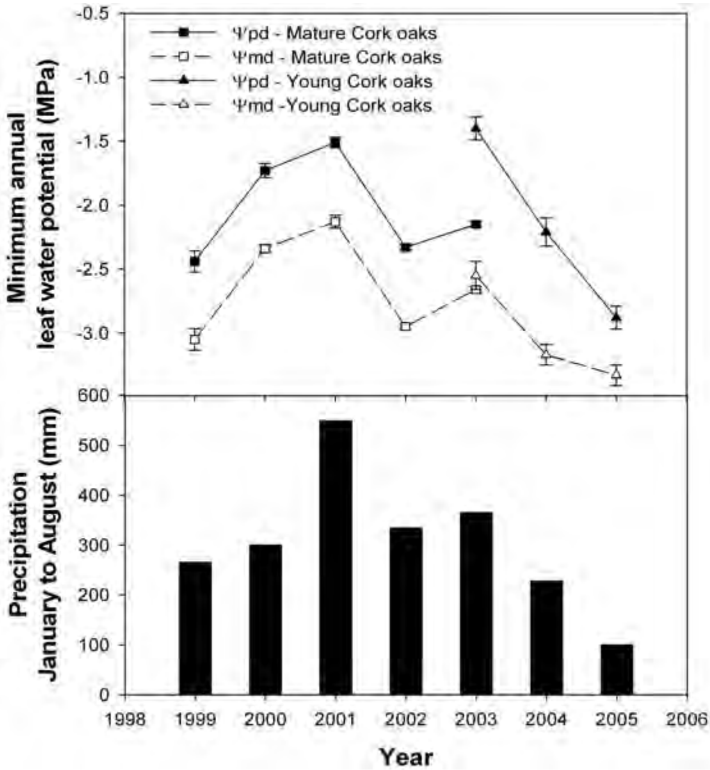


FIGURE 6.1. Interannual variation of precipitation (January to August) and minimum leaf water potential, indicating both predawn (Ψ_{pd}) and midday leaf water potential (Ψ_{md}), measured from 1999 to 2005 on mature (n = 4 to 6; David et al. 2007) and young cork oak trees (n = 18 to 27), in Herdade da Mitra, Évora, Portugal. Error bars are standard errors of the means. The annual precipitation was significantly correlated to predawn ($R^2 = 0.61$, $p = .02$) and midday ($R^2 = 0.73$, $p = .009$) minimum annual leaf water potentials.

The Control of Water Loss

How do trees manage their water status so as to avoid disaster? It is currently assumed that stomatal functioning evolved to control water losses so that plant water status is maintained above the threshold of xylem runaway embolism, thus preventing the plant from losing its water transport capability (Jones and Sutherland 1991; Jackson et al. 2000). How does cork oak compare to other plants in terms of xylem vulnerability? Compared with another evergreen species, western holm oak (*Quercus ilex* subsp. *rotundifolia*), whole-tree hydraulic conductance and minimum midday leaf water potential were higher in cork oak, suggesting greater drought resistance of holm oak

(David et al. 2007). In fact, western holm oak occupies drier sites than cork oak when they occur sympatrically. However, when compared with less drought-resistant, deciduous oaks, cork oak has been shown to have lower hydraulic vulnerability limits (Tyree and Cochard 1996; Nardini and Tyree 1999).

Using water sparingly is just one way for plants to resist drought or avoid it altogether. It is costly to the plant because when stomata close, transpiration is indeed reduced, but photosynthetic carbon assimilation drops as well. Cork oak trees keep their stomata more open at lower leaf water potentials than do more *mesophytic* species, such as turkey oak and Portuguese oak (Ksontini et al. 1998; Nardini et al. 1999), confirming this species' intermediate drought tolerance between the more mesophytic deciduous oaks and the evergreen holm oak. But if a drought-resistant plant keeps its stomata open when water runs short, it must compensate somehow for water loss. This is the topic we explore in the next section.

Water Acquisition, Root Systems, and Hydraulic Lift

To avoid dehydration and compensate for water loss, many Mediterranean woody plants have deep roots and extract water from a large volume of soil (Pereira et al. 2006). In a study carried out in Portugal, more than 70 percent of the water transpired by holm and cork oaks during the dry season was derived from groundwater (David et al. 2007). As a result, these deep-rooted species do not reach leaf water potentials as low as those observed in semideciduous, shallow-rooted rockrose species in the same region that dehydrate to the point of –5.5 MPa leaf water potential (Werner et al. 1999).

Mediterranean evergreen oak trees have a large number of roots growing horizontally and extending much farther than the crown projection limits and a few root branches growing geotropically toward the subsoil (Verdaguer et al. 2000; David et al. 2004). One study in Portugal showed that cork oak trees had root activity in two layers of the soil, one 40 to 100 centimeters deep and another reaching deep subsoil layers or the groundwater table (Kurz-Besson et al. 2006; Otieno et al. 2006). The upper (horizontal) roots allow the plant to acquire nutrients and water in the wet season, whereas deeper roots obtain water after desiccation of the upper soil horizons during the dry season. Survival through the summer results from the combination of low transpiration (stomata closed) and water uptake from deeper soil. In summer this root positioning allows some redistribution of groundwater to the shallower root system at night, through the process known as *hydraulic lift* (Figure 6.2).

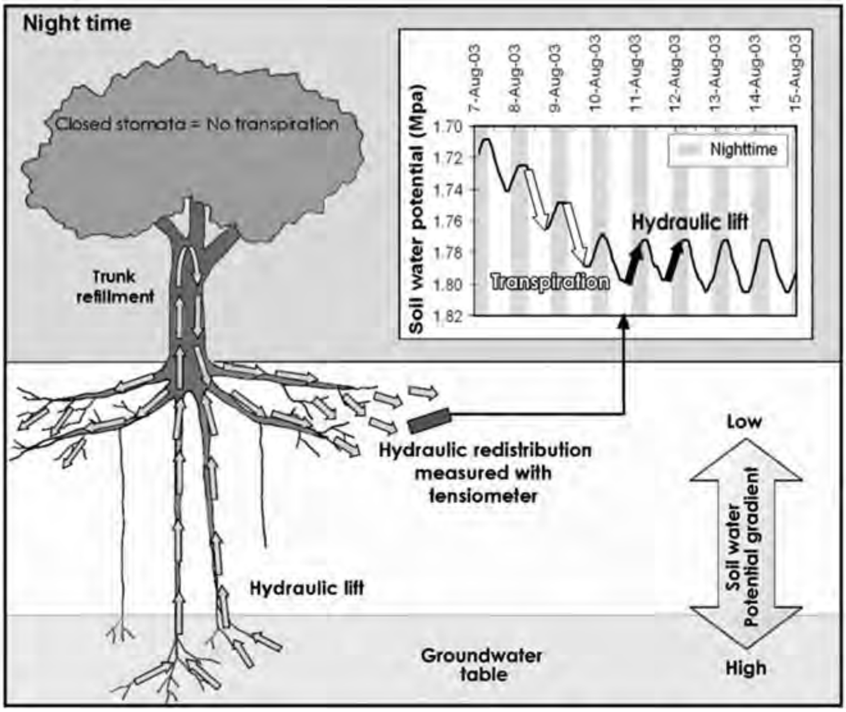


FIGURE 6.2. Hydraulic lift occurs at night, when cork oak stomata are closed. The soil water potential gradient between shallow and deep soil layers induces water transport through roots from deeper to shallower soil layers via hydraulic lift. After trunks are refilled, some water may be available for redistribution into shallow soil layers through fine roots (hydraulic redistribution). Hydraulic lift was illustrated using tensiometer measurements. The daily fluctuation in soil water potential resulting from transpiration (decrease) and hydraulic lift (increase) is illustrated in the insert (data in insert from Kurz-Besson et al. 2006).

Hydraulic lift is a passive mechanism driven by a water potential gradient that transports water through the root system of a tree or shrub, from deep, moist soil layers up to shallower and drier soil layers (Richards and Caldwell 1987). This mechanism can contribute to an increase plant transpiration the next day by providing water temporarily stored in upper soil layers. This water is also available to shallower-rooted neighboring plants (Dawson 1993; Caldwell et al. 1998; Kurz-Besson et al. 2006). Hydraulic-lifted water appears to help maintain some fine root activity in the upper soil horizons during the dry summer, thus permitting some nutrient uptake at a time of limited nutrient availability.

To survive drought, roots must be able to absorb water from soil that is drying out. This can be accomplished through the decrease of cell water potential achieved by osmotic adjustment. Because water moves from less negative to more negative potentials, a decrease in cell water potential, due to solute accumulation, should enable trees to extract water from a drying soil (i.e., more negative potential). Otieno et al. (2006) found a substantial osmotic adjustment in cork oak trees between May and July and observed a decrease in cell wall elasticity, allowing leaf water potential to decrease without forcing the tissue to lose too much water. More rigid cell walls also allow a rapid resumption of water uptake after rain and plant recovery. This is of great importance for survival in climatic regions with a long dry season and highly variable rainfall (Pereira et al. 2006).

Water Deficits and Growth

Water deficits affect plant growth by inhibiting cell growth, including the leaf area displayed for photosynthesis, and by causing a decrease in net carbon gain through decreases in the rates of photosynthetic carbon assimilation caused by stomatal closure. If leaf tissues become even more dehydrated, the chloroplast chemical machinery may be adversely and permanently affected (Chaves et al. 2002).

The evergreen habit is advantageous in Mediterranean-type climates because it allows plants to take advantage of every environmentally favorable opportunity for carbon uptake and growth (Larcher 2000). However, as summer drought progresses, foliage must withstand high temperatures and high exposure to sunlight. Simultaneously, as stomata close, transpiration decreases, thus reducing the capability for leaf evaporative cooling. Under these circumstances—high temperatures and high light—the energy of incident solar radiation becomes excessive and may inhibit photosynthesis or damage leaf tissues. Thus, not all the energy captured by leaf pigments can be used for assimilation because the supply of carbon dioxide is limited by stomatal closure.

To avoid damage to the photosynthetic apparatus, various protective adaptations are needed. Anatomical or morphological adaptations, including small and thick leaves, which are well adapted to hot, dry summers, allow efficient heat dissipation and an efficient control of water loss by stomatal closure (see Chapter 1). Dense trichome layers (Larcher 2000) and steep leaf angles (Werner et al. 1999) also help reduce incident light intensity. Thick leaves with high leaf area:mass ratios optimize carbon gain per unit of water lost by transpiration during the prolonged hot and dry periods (Givnish 1979).

As a consequence of the combination of stresses occurring in summer, photosynthesis declines in the second half of the season, as compared to early July (Faria et al. 1996, 1998). This late-summer decrease in net CO_2 uptake, affecting most Mediterranean woody species, is associated with a decrease in photochemical efficiency, most marked during the warmest part of the day, when carbon assimilation is limited by low stomatal conductance. This results from increased internal dissipation of excess energy in chloroplasts. In fact, more than 60 percent of the light energy absorbed by tree leaves at midday is dissipated on a hot September day. This serves as an important protective mechanism under drought conditions and is associated with the existence of large pools of xanthophyll pigments (carotenoids) that are able to dissipate the excess energy in the chloroplasts (Garcia-Plazaola et al. 1997). The fraction of excitation energy that is not thermally dissipated in the chloroplast may induce oxidative stress. High concentrations of antioxidants occur in cork oak leaves in the summer (Faria et al. 1996). The loss of chlorophyll in response to summer stress, observed in cork oak leaves, is also a form of protection of photosynthetic machinery because a lower proportion of the incident light is absorbed by the chloroplasts, thus avoiding oxidative stress.

In southwestern Europe, 2004 and 2005 were exceptionally dry; in southern Portugal, it was the driest episode in the last 140 years. From October 2004 to June 2005, total precipitation was roughly 40 percent of the long-term average (Garcia-Herrera et al. 2007). The cork oak trees studied by Otieno et al. (2006) suffered severe water stress during this season, with low carbon assimilation rates and a 32 percent decrease in annual trunk diameter increment as compared to 2004. During dry years, trees tend to produce narrow annual rings. In some cases, the annual ring is not formed at all or a second "false" ring occurs when cambial activity resumes after a dry period (Cherubini et al. 2003). In the next section we will see how this relates to cork production.

Water Deficits and Cork Stripping

Cork stripping may induce generalized stress in trees. The nature of this stress remains obscure, although stomata appeared to be more sensitive to water deficits in stripped trees (closing at higher leaf water potential than those in control trees) (Werner and Correia 1996). Concurrently, bark stripping stimulates the phellogen, the plant meristem that produces cork. Shortly after stripping, cork production takes precedence over wood growth, and as a result, the annual ring of wood is not formed or remains vestigial for one or even two years. In extremely dry years, a major problem may result from the inhibition of phellogen activity. The attempt to strip the cork will be frustrated by sealing of the interface *phelloderm*; cork and the bark will separate not through the phellogen layer (see Chapters 1 and 5) but through the vascular *cambium*. Unlike the phellogen, the vascular cambium does not regenerate, and stripping the bark under such conditions may lead to trunk damage (large scars) and eventually tree death. The timing of the onset of plant water deficits determines the deadline of safe cork stripping in late spring and early summer. The period during which cork can be stripped ends earlier in dry than in wetter locations.

Conclusions

Cork oaks are good examples of *isohydric* trees, that is, plants that survive dry seasons by avoiding severe dehydration. For that purpose, they rely heavily on water supply from large, deep root systems to compensate for transpiration water loss, which persists even with stomata partly closed. Deep rooting gives trees access to soil water unavailable to shallow-rooted plants. This has two major practical consequences. First, as discussed in Chapter 10, seedling survival will be negligible if roots do not reach a safe soil depth before the onset of the first dry summer. Therefore, restoration techniques must be geared to support early growth of a healthy, well-formed root system (but see also Chapter 11). Second, adult cork oak trees may become vulnerable to drought if repeated dry years (or a shift in climate toward greater aridity) prevent the replenishment of groundwater supplies. As a consequence, the successful restoration of cork oak ecosystems depends on an understanding of plant and soil water relationships and matching of restored and managed landscape features so as to optimize cork oak trees' access to water during the dry season. Likewise, chronic infections by root pathogens and poor root system development caused by soil characteristics or poor silvicultural techniques may reduce the effective size of the active root system, reducing the trees' ability to cope with drought. Therefore, all these factors must be monitored carefully. In the next chapter we will consider yet another contributing factor to cork oak trees' ability to cope with drought: the symbiotic relationship of tree roots with mycorrhizal fungi.

Acknowledgments

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Chapter 7

Mycorrhizal Symbiosis and Its Role in Seedling Response to Drought

Daniel Mousain, Hassan Boukcim,
and Franck Richard

As shown in Chapter 6, seasonal drought is an important limiting factor for photosynthesis and growth of Mediterranean trees and shrubs. Indeed, plant responses to drought involve adaptive mechanisms that vary depending on their genotype and on the type and combination of environmental stresses. Because plant (root)–soil (microorganisms) interactions are crucial to the mechanisms involved in plant response to drought, in this chapter we discuss the role of the most widespread mutualistic association between fungi and fine roots: *mycorrhizal symbiosis*. We give special attention to how these symbiotic relationships may modify the ecophysiological response of cork oak seedlings to drought. Because many readers may be unfamiliar with this area of study, we first review what is known from the literature and then present and discuss unpublished data from recent studies and experiments.

Mycorrhizal Symbiosis Diversity in Mediterranean Oaks

Schematically, mycorrhizal fungi are classified as ectomycorrhizal or endomycorrhizal, depending on their morphological relationship with the host plant, that is, whether the fungi occur outside or inside the root cells (Bergero et al. 2000). In both kinds of mycorrhizal symbiosis, the fungus enhances the absorption of soil nutrients by roots while obtaining recent photosynthate from the plant as an organic carbon source. *Ectomycorrhizae (ECMs)* are generated by septate fungi belonging to the Ascomycetes and Basidiomycetes, which associate with the roots of most extratropical trees, such as pines (Pinaceae), oaks (Fagaceae), birches (Betulaceae), hazelnuts (Corylaceae), willows and poplars (Salicaceae), eucalypti (Myrtaceae), and the giant tropical Asian trees of the Dipterocarpaceae (Smith and Read 2008). Worldwide, at least 6,000 species of fungi are known to be involved in ectomycorrhizal symbiosis. However, the most widespread association involves only a few hundred fungal species from the Glomeromycetes (orders Glomales and Gigasporales) that form endomycorrhizae, known as *arbuscular mycorrhizae (AMs)*, with the roots of a wide variety of plants in all terrestrial ecosystems (Smith and Read 2008). A third form of mycorrhiza, *ericoid mycorrhiza (ERM)*, occurs in most members of the heath family (Ericaceae) and involves restricted groups of Ascomycetes that are predominantly absent from ectomycorrhizal tree species (Vrålstad 2004; Villarreal-Ruiz et al. 2004).

Symbiotic fungi associated with the various Mediterranean oaks have only recently begun to be documented, but it is clear that both ectomycorrhizal and *saprobic* fungal communities are highly diverse (Richard et al. 2004; Smith et al. 2007). Cork oak, in particular, has been shown to associate with a wide range of ectomycorrhizal fungi (Ortega and Lorite 2007). Like most oak species (Bergero et al. 2000; Dickie et al. 2001; Egerton-Warburton and Allen 2001), this ectomycorrhizal plant species could also be associated with both arbuscular and ericoid fungi, either concomitantly or successively during tree development. Interestingly, this sharing may affect fruiting patterns of macrofungi—including edible species of *Amanita*, *Boletus*, *Russula*, and *Tricholoma*—that grow under Mediterranean oaks (Berrahmouni et al. 2007). For example, in Andalusia, southern Spain, cork oak woodlands show a higher macrofungal diversity than holm oak forests because of a richer ectomycorrhizal guild (Ortega and Lorite 2007). Therefore, cork oaks might be a source of biological and culinary diversity via their ectomycorrhizal partners.

Coming back to our main subject, we recall that a critical bottleneck for cork oak woodland dynamics is the low seedling survival during the summer drought period (see also Chapters 1 and 11). Despite the lack of knowledge about the composition of mycorrhizal associations involving cork oak seedlings, the well-known influence of ectomycorrhizal fungi in oak ecology (Dickie et al. 2002) suggests that ectomycorrhizal fungi should be taken into account in the outcome of seedling establishment. In the next section we review some of the beneficial effects of the mycorrhizal symbiosis on drought tolerance and water balance in host trees (through improvement of their mineral nutrition) and then address the potential benefits of ECMs for cork oak, in terms of both morphological and physiological responses to drought.

The Role of Mycorrhizal Symbiosis in Drought Tolerance of Trees

Many experiments have shown that plants associated with ectomycorrhizal fungi make better use of soil water when its availability is reduced (Garbaye and Guehl 1997). The mycelial networks could also play a crucial role in the absorption and transport of water, especially under drought conditions (Lamhamedi et al. 1992; Plamboeck et al. 2007). These hyphal links may create continuous connections between the soil solution and root systems. This fungal interface reduces damages on roots that could be caused by soil shrinkage and cracking (Reid 1978). In addition, mycorrhizal fungi are more efficient than roots in extracting water at very low water potential (Garbaye and Guehl 1997 and references therein). At the specific level, there are great differences between mycorrhizal fungi and plants, respectively, in their ability to influence root *hydraulic conductance and conductivity* of host plants (Nardini et al. 2000; Augé 2001; Mushin and Zwiazek 2002).

Ectomycorrhizal fungi improve mineral nutrition and induce changes in production, by the host plant, of abscisic acid and cytokinins, two hormones that regulate the water status of plants (Garbaye and Guehl 1997. In particular, mycorrhizal symbiosis stimulates the absorption of P by the plant, and the fungus stores *polyphosphate* (Mousain et al. 1997). Interestingly, the accumulation of assimilated P is also influenced by the form of the available mineral N (Smith and Read 2008). Some ectomycorrhizal fungi have been shown to modify the osmotic adjustment in host tree cells resulting from the accumulation of mineral ions and synthesis of organic acids (Plassard et al. 1997). Because of root colonization by some ectomycorrhizal fungi, increases of net photosynthesis and improvement of water status that are often observed in host tree seedlings can be partly attributable to the improvement of their osmotic regulation and P nutrition (Coleman et al. 1990; Guehl and Garbaye 1990; Rousseau and Reid 1990, 1991; Guehl et al. 1992). These mycorrhizal effects are observed only at low P concentration in leaves ($<<$0.01 percent; Guehl and Garbaye 1990; Rousseau and Reid 1990, 1991).

The effects of ectomycorrhizal fungi on the ecophysiology of host trees vary according to changes in environmental conditions and interspecific and intraspecific variation in both host trees and fungal symbionts (Smith and Read 2008). For instance, holm oak seems to be more adapted to drought than cork oak (Faria et al. 1998) because of distinct rooting strategies in the two species (Chaves et al. 2002). Indeed, root system architecture in general has a crucial role in the adaptation of seedlings to environmental conditions because root dynamics directly affects both nutrient and water uptake by plants and their mycorrhizal colonization (Boukcim et al. 2001).

Cork Oak Response to Drought and ECMs

Root architecture responses of cork oak to drought may result from their geographic origins and their genetic introgression with holm oak (Chapter 2; Boukcim et al. unpublished data). To date, few studies have been made on the effects of phylogeography on oak physiology and ecology. Here we report original data on the effect of water restriction on the root system architecture of cork oak and holm oak seedlings from various geographic provenances, both under controlled conditions and in the field. Correlations between cork oak provenances and the physiological responses of ectomycorrhizal symbiosis were specifically sought along lines used by Boukcim and Plassard (2003) to address the same question in European spruce (*Picea abies*).

In particular, we compared cork oak populations from two origins: a genetically introgressed provenance (i.e., hybridized at the cytoplasmic level with the more drought-resistant holm oak) and nonintrogressed populations. For purposes of inoculation, we used a species of the genus *Pisolithus* (Basidiomycetes), which is widespread in warm temperate regions around the world and frequently found in cork oak woodlands (Marx 1977). When associated with cork oak, *Pisolithus* species generate simple branched, yellowish

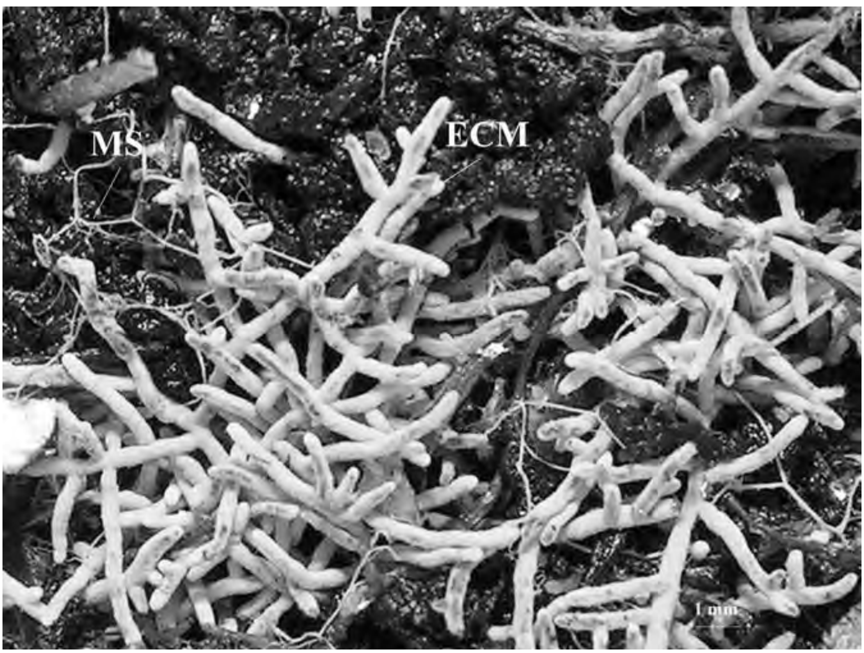

FIGURE 7.1. Cluster of *Quercus suber* and *Pisolithus arrhizus* ectomycorrhizae, with emanating mycelial strands. (Negative from G. Héry)

ECMs, from which mycelial strands emanate (Figure 7.1). The potential adaptation of these fungi to soil stresses (Marx et al. 1984) led us to consider *Pisolithus* spp. as prime candidates for studying the role of mycorrhizae in promoting drought tolerance in cork oak.

There is a known correlation between the drought tolerance of ectomycorrhizal fungi cultivated in vitro and that of their plant associate (Garbaye and Guehl 1997). In this light, we conducted a greenhouse experiment to test whether the fungus *Pisolithus arrhizus* (see Martin et al. 2002) could improve the recovery of eighteen-month-old cork oak seedlings that were submitted to an artificial drought–irrigation cycle of fifty-two days. Next, using the same fungal strain, we conducted a complementary field trial to study the impact of nursery mycorrhization on performance of cork oaks in the field. Here, we summarize our findings.

Greenhouse Experiment

Inoculated and noninoculated seedlings from two geographic origins (Espadà, Spain and Var, France), known to be genetically distinct (Lumaret et al. 2005; Chapter 2), were exposed to two watering regimes (well irrigated and water restricted). In the water restriction treatment, mycorrhization yielded contrasting effects on predawn leaf water potential values ($\boldsymbol{\Psi}_{pd}$), according to the phylogeographic origins of cork oaks: Mycorrhized seedlings from Espadà recovered entirely, noninoculated seedlings from Espadà and Var recovered only partly, and mycorrhized seedlings from Var did not recover at all. In other words, during the water restriction phase, inoculated seedlings from Espadà maintained $\boldsymbol{\Psi}_{pd}$ at higher values (higher than –3.6 MPa) than all the inoculated seedlings from Var ($\boldsymbol{\Psi}_{pd}$ less than –5.5 MPa), whereas noninoculated seedlings from the two provenances showed only several $\boldsymbol{\Psi}_{pd}$ values less than –5.5 MPa. Seedlings from Espadà that were exposed to the same treatment showed stomatal conductance values between 0.08 and 0.25 mol/m^2/s for most of them when inoculated and values ranging from 0.04 to 0.13 mol/m^2/s when noninoculated. In contrast, these patterns were not observed in seedlings from Var. In conclusion, there was an interaction between mycorrhization and geographic origin of cork oak for seedling recovery at the end of the drought–irrigation cycle.

Field Experiment

A field plot was established at Montesquieu-des-Albères (Eastern Pyrenees, southern France) in December 2004, in a site that was exposed to periodic droughts, in order to study the impacts of nursery mycorrhization with *P. arrhizus* and phylogeographic provenances on cork oak ecophysiology. The purpose was to compare inoculated and noninoculated seedlings from both Eastern Pyrenees (P-O) and Sardinia (SAR). In addition to growth and ecophysiology of seedlings, the persistence of the inoculated strain and its distribution on the roots were examined.

One year after the beginning of the experiment, shoot elongation was significantly enhanced by mycorrhization with *P. arrhizus* in P-O seedlings only. This effect clearly resulted from the stimulation of branching and length of thin branches (Figure 7.2).

We also assessed leaf C isotope discrimination ($\Delta^{13}C$) of seedlings, after both one and two years, and determined that it was influenced by mycorrhization with *P. arrhizus*, regardless of geographic origin. Irrespective of the cork oak origin (P-O vs. SAR), averaged $\Delta^{13}C$ values were significantly lower in inoculated than in noninoculated seedlings. Isotopic signature has been used to estimate *water use efficiency (WUE)* in C_3 plants: $\Delta^{13}C$ values are inversely correlated with WUE on a growing season time scale (Farquahr et al. 1989). This result suggests that *P. arrhizus* mycorrhizae increased the intrinsic water use efficiency in cork oak seedlings.

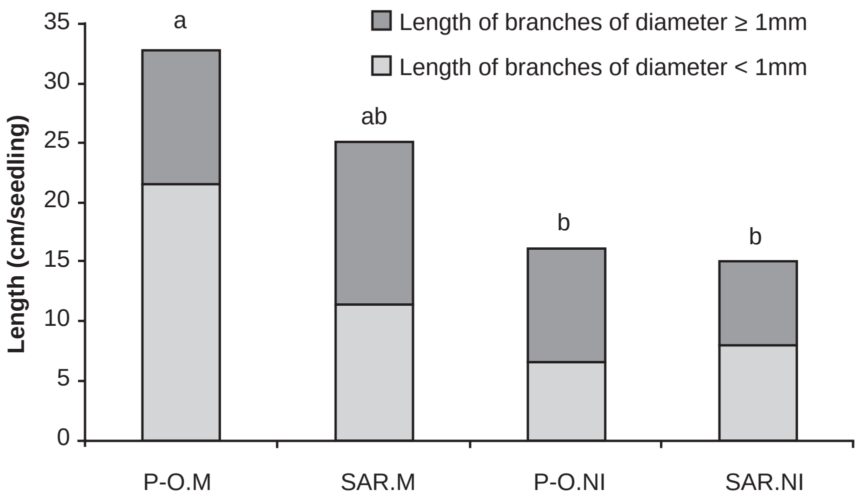

Figure 7.2. Effects of nursery mycorrhization with *Pisolithus arrhizus* on elongation of shoot branches in cork oak seedlings from eastern Pyrenees (P-O) and Sardinia (SAR) after 1 year (Montesquieu-des-Albères, P-O, southern France). M, nursery mycorrhized seedlings; NI, noninoculated seedlings. Values with different letters are significantly different ($p < .05$). (Mousain et al. unpublished data)

Two years after the beginning of the experiment, only nursery-inoculated seedlings growing in the field still showed *Pisolithus*-like ECMs. Genetic markers confirmed that these ECMs were generated by the strain that was initially inoculated in the nursery. In contrast, and despite the occurrence of *Pisolithus* spp. fruitbodies lasting many years in the same site, no *Pisolithus*-like ECMs were detected on any noninoculated seedlings.

These results indicate that the effects of ectomycorrhizal fungi, such as *Pisolithus arrhizus*, resulted in a stimulation of cork oak growth and increased water use efficiency of seedlings during the first two growing seasons. These data are of obvious interest for those seeking to establish cork oak seedlings in the field.

Conclusions

Throughout its geographic range, cork oak suffers frequent periods of water deficits; a crucial step in afforestation and restoration projects in the Mediterranean area is thus achieving seedling survival during the critical first growing season (Gómez-Aparicio et al. 2004). As mentioned earlier, ectomycorrhizal symbiosis has beneficial effects on the regulation of water status of cork oak, particularly via an improvement of its mineral nutrition, as well as through indirect mechanisms. Our studies showed a genetically dependent response of seedlings to drought, in terms of both resistance and recovery dynamics. Furthermore, comparison between inoculated and noninoculated seedlings showed that inoculation helps seedlings survive long-term drought. Complementary experiments, including long-term monitoring of inoculated seedlings, are needed to refine our understanding of the ecophysiological responses of cork oak to drought and assess the impacts of nursery-based mycorrhization with a selected fungal strain in the field. In the next chapter the authors discuss the equally important topic of the soils associated with the cork oak tree.

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Chapter 8

Soil Properties Constraining Cork Oak Distribution

Isabel Serrasolses, Marian Pérez-Devesa, Alberto Vilagrosa, Juli G. Pausas, Teresa Sauras, Jordi Cortina, and V. Ramon Vallejo

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

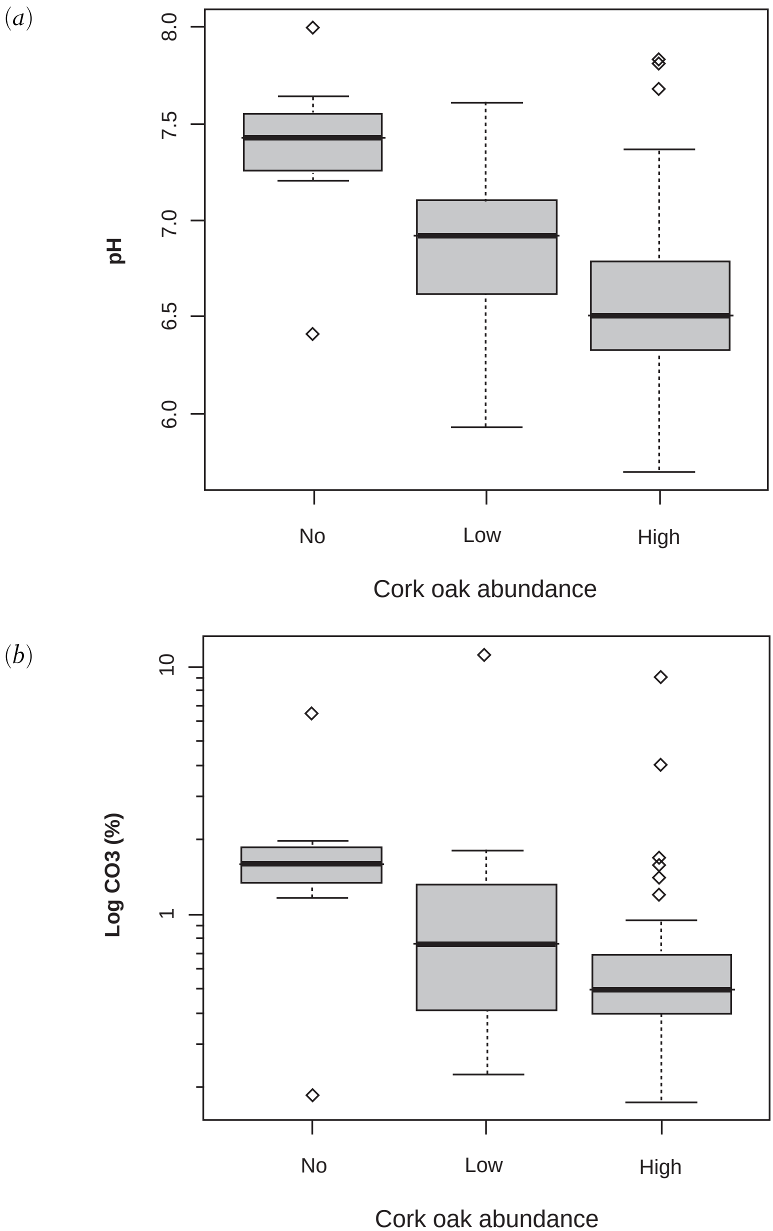

FIGURE 8.1. Relationships between cork oak abundance classes and *(a)* soil pH and *(b)* soil carbonate content in Pinet forest (eastern Spain; data from Pausas et al. 2006). In both cases, differences are statistically significant (one-way ANOVA, $p <$ .0001). Box plots indicate medians, quartiles *(boxes)*, 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.

(*a*)

(*b*)

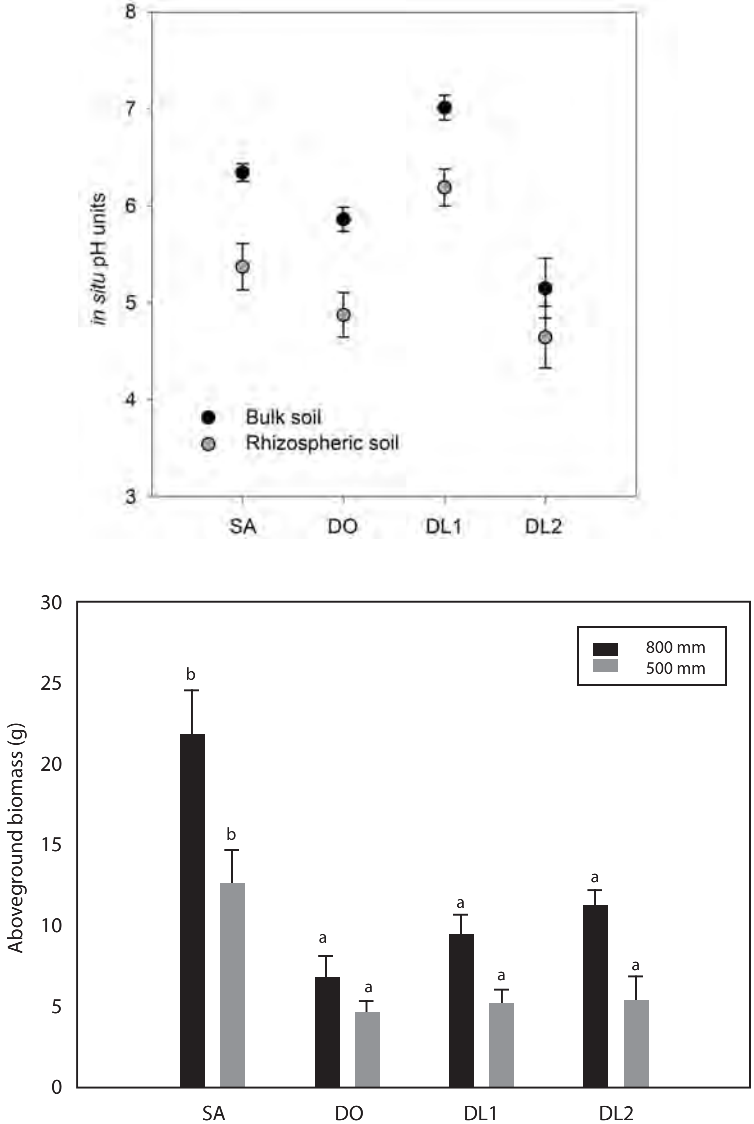

FIGURE 8.2. *(a)* In situ pH of bulk and rhizospheric soil of cork oak seedlings planted in four contrasted soil types: 2 carbonate-free soils derived from siliceous sandstone (SA) and dolomite (DO) and 2 carbonated soils developed from dolomitic limestones (DL1 and DL2). *(b)* Aboveground biomass of 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.

Acknowledgments

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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).

Chapter 9

Coping with Pests and Diseases

Manuela Branco and Ana Paula Ramos

As mentioned in previous chapters, cork oak trees are vulnerable to several kinds of biotic agents in various ways and at all stages of their lives. Vertebrates, including large mammals and rodents, as well as dozens of insects and microbial pathogens all affect cork oak seeds and seedlings and, consequently, the natural regeneration and afforestation of cork oak woodlands (see Chapters 10 and 12). Mature stands of trees are also subject to a wide variety of pests and diseases, with profound implications for tree vigor, mortality, and productivity of individual trees and entire stands or populations. At moderate to high levels of incidence, the effect of biotic agents may trigger the decline of ecological functions of this type of forest and endanger its sustainability. In particular, tree mortality, crown cover reduction, and reduced natural regeneration may directly influence the floristic composition of the herbaceous and shrub layers of vegetation, as well as fauna and the overall hydrologic regime of the woodland. The sociological and economic importance of herbivores, insect pests, and diseases can also be high because they can reduce the quantity and quality of cork produced, with consequent impact on income for landowners and employment opportunities for local people. A reduction in acorn production and seedling mortality, affecting both natural regeneration and restoration success, also has adverse economic impacts with respect to animal production, stand age structure, tree density, and the eventual costs of replanting cork oak trees.

Until recently, pests and diseases did not markedly affect cork oak, except for periodic outbreaks of defoliator insects. However, in the last few decades a dramatic decrease in holm oak and cork oak regeneration and an increase in both trees' vulnerability to pests and diseases have been confirmed throughout the western Mediterranean (e.g., Gallego et al. 1999; Sousa and Debouzie

1999). Increasingly intensive management practices and the documented increase in aridity during recent decades in the Mediterranean region may have augmented the vulnerability of various oak and other tree species to pests and diseases (Vannini et al. 1996; Martín et al. 2005; see also Chapters 18 and 19). Therefore, a better understanding of how biotic agents affect tree health is pertinent to the subject of this book.

Biotic Factors Affecting Acorns, Seedlings, and Young Plantings

Insects, such as weevils (e.g., *Curculio elephas*) and moths (e.g., *Cydia* spp.), severely affect the viability of immature cork oak acorns. The numbers of insect-attacked acorns vary greatly between years and stands, depending in part on local acorn production in previous years. Such attacks often exceed 60 percent of the acorns produced (Branco et al. 2002). Larval feeding activity seldom causes direct damage to the embryo, and the ability of seeds to germinate is only weakly affected. However, acorns that are intensely attacked are lighter and tend to have a higher water content. As a result, they are much more vulnerable to rotting fungi than acorns escaping predation. Consequently, higher postgermination mortality occurs, and more seedlings with reduced vitality are produced (Branco et al. 2002).

Having fallen from the tree to the ground surface, pregerminated acorns are heavily attacked by a variety of vertebrates, such as cattle, wild boars, and mice, and many invertebrates as well (Herrera 1995). After emergence of the epicotyls, young seedlings are prone to browsing by vertebrates, such as mice, rabbits, and deer. In open cork oak woodlands, these successive mortality factors dramatically reduce seedling establishment, and regeneration may be heavily or even totally compromised.

Restoration and nursery activities may also be seriously compromised if biotic agents are not taken into consideration. The humid conditions necessary to maintain acorn viability during storage provide optimal conditions for fungal pathogens, such as *Cylindrocarpon didymum* and *Ciboria batschiana* (Guthke and Spethmann 1993). Additionally, insects are able to maintain their feeding activity during storage. Therefore, to prevent further damage during storage or sowing, heat treatment of acorns is advisable (see Chapter 11).

Fungi, such as *Botrytis cinerea*, *Fusarium* spp., *Erysiphe alphitoides*, *Phytophthora* spp., and *Pythium* spp., may also affect the emergence and survival of seedlings. Robin et al. (2001) and Rodriguez et al. (2002) reported that *Phytophthora cinnamomi* could be pathogenic to cork oak seedlings, although these were less susceptible than seedlings of holm oak. Depending on the pathogen, symptoms may consist of yellowing, browning, or wilting of leaves and damping-off or extensive necrosis of fine roots, resulting in poor growth and death of seedlings. The incidence of most diseases affecting seedlings, such as damping-off, gray mold (caused by *B. cinerea*), and powdery mildew (caused by *E. alphitoides*), is increased by soil flooding. Therefore, the control of these diseases in nurseries is readily achieved by removing infected and infested debris and providing proper ventilation. Yet chemical treatments may also be necessary in periods of cool, damp weather.

After planting, heavy losses are caused by biotic factors, such as browsing by vertebrates and root-feeding insects. Roots of young plants, two to six years old, may still be intensely attacked by mice and moles, and their stems browsed by rabbits, cattle, and deer. Devices to protect young plants from browsing are widely used in cork oak plantations (see Chapter 12). However, these devices do not prevent attacks on roots from rodents and insects. The use of baits or repellants or the removal of refuges, such as shrubs and pasture plants, may be necessary in the case of intense rodent attacks. Additionally, repeated attacks by insect defoliators may reduce tree growth, and repeated infections in the foliage, such as powdery mildew, might cause young tree death.

In conclusion, several biotic agents affecting acorns, seedlings, and young plants may threaten both natural regeneration and afforestation projects in cork oak ecosystems. Anthropogenic factors, such as woodland multiuse, associating pastures or agricultural crops with low-density woodland stands (which characterize mainly the Iberian *montados* and *dehesas* and related systems in North Africa), may further compromise the regeneration of these cultural landscapes and ecosystems.

Biotic Factors Affecting Mature Trees

Seedlings and young trees are more vulnerable to pests and diseases than adult trees. With age, trees become more tolerant and resistant. Nevertheless, insect pests and diseases also affect mature oak trees in a surprising number of ways, as discussed in this section.

Insects Feeding on Foliage

Cork oak trees often are vulnerable to defoliation by insects during outbreaks, which may extend to several thousands of hectares and persist for two or more successive years. Moths (*Lymantria dispar*, *Malacosoma neustria*, *Euproctis chrysorrhoea*, and *Tortrix viridiana*) are the most important cork oak defoliators throughout the Mediterranean (Luciano and Prota 1995; Villemant and Fraval 1999). In some areas, severe cork tree defoliations, caused by the diprionid *Periclista andrei* and weevils (*Orchestes* spp.), have also been reported (Ferreira and Ferreira 1991; see Color Plate 11c).

The populations of most of the cork oak defoliator species are likely to reach outbreak proportions. However, whereas outbreaks of *T. viridiana* and *P. andrei* are observed to be sporadic and temporary (Luciano and Prota 1995), those of *M. neustria* and *L. dispar* are periodic, with gradation periodicity amplitude varying from five to twenty years in different regions (Luciano and Prota 1995; Villemant and Fraval 1999). Numerous natural enemies may contribute to the control of the cork oak defoliators, namely parasitoids, predators, and *entomopathogens*. Some of these agents may be important mortality factors. However, for the most part their role in the regulation of defoliator species and their population dynamics are not well understood. Alternatively, interactions with host species may influence the performance of these herbivorous insects and consequently their population dynamics. Their populations may be regulated by food depletion and reduction of foliage quality during outbreaks. The evolutionary history of herbivorous insect species and populations with their hosts may further account for their population dynamics. This effect might explain why higher performance of the gypsy moth is observed while they feed on cork oak foliage (Luciano et al. 1999), whereas *M. neustria* larvae showed higher performance in holm oak and downy oak (*Quercus pubescens*) leaves (Verdinelli and Sanna 2003).

Severe cork oak defoliations reduce acorn production, stem diameter growth, and cork growth (Magnoler and Cambini 1973). Cork quality and cork stripping are also affected in subsequent years. For this reason and to minimize stress to the damaged trees, cork extraction should not be done in the two years after a defoliator outbreak. Additionally, trees weakened by intense defoliation are exceptionally vulnerable to other pests and diseases. Conversely, adequate silvicultural practices, such as water and fertilization, can reduce the effect of severe oak defoliations (Cesaroli et al. 2004).

The importance of insect-caused defoliation for the economy of cork oak woodland justifies efforts to control of these pests. In the first half of the twentieth century, broad-spectrum insecticides (DDT and arsenates) were used against cork oak defoliator insects (Neves 1950), but in recent decades particular attention has been paid to integrated and ecologically sound pest control strategies (e.g., *Bacillus thuringiensis* strains, *antiquitines*, and pheromone-based traps) (Serrão 2002).

Insect defoliators are the major biotic agents affecting mature foliage. Other herbivores, such as gall makers and sapsucker insects, mainly aphids, occur frequently on cork oak trees. However, their damage usually is minor. Nevertheless, sporadic outbreaks of aphids may occur in favorable circumstances, evidenced by the sooty mold fungi and honeydew in the foliage (Roversi et al. 1997). Apart from insects feeding on foliage, other biotic agents may cause symptoms on the tree crown, such as discoloration of leaves, crown transparency, branch death, and dieback, as reviewed in the following sections.

Bark- and Wood-Boring Insects

Wood-boring insects affect primarily trees that are stressed, weakened, or decaying. Therefore, the economic impact of this guild of phytophagous insects is usually minor. However, in favorable circumstances some species may become major pests through aggregation behavior, local increases in population densities, or associations with pathogenic fungi. Three main groups of bark- and wood-boring insects are associated with cork oak trees: ambrosia beetles (especially *Platypus cylindrus*), two buprestids of the genus *Coroebus*, and longhorn beetles (*Cerambix cerdo*, *C. welensii*, and *Prinobius* spp.).

The ambrosia beetles, recognizable by the transport spores of fungi with which they colonize brood galleries inside trees, are usually known to attack decaying trees. However, increasing population levels of *P. cylindrus* have been found in cork oak stands in recent decades, and attacks on apparently healthy and young trees have been observed, suggesting an association with cork oak forest decline (Sousa and Debouzie 1999).

The buprestid *Coroebus florentinus* makes larval longitudinal and annular galleries under the bark of the branches, interrupting the sap flow and thereby causing branch death. Economic damage reflects the loss of tree foliage and consequent tree growth loss. This species is endemic to almost all cork oak stands, usually at low density. Isolated or edge trees and tree parts exposed to sunlight are reported to be more prone to attacks (Ferreira and Ferreira 1991). Pruning and burning of the attacked branches before the emergence of the adults is the main control strategy prescribed for this species.

Another buprestid, *C. undatus*, is frequently found in cork oak stands. The larvae feed under the bark of the tree trunk, excavating galleries in the cambium, where the new cork tissue is formed. Consequently, severe economic losses in cork production and cork quality occur (Merle and Attie 1992). Cork removal is further hindered by larval activity. The attack becomes most visible after peeling, when larval galleries are observed on the inner sides of cork planks. Drought stress; sandy, poor, and skeletal soils; and south-facing slopes are associated with a higher incidence of this pest (Merle and Attie 1992). Severe damage to cork by *Crematogaster scutellaris* (Hymenoptera: Formicidae), resulting from their nest building activity, has been also observed (Soria et al. 1994).

The longhorn beetles, such as the genera *Cerambix* and *Prinobius*, are xylophagous species whose immature stages develop inside the trunks of decaying trees. Despite being secondary pests, *Cerambix* spp., particularly *C. cerdo*, are associated with cork oak decline and are able to induce tree death (Martín et al. 2005). Tree weakening caused by increased aridity in Mediterranean areas benefits *C. cerdo* and several other xylophagous pests. Damage caused by inappropriate cork removal or pruning may be a prime cause of the increase in holes made by *C. cerdo* beetles, which act as entryways for fungal infection by *Biscogniauxia mediterranea* (Martín et al. 2005). Nevertheless, because of its recognized association with decaying or dead trees, which tend to disappear in European forests because of sanitary management practices, the European Directive (Habitat Directive, Annex IV, 1992) listed *C. cerdo* as a protected species.

Diseases Affecting Mature Trees

Franceschini et al. (1993) reported more than 300 fungal species occurring on cork oak. However, the majority of these fungi are secondary pathogens with either *endophytic* or saprophytic behavior (Luque et al. 2000). Cork oak canker (causal agent *Botryosphaeria stevensii*), charcoal disease (causal agent *B. mediterranea*), and root diseases caused by *Armillaria mellea* and *P. cinnamomi* are the four main fungal diseases of cork oak stands (Franceschini et al. 1993; Robin et al. 2001). Stress and trunk wounds are the main predisposing factors for both charcoal disease and cork oak canker; therefore, the best control for these diseases lies in proper management practices to improve tree vigor and prevent trunk injuries.

P. cinnamomi has been regarded as the principal cause of cork oak mortality in Portugal and southern Spain (Brasier 1996; Moreira and Martins 2005). Both root and butt symptoms (e.g., necrosis of fine roots, root rot, butt rot, cankers, and tarry exudations) and crown symptoms (e.g., foliage wilting, yellowing, and defoliation) may be observed. Several studies have demonstrated the pathogenicity of the fungus on seedlings that are one to two years old or on excised shoots (e.g., Gallego et al. 1999). However, there is evidence that cork oak is less susceptible to *P. cinnamomi* than other oaks (Robin et al. 2001; Rodriguez et al. 2002). Fernandez-Escobar et al. (1999) showed that injecting potassium phosphonate into the trunk of diseased cork and holm oak trees appeared to arrest the development of symptoms when

P. cinnamomi was present. Although the results of the experimental treatments are promising, more research is needed to evaluate their long-term effectiveness.

Decline and Loss of Productivity in Adult Stands: Forestry Practices and Protection

In the last three decades, a decrease in vigor of cork oak trees has been documented throughout the western Mediterranean. The oldest references to cork oak decline in the Iberian Peninsula date back to the end of the nineteenth century (e.g., Câmara-Pestana 1898); however, it was only in the 1980s that cork oak mortality became a matter of concern for the future of these ecosystems. The most common symptoms of cork oak decline are trunk cankers, wounds, tarry exudates from the bark, reduced branch growth, *epicormic* shooting, necrotic lesions in the root cortex, defoliation and transparency of the crown, *chlorosis*, dieback, and finally death. This may occur suddenly in one season (young trees) or two to three seasons (mature trees), or as a chronic process evolving slowly for several years until tree death. Oak tree decline can affect single, scattered trees or occur in foci within stands.

A wide range of factors have been associated with this general decline, including recurrent periods of severe drought, air pollution, the occurrence of compact layers and waterlogging, changes in traditional uses of forests, attacks by wood-boring insects, and diseases caused by fungi, bacteria, mycoplasma-like organisms, and viruses (Ragazzi et al. 1995). Biotic agents associated with cork oak decline vary between regions. In Italy, much emphasis has been given to defoliator insects (e.g., Luciano and Prota 1995). In Portugal, although intense outbreaks of defoliator insects were often reported in the first half of the twentieth century (Neves 1950), since the 1970s these attacks have declined in intensity and are restricted to limited areas in the Tagus River valley (M. Serrão, personal observations, 2002). Wood borers and fungi, particularly *P. cinnamomi*, seem to be the major biotic agents associated with cork oak decline on the Iberian Peninsula. In fact, the involvement of soilborne pathogens seems to be the most plausible explanation for the decline symptoms. The fact that *P. cinnamomi* has been isolated from the *rhizosphere* and the roots of a large number of holm and cork oak trees in Spain and Portugal corroborates the hypothesis of this fungus being the major pathogen involved (Brasier et al. 1993; Moreira and Martins 2005). As argued by Brasier (1996), because cork oak is more resistant to the pathogen than other tree species (e.g., chestnut, *Castanea sativa*), the infection may be maintained at low levels for a long time. The infected trees may be then more vulnerable to the effects of environmental stresses, such as drought (see Chapter 6).

Indeed, abiotic factors, such as drought or alternating drought and wet periods in poorly drained soils, seem to play an important role in cork oak decline (see Color Plate 11a). For example, Brasier (1996) analyzed the potential influence of global warming in enhancing *P. cinnamomi* spread (see also Chapter 18). Some management practices, such as herbicide use (Marks and Cerra 1991) and soil compaction by heavy machines (Moots et al. 1988), might also contribute to cork oak decline and, in particular, to the increasing incidence of *P. cinnamomi*. Robin et al. (1998) detected *P. cinnamomi* more often in managed forests than in undisturbed ones, which highlights the importance of human activities in the spread of the pathogen.

Recently, Jiménez et al. (2008) reported *Pythium spiculum* and *Pythium sterilum* on holm and cork oak trees, in Spain and Portugal, causing root rot similar to that induced by *P. cinnamomi*.

Despite all the recent studies, the precise causes of generalized cork oak decline remain unclear. Cork oak stands are complex and sensitive ecosystems where an array of land uses, from cattle rearing and other agricultural practices to cork stripping, coincide. Any changes in the physical and biotic parameters may increase stress in trees, affecting their defense mechanisms against insects and pathogens. The increasing incidence of *P. cylindrus*, *Cerambix* spp., and *B. mediterranea* may be seen as a reflection of such a situation. Inadequate site conditions, such as soil compaction, poor soil chemistry, and erosion, are predisposing factors that weaken the trees in the long term without necessarily producing decline symptoms (Thomas et al. 2002). A second set of abiotic and biotic stress factors, such as drought and defoliation, may also reduce tree vigor, soil fertility, and the diversity of mycorrhizae associated with cork oak stands (see Chapter 7). Bark injuries and bad pruning practices may further expose unprotected surfaces of the trunk to pathogen invasion (Vannini et al. 1996). Finally, stressed trees succumb to insects and fungi that usually do not affect healthy trees but under favorable conditions can induce or accelerate the death of trees and the degradation of stands, whether alone or in synergistic relationships.

Conclusions

Cork oak decline is a major concern throughout the western Mediterranean. Biotic agents are important factors affecting tree mortality and regeneration. Nevertheless, the effect of such agents depends on abiotic factors, such as drought and poor soil drainage, as well as management practices. This is why particular attention should be paid to the interactions between trees, biotic and abiotic factors related to pests and diseases, and management practices. In this context, cork oak protection depends on the involvement of landowners and other stakeholders. There should be wider efforts to raise awareness of the impact of exploitation practices on trees. Therefore, in Chapter 10 the importance of restoration and best management practices to natural tree regeneration is described.

SITE PROFILE 9.1

Maremma, Italy

The cork oak woodlands at this Italian site have recently shown symptoms of pests and diseases, a problem that is increasingly common throughout the region and made worse by increasing drought.

Geographic and biophysical description	Several patches in southwest Tuscany (Maremma), mainly north of Grosseto, are considered here. There are two main areas: several thousand hectares of mixed cork oak and holm oak (*Quercus ilex*) at Monte Leoni (42°0.50′–43°0.00′N, 11°0.00′–11°0.16′E) and Poggio Ballone-Monte Alma (42°0.47′–42°0.54′N, 10°0.48′–10°0.58′E) and several hundred hectares of pure stands of cork oak in the same 2 areas. Smaller woodland patches are found on the hills between Roccastrada and Montemassi, and others are scattered in southwestern Tuscany. These woodlands occupy gently rolling hill slopes between 50 and 550 m above sea level, rarely in plains. The climate is meso-Mediterranean, with mean annual precipitation of 700–880 mm and mean annual temperature of 13.5–14.5°C. Siliceous bedrocks of quartzites, anagenites, sandstones, volcanic rhyolites, or rarely alluvial sands underlie shallow layers of acid soil (entisols) or brown Mediterranean soils with subacid humus.
Physiognomic description of the cork oak woodlands and their landscapes, including woodland dynamics	Cork oak and holm oak form the dominant layer of tall (ca. 12–18 m) and dense maquis, with tree heath (*Erica arborea*), strawberry tree (*Arbutus unedo*), laurustinus (*Viburnum tinus*), and other sclerophyllous shrubs. In the absence of coppicing, vegetation tends toward a holm oak–dominated forest in which cork oak is shaded out. In managed situations, cork oak is the dominant tree of a lower, open maquis, with heliophylous shrubs including myrtle (*Myrtus communis*), broom (*Cytisus villosus*), lavender (*Lavandula stoechas*), and rockrose (*Cistus* spp.).
History of land uses, land tenure (and socioeconomic drivers), and current land uses, economic activities, and context	In most cases, the mixed holm oak–cork oak maquis derives from coppicing practiced since the Middle Ages for the production of fuelwood and charcoal. The holm oak trees are still cut every 15–18 years, but cork oak is always preserved for cork production, a practice dating from the late nineteenth century. After a period of abandonment in the 1940s and 1950s, production has revived and is active again today, both on private property and on public lands, where they are managed by local authorities or reserved for use by local people.

Disturbance regime (fires, pests, overgrazing)	Fire is a problem in only a small part of the cork oak areas, where maritime pine can be an aggressive competitor. Introduced in the twentieth century, this pine replaces the cork oak in part of its potential area. Symptoms of cork oak decline have appeared in recent years because of parasite attacks and drought. Isolated plants or pure, small stands seem more vulnerable than dense stands.
Constraints and conflicts, protective measures, restoration actions, land use regulations, and relevant policies	Cork oak trees are protected by law and cannot be cut without official permission. However, there are no legally protected areas (e.g., nature reserves, parks) with representative cork oak habitats. Partly with the help of European Union funds, local patches of cork oak are being revitalized by clearing pines and shrubs to allow cork collection and growth of seedlings and to lower the risk of fires.
Current trends and prospects for the future	There is a clear need to establish protected areas including cork oak woodlands. In addition, plantings are needed to increase cork oak populations in suitable areas. This could entail eliminating patches of maritime pine from areas formerly covered by cork oak vegetation. Intensified monitoring of health conditions and parasite activity on cork oak are also needed.
Source	Federico Selvi, University of Firenze, Italy

Site Profile Figure 9.1. Versegge, in the southwestern part of Monte Leoni, north of Grosseto, Italy.

Chapter 10

Natural Regeneration

JULI G. PAUSAS, TEODORO MARAÑÓN,
MARIA CALDEIRA, AND JOSEP PONS

In plants, the colonization of forest gaps and new habitats and the maintenance of genetic diversity and evolutionary potential are achieved mostly through sexual *regeneration*. It is therefore surprising that despite more than a century of interest by foresters, very little detailed information is available on the regeneration cycle of the cork oak and the dynamics between its different regeneration stages. Yet understanding natural regeneration is critical for any efficient conservation and restoration plan. By regeneration we mean the complex processes occurring from the time a seed is produced to the time offspring reach maturity (i.e., seed to seed). Thus, for cork oak, the cycle includes production, predation, dispersal, and germination of acorns, establishment of new individuals (recruitment), and growth to mature (reproductive) trees.

In this chapter we review what is known about cork oak regeneration, based on our own research in Spain and Portugal over the past decade. We first review the different stages of the regeneration process in cork oak populations and the performance (survival and growth) of the seedling. Then, we discuss recruitment and regeneration patterns in three Iberian areas. Finally, we discuss the relevance of our findings for the conservation, restoration, and holistic management of cork oak woodlands. The process of postfire vegetative regeneration was discussed in detail in Chapter 1 (see also Pausas 1997).

From Seed to Seedling

The seed regeneration mechanism of cork oak is similar to that of many oaks in that they share dispersal vectors, acorn predators, and seedling establishment problems (i.e., first summer drought mortality under Mediterranean

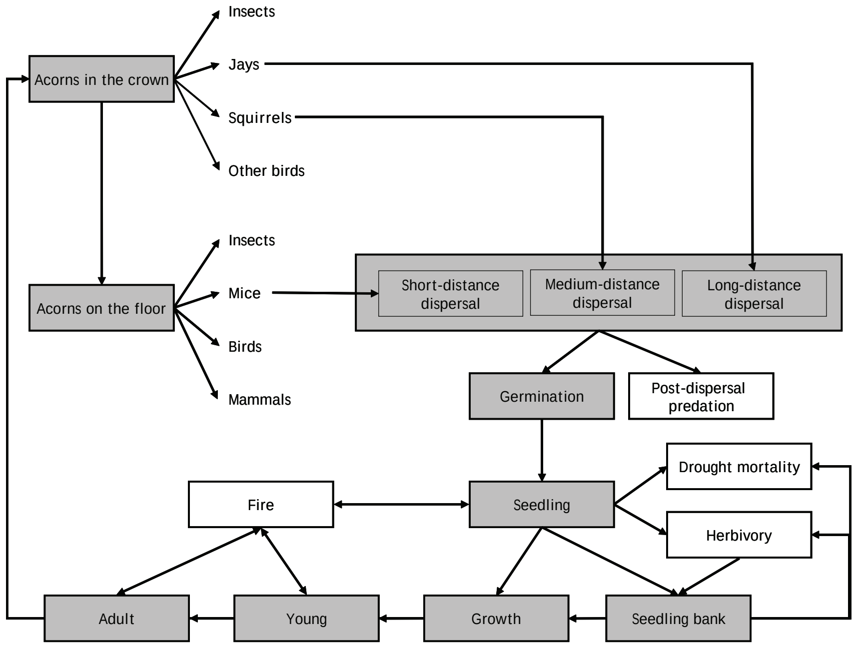

FIGURE 10.1. Conceptual model of the cork oak regeneration process (simplified). Gray boxes indicate the pathway of successful regeneration.

climate conditions). The outcome of each regeneration process determines the success or failure of the regeneration. In other words, the collapse or failure of any one of them will impede or halt the overall regeneration of the population (Figure 10.1).

Acorns are large, single-seeded fruits (1.5 to 3 centimeters long) that constitute highly digestible, high-energy (lipids), low-protein food for many animal species. They ripen either in the autumn of the flowering year (annual acorns) or in the autumn of the next year (biennial acorns) (Elena-Roselló et al. 1993). The main dispersal agent of most European oaks, including cork oak, is the European jay (*Garrulus glandarius*), which is a forest bird occurring not only in Europe (as the name suggests) but also in North Africa and Asia. The strong evolutionary relationship between this corvid and oaks has led to acorns becoming a very important food source for the former, and jays have become a very important dispersal agent for oaks (Bossema 1979; Pons and Pausas 2007a, 2007b, 2008). It is worth noting that both squirrels and mice also move and sometimes disperse acorns, though over shorter distances than jays (Figure 10.1; Pons and Pausas 2007a, 2007b, 2007c); however, mice may also play a crucial role in oak woodlands that lack jays.

In autumn, jays harvest healthy acorns from the tree crowns. They bury these acorns for later consumption, preferentially in open spaces, such as open grasslands, clear shrublands, recently abandoned old fields, and pine woodlands with low shrub cover (Bossema 1979; Pons and Pausas 2006; Pausas et al. 2006). A pair of jays may scatter and hoard several thousand acorns in a single season (Cramp 1994). As a result, cork oak dispersal ranges from a few meters to a few kilometers (Pons and Pausas 2007a). A few months later, when the acorn season has passed, and especially during the breeding season, when they need extra food to feed their progeny, jays collect the acorns they have stored in advance. By that time (April and thereafter), most of the acorns have already germinated, but the resulting seedlings do not necessarily die when the acorn, which is still attached to the seedling, is removed by the jay (Sonesson 1994). Two additional birds that feed heavily on cork oak acorns are the woodpigeon (*Columba palumbus*) and the common crane (*Grus grus*), which overwinter in many Iberian and North African oak woodlands. However, there is no published evidence that they contribute to acorn dispersal.

Mice (*Apodemus* and *Mus* species) are also major acorn predators, especially of acorns that fall from the tree to the ground (Pons and Pausas 2007c). Acorns buried by jays are usually safer from mice because jays tend to hoard in open spaces, where high rodent exposure to predation (e.g., raptors) results in low rodent activity. However, mice may also contribute to dispersal, especially in *mast years*, when high acorn availability satiates rodents. Although mice may disperse acorns at short distances (a few meters; Pons and Pausas 2007c), they may promote the persistence of oak populations through within-stand replacement dynamics and in systems lacking jays, such as some open oak forests (*dehesas*). Similarly, squirrels (*Sciurus vulgaris*) also scatter-hoard acorns, although no studies have yet quantified their role in oak recruitment. They probably play a minor role because squirrels inhabit dense forests, where tree seedlings have few opportunities to grow; indeed, most of the germinated acorns remain as a seedling bank on the forest floor, waiting for the occurrence of a major disturbance that would allow them to grow up to fill the new gap created in the forest canopy.

Acorns are also a food source for insects, and it is very common to find small exit holes, made by larvae of the acorn moth (*Cydia* spp., Lepidoptera) or the acorn weevil (*Curculio* spp., Coleoptera), in both cork oak and holm oak trees. The proportion of acorns predated by these insect larvae is highly variable; values from 17 to 68 percent have been reported (Branco et al. 2002; Pérez-Ramos 2007). Although many damaged acorns maintain their germination ability, the resulting seedlings show reduced vigor and a lower probability of surviving drought stress. A striking case of oak–insect interaction involves the dung beetle (*Thorectes lusitanicus*), which buries cork oak and Algerian oak acorns and eats them over a period of a few weeks. Sometimes buried acorns are abandoned after being partially consumed and can still germinate and establish themselves as rooted seedlings, but the distances the acorns are moved are very short (centimeters; Pérez-Ramos et al. 2007).

Finally, large vertebrates, such as red deer and especially wild boar, consume large amounts of acorns under cork oak trees. Similarly, in *dehesas* and related cork oak woodland agrosystems, livestock (pigs, cows, sheep, goats) are also acorn consumers; in fact, in Spain and Portugal, domesticated pigs are encouraged to eat acorns freely because the quality of their meat is closely related to the amount of acorns they eat (see Chapter 4). By the end of winter, in open *dehesa* woodlands, most of the annual acorn crop below the parent trees is usually eaten by the various seed predators of all shapes and sizes (Pulido and Díaz 2005b).

Seedling Performance

After germination, acorns quickly develop a strong taproot. This facilitates access to water and permits the seedling to allocate reserves and have protected buds in the root collar. The aerial part usually appears at the beginning of spring, although under certain conditions, such as extreme drought, some acorns—generally less than 10 percent—will delay aerial shoot appearance until the first rains of September. In cases of severe summer drought or strong competition occurring in the understory (Figure 10.1), many seedlings lose their aerial parts but resprout again in autumn. In understory conditions, saplings may remain as a resprouting sapling bank and complete the final regeneration process only when there is an opening in the canopy that allows the sapling to grow and reach maturity (Pons and Pausas 2006). Browsers, such as deer, sheep, and cows, can also heavily defoliate seedling shoots. Although seedlings are generally able to resprout, repeated browsing and soil compaction can kill most oak seedlings and impede natural regeneration. In such situations, seedlings growing under spiny shrubs may benefit from the nurse shrub effect (Castro et al. 2004b), which allows them to grow safely above the browsing line. However, the balance between the positive and the negative (increased competition) effects, induced by the nurse plant, may depend on the environmental conditions (Callaway 1995; Maestre et al. 2005).

Cork oak seedling survival and growth may be severely limited by summer water deficits. The longer the seasonal drought, the lower the survival rate (see Chapter 6). Moreover, cork oak seedling recruitment may occur in the forest understory, where light levels can be as low as 5 percent of the incident radiation. Light and water deficits often interact as limiting resources for young seedlings. However, in areas where dispersers are abundant, seeds can also reach open spaces, and therefore seedlings need to cope with high solar irradiance and potential evapotranspiration in summer. Although mature cork oak is considered to be shade intolerant, seedlings can tolerate some degree of shade. For example, Cardillo and Bernal (2006) found that well-watered seedlings had similar relative growth rates at 20 percent of full light and full sunlight and that etiolation symptoms and growth stoppage were apparent at 5 percent of full light. Light is essential for seedling growth, but shade and canopy protection can also be important for seedling survival during the summer drought. In fact, in Mediterranean woody species, the impact of drought on survival and growth is often higher in exposed conditions than under shade (Sánchez-Gómez et al. 2006; Quero et al. 2006).

The interaction between shade and drought on cork oak performance has been subject to some debate (e.g., Sack 2004; Quero et al. 2006). Recent studies of cork oak seedlings (Aranda et al. 2005b; Pardos et al. 2005) showed no significant interaction between shade and drought, although seedlings growing in shade were less efficient at developing physiological mechanisms of water stress tolerance, such as osmotic adjustment. However, in a greenhouse experiment, cork oak seedlings grown in deep shade under drought conditions were able to achieve higher photosynthetic rates, stomata conductance, and leaf N concentrations than those grown in full light, indicating an apparent alleviation of the impact of drought under shade (Quero et al. 2006). Indeed, the integrated response of tree seedlings to shade and drought involves several physiological and structural mechanisms. In a recent field study in Portugal (unpublished), cork oak seedling survival was higher under the canopy of mature oak trees than in the open, and the difference in survival increased by about 30 percent in a dry year, confirming that facilitation by canopy cover can be crucial in stressful conditions.

Thus, these experiments, carried out under controlled conditions, suggest that shading may alleviate drought stress in cork oak seedlings. However, we need to consider the complex ecosystem interactions (e.g., predators and grazers, often excluded from field experiments) to fully understand the limiting factors for regeneration. This is because environmental conditions that may be optimal for one aspect of regeneration may be limiting for others. This is the case for the higher seedling survival but also higher acorn predation and lower seedling growth observed in shaded sites as compared to open sites.

Recruitment Patterns: Three Case Studies

We now summarize the information available on recruitment patterns in three case studies carried out in different parts of the Iberian Peninsula that encompass a large range of the known variability in cork oak regeneration processes. Very little is known about the regeneration of cork oak stands outside the Iberian Peninsula, but regeneration patterns there probably are comparable to those presented here.

Case Study 1: Eastern Iberian Woodlands

In the Iberian Peninsula, the core area of cork oak is the center-west and the south; however, farther east, fragmented cork oak woodlands also occur (Pausas et al. 2004c, 2006; Pons and Pausas 2006, 2007a, 2007b, 2007c, 2008), occupying about 80,000 hectares in the Valencia region (see Site Profile 8.1). One of the main characteristics differentiating these eastern Iberian woodlands is the absence of large herbivores. The observed patterns of seedling recruitment and regeneration in this area are summarized in Figure 10.2.

There is a clear dynamic process in the colonization of old fields (Figure 10.2, *left*): Recruitment is observed at the beginning of abandonment. Then, as the vegetation cover increases, the rate of new seedling arrival decreases,

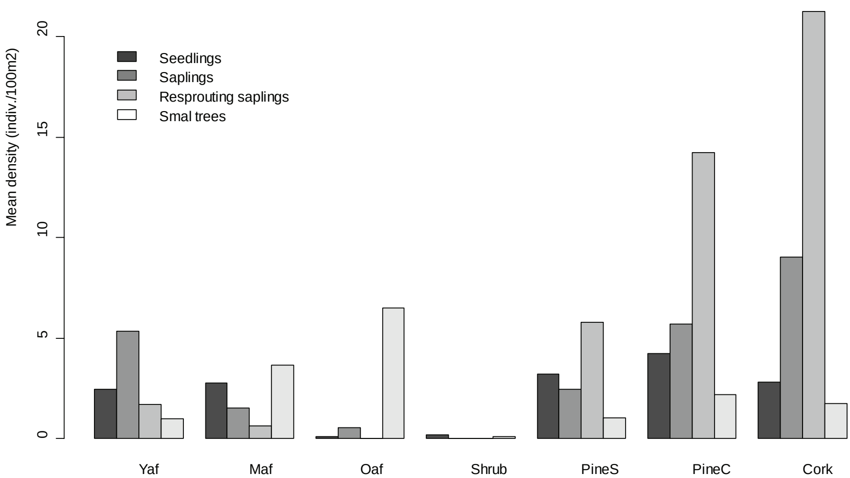

FIGURE 10.2. Cork oak recruitment density in different vegetation types in the eastern Iberian Peninsula. Recruits were classified as seedlings (with acorn attached and thus 1 or 2 years old), saplings (juveniles with no acorn attached), resprouting saplings (with symptoms of topkilling and resprouting), and small trees (<3 m). Lines and arrows indicate the main trends. (Modified from Pons and Pausas 2006)

and the seedlings present develop into saplings and then into full-sized trees. Finally, when shrubs and herbs achieve nearly full soil cover, no new seedlings appear (as in the shrublands), suggesting that the recruitment window is closed, and the initial saplings develop into young trees. Thus, in these conditions regeneration occurs thanks to the arrival of seeds soon after abandonment. The low proportion of saplings that have suffered top dieback (resprouting saplings in Figure 10.2) suggests very low stress conditions in old fields.

In contrast, there is very limited recruitment of cork oak in shrublands (Figure 10.2). Although we cannot yet pinpoint the causes, possible hypotheses include limited seed arrival, high seed predation, germination failure, and competitive exclusion. Because all of these are sequentially connected, the first seems to be the most limiting one because the jay's habit of directing dispersal to open soil and actively avoiding closed shrublands has been widely reported (Bossema 1979; Frost and Rydin 2000; Gómez 2003; Pons and Pausas 2007a). Furthermore, the highest acorn predator densities (mice in particular) are often found under shrublands (Hulme 1997). Indeed, there is evidence from other parts of the cork oak area of distribution suggesting that shrublands block cork oak colonization by limiting different regeneration processes (Acácio et al. 2007).

Finally, in mixed oak–pine forests, there is a high recruitment of new cork oak individuals; however, seedling desiccation and topkilling are very important processes in these habitats, with the result that many sprouted seedlings accumulate in a "sapling bank" without developing into trees (Figure 10.2, right).

Case Study 2: Dense Forest in Southern Spain

Cork oak dominates a dense and continuous forest of about 90,000 hectares in southern Spain, currently preserved as Los Alcornocales Natural Park (see Site Profile 17.1). In this area, rainfall is quite high (ranging between 700 and 1,300 millimeters annually) in comparison with other Mediterranean regions, but there is still a prolonged drought period in summer. The strong grazing pressure from free-range cattle and the increased deer population in the area has led to very poor cork oak regeneration and a general decline in the oak population. Currently, managers are striving to stimulate cork oak regeneration by regulating the deer population (e.g., building fences and hunting) and by planting oak seedlings.

Recent studies in these protected forests suggest high interyear variability in acorn production, including some years with very poor production

(Pérez-Ramos 2007). During the period 2003–2005, approximately 70 percent of the acorns on the trees aborted and fell, and fully half of the well-developed fruits were infested by insect larvae. Thus, only 17 percent of the seeds collected in seed traps placed under cork oak trees proved to be viable. After acorns fell to the ground, they were heavily predated, particularly those falling in deep-shade microsites, where rodents tend to forage. When the viable acorns collected in the seed traps were artificially dispersed in the field, about 70 percent germinated, and of these about 82 percent emerged as seedlings. Soil water content generated a double environmental stress consisting of high water content (waterlogging) in winter and very dry conditions (water deficit) in summer. Open microsites showed very different conditions compared with shaded sites (under trees) because waterlogging in winter and water stress in summer were more common on open sites than on shaded sites. Thus, both germination and emergence diminished exponentially as winter soil moisture increased, and seedling survival was higher under oaks (49 percent) than on open microsites (33 percent) (Pérez-Ramos 2007). In fact, the best predictor for seedling survival was emergence time, as winter waterlogging delayed seedling emergence and thus reduced summer survival. However, the surviving seedlings showed higher growth rates in the open than in the shaded microsites, under both field (Pérez-Ramos 2007) and greenhouse conditions (Quero et al. 2006). Thus, environmental conditions that are optimal for one aspect of the recruitment process may be suboptimal for others (Schupp 1995; Marañón et al. 2004).

Case Study 3: Open Woodlands (Dehesas and Montados)

The *dehesa* and *montado* agroforestry systems described in Chapter 3 (see also Site Profiles 4.1 and 13.1 and Color Plates 4–6 and 7a) have scattered oak trees, mostly evergreen, over low vegetation, often used for raising livestock (cows, sheep, and pigs). The land is sometimes plowed for cultivation of cereal crops (see Chapters 3 and 4 and Color Plate 5). Most of these open cork oak woodlands have an even-sized class distribution, almost devoid of younger trees. This is a worrisome pattern, indicating a lack of regeneration to counteract current mortality, stressing, and overall lack of sustainability of the land use system as it is currently practiced.

In these managed woodlands, many or most oak trees receive high solar radiation, and they have access to enough soil water to survive the dry summer and produce many more acorns than oak trees in a dense forest. Livestock, birds, and rodents consume most of the acorn crop, and the surviving seeds germinate and grow mainly under the mother trees. The lack of seed dispersal appears to be the key factor limiting tree recruitment in clearings (Pulido and Díaz 2005b). Jays and squirrels are absent from these open woodlands because they need a forest habitat (Pons and Pausas 2008). Mice are present only in shrubby microsites, where they can hide from predators. Given the high density of domestic animals in open, grazed pastures, the few surviving oak seedlings are almost completely defoliated. They can resprout several times, but overgrazing often drives them to death. Thus, the lack of acorn dispersal agents and overgrazing are the two key factors limiting oak regeneration in *dehesa* and *montado* woodlands.

Conclusions

There is a general decline and an alarming lack of regeneration in many Iberian cork oak populations throughout the western Mediterranean, despite successful regeneration in some places. Our results suggest that in the eastern Iberian Peninsula, cork oak colonizes abandoned croplands, and recruitment in shrublands is very limited. It also colonizes pine forests, but seedling growth is very low there, forming an understory sapling bank. In this region, acorns are abundantly dispersed by jays, but there is much seed predation by rodents, particularly in shrublands, and a very low predation of seedlings and saplings by herbivores (Table 10.1). In the dense woodlands of southern Spain, the patterns are similar with respect to seed dispersal and predation, with one very important difference: the high browsing pressure by the overly abundant red deer (Table 10.1). In the *dehesas* and *montados* of central and western Iberian Peninsula, acorn production is very high, but there is a lack of both dispersal and safe sites for recruitment. In addition, the very high grazing pressure limits the growth of the few surviving seedlings. In conclusion, to understand cork oak regeneration, it is important not only to consider the different socioeconomic and ecological conditions but also to adopt a landscape perspective, because different processes may occur in different landscape units. Our point is that it is important to understand the sequential demographic stages involved in the regeneration cycle and then to quantify each transition in order to detect the main factors limiting regeneration in the different patches and regions (Table 10.1).

Our findings on oak regeneration patterns and mechanisms can be transferred to woodland managers to help design practices and recommendations aimed at the conservation and sustainable management of cork oak stands and ecosystems. These practices may include management of both vegetation and fauna, with the objective of increasing acorn dispersal and establishment (passive restoration). Different woodlands with different socioeconomic

TABLE 10.1.

Comparison of the three systems studied (eastern, alcornocales, *and* dehesas*), and with the theoretical equilibrium (natural, currently nonexistent).*

	Dispersal agents	Herbivores	Herbivore predators	Regeneration
Natural	=	=	=	Yes
Eastern	=	–	–	Yes
Alcornocales	=	+	–	Low
Dehesas	–	+	–	No

Symbols: =, in equilibrium; –, too low (e.g., undergrazing); +, too high (e.g., overgrazing).

and ecological conditions, such as the three case studies presented here, will require different management approaches. For instance, sustainable management of the aged *dehesa*-type woodlands seems to call for landscape mosaics that include both shrubland patches, where mice can disperse acorns, and dense tree canopy patches to provide the habitat for jays. Shrubs can also facilitate oak seedling survival and growth by alleviating drought stress and protecting seedlings from grazers (the nurse effect from spiny shrubs). Temporary reductions or even exclusion of grazers from certain patches, in both *dehesa*-type woodlands (see Case Study 3) and forests with high grazing pressure (see Case Study 2), would allow saplings to reach sufficient height above the browsing line to become reproductive oak trees. In contrast, to conserve and increase population size in eastern Iberian cork oak patches, shrub clearing may be necessary to open the regeneration window. In the chapters that follow we will learn about specific techniques that may help to restore cork oak woodlands, especially when managing natural regeneration is not sufficient.

Acknowledgments

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SITE PROFILE 10.1

Hayouna, Morocco

In this site, as in some others discussed previously, natural regeneration of cork oak is occurring, but only under dense stands of shrubs. Government efforts are under way to increase protection and improve management practices in coordination with local communities.

Geographic and biophysical description	This area occupies 1,159 ha on west-facing slopes of the Laou River Valley, in the Chefchaouen region of the western Rif mountains, northern Morocco. Altitudes range from 350 to 915 m, and a humid climate prevails, with mean annual precipitation of 700 and 1,000 mm, an M (the average of the maximum daily temperatures of the warmest month of the year) around 32–33°C, and an m (the average of the minima of the coldest month) between 5.5 and 2.5°C. Stony soil prevails, with high sand and clay content. Cork oak is co-dominant, associated with olive tree (*Olea europea*), carob (*Ceratonia siliqua*), strawberry tree (*Arbutus unido*), tree heath (*Erica arborea*), rockroses (*Cistus crispus*, *C. monspeliensis*, *Tuberaria vulgaris*, *Halimium lasiocalycinum*), myrtle (*Myrtus communis*), laurustinus (*Viburnum tinus*), lavender (*Lavandula stoechas*), heather (*Calluna vulgaris*), gorse (*Ulex boivini*), and bracken fern (*Pteridium aquilinum*).
Physiognomic description of cork oak woodlands and their landscapes, including woodland dynamics	Dense to open cork oak stands occur, with natural regeneration occurring under dense shrubland. Pine plantations are common in the cleared areas.
History of land uses, land tenure (and socioeconomic drivers), and current land uses, economic activities, and context	Cork stripping occurs roughly every 12 years, yielding a mean production of 10 m^3/ha. Grazing occurs throughout the year. In addition, maritime pine (*Pinus pinaster*), Monterey pine (*P. radiata*), Aleppo pine (*P. halepensis*), Turkish pine (*P. brutia*), Canary Island pine (*P. canariensis*), and *Eucalyptus* spp. were introduced from 1960 to 1985 over a total area of about 100 ha, to produce wood. Other market products include edible mushrooms and aromatic and medicinal plants. Intense hunting activity also exists. The forest belongs to the state and is administered by the High Commissionership of Water and Forests, and Combating Desertification.
Disturbance regime (fires, pests, overgrazing)	Clearing, cultivation, and fires are frequent. Overgrazing by goats is a chronic problem.

Constraints and conflicts, protective measures, restoration actions, land use regulations, and relevant policies	High human and domestic animal pressures exist. Promotion of natural regeneration and more appropriate silvicultural techniques for cork oak are needed. Introduction and cultivation of fast-growing pines will also continue in appropriate areas. Nonwood forest products and ecological tourist trade promotion are prospects to be explored.
Current trends and prospects for the future	Current objectives of the guardianship administration include conservation, restoration, and product promotion.
Source	Mohamed Abourouh, Forestry Research Center, Rabat, Morocco

SITE PROFILE FIGURE 10.1. A part of Hayouna cork oak forest.

PART III

Restoration in Practice

In the last chapter of Part II the topic was passive restoration and autoregeneration, eg., through encouraging natural dispersal of acorns by animals and the subsequent colonization of trees. In Part III we address seeding and planting techniques, used for afforestation and the active restoration of cork oak woodlands. Both processes entail several steps. The first steps—germplasm selection and ensuring quality of plant material in the nursery (Chapter 11)—are critical, but later steps, such as site preparation, protection of seeds and seedlings, and other field techniques (Chapter 12), also require careful planning, execution, and monitoring.

In Mediterranean climate regions, drought is the main threat to survival of nursery-raised seedlings. In the critical period just after planting and before seedling roots have colonized the soil outside their containerized soil masses, a few days of drought can be fatal. Therefore, nursery techniques must be tailored to reduce transplant shock and to favor successful seedling acclimation through a combination of biotic and abiotic manipulation techniques. In addition, fine-tuned germplasm selection has still a long way to go to significantly contribute to restoration in practice, especially in the face of climate change and global warming. Similarly, field techniques should be designed to increase water supply to and reduce transpiration from newly planted seedlings.

In Chapters 11 and 12 the reader will find much useful information and discussion of all these issues. However, recall that planning, execution, and monitoring should be flexible and will vary somewhat between sites. No standards can guarantee project success because unpredictable and uncontrollable factors often intervene. Furthermore, as we shall see in Parts IV and V, there are major obstacles to putting these strategies and techniques into action that derive from continental and global drivers of a socioeconomic and cultural nature.

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Chapter 11

Germplasm Selection and Nursery Techniques

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In the context of forest transition (Mather 2001) and given its potential economic value, large areas of southwestern Europe have been afforested with cork oak in recent decades (see Chapters 1 and 13, and Color Plate 13a, 13b). However, planting had heterogeneous results, with low survival rates. This suggests the need to improve seed handling and nursery and planting techniques. Afforestation programs must also use suitable genetic material. This may become more critical for success in the context of climate change (see Part V). In the European Union (EU), cork oak reproductive material marketed for forestry purposes is controlled by EU Directive 1999/105/CE. The implementation of this directive at the national level favors the use of high-quality *forest reproductive material (FRM)* that is genetically and phenotypically suited to the site. In this chapter we discuss the selection and handling of cork oak acorns and nursery-grown seedlings. Afforestation is a long-term investment. Therefore, ensuring that high-quality propagation material is available at the appropriate time is crucial to the economic and ecological success of new cork oak woodlands. Also, many existing stands need new plantings to fill gaps and improve age structure.

Germplasm Selection

Afforestation in Mediterranean woodlands, as elsewhere, has often been done the cheapest way, with little concern for the genetic quality of the *planting stock*. But proper choice of acorns or nursery stock can be one of a landowner's most cost-effective decisions because the quality of the acorns or seedlings used largely determines success in the long term.

To choose the most appropriate genetic material for restoration and afforestation, it is important to define *regions of provenance* and carry out provenance field trials because most of the variability for adaptive traits of trees is found at the population level. At present only environmental parameters are used to define regions of provenance. For cork oak, insufficient information is available about the variability and genetic control of adaptive traits. However, in forest areas severely affected by oak decline, randomly distributed trees may present high tolerance, maintaining their robustness and health characteristics (Zobel and Talbert 1984). Therefore, seeds should be collected only in high-quality stands, from healthy trees selected in advance. Because of inbreeding risk, collection from isolated trees should be avoided.

Availability and Quality of Initial Acorn Stock

Cork oak trees often have variable and unpredictable reproduction patterns, with some trees producing seeds only once every two to five years (see Chapter 1). Also, acorns rapidly lose their value through desiccation, infection (e.g., from the fungus *Ciboria batschiana*), and insect attack (e.g., chestnut weevil, *Curculio elephas*) (see Chapter 9). Cold storage can help overcome irregular acorn production and maintain a regular supply of acorns to nurseries, with limited viability loss.

Traditional acorn harvesting usually is spread over a period of several weeks. The risks of seed viability loss, acorn predation by animals, and pregermination increase with time. To avoid these risks and reduce the time and cost of harvest, acorn collection should be planned and performed when massive drop occurs in order to preserve the initial acorn quality. At that time, it is advisable to shake the trees gently by means of a rope wrapped around the fine branches. Acorn color and morphology indicate acorn viability (Color Plate 14): Light brown acorns usually have been on the ground for several days and have become dehydrated, whereas a dark brown color indicates that acorns have been infested by fungi.

Acorn Manipulation, Storage, and Quality Assessment

Cork oak acorns are vulnerable to dehydration, like all acorns. This makes their long-term storage extremely difficult (Stiti 1999; Peñuelas and Ocaña 2000; Montero and Cañellas 2003a). Traditionally, acorns were stored in mesh bags with a simple fungicide application, but this resulted in almost total loss of viability in just three months. A new long-term storage technique (Merouani et al. 2001c) allows storage of cork oak acorns for at least seventeen months without loss of acorn quality (Merouani et al. 2004). The key is efficient organization of all steps in the storage process, starting at the time of seed harvest. The main steps are ensuring initial acorn quality (e.g., maturity, moisture content), choosing the time and type of harvest (controlled or traditional), treating acorns (*thermotherapy* and drying), choosing the type of storage bags, and maintaining storage conditions (temperature and relative humidity) (Merouani et al. 2001a, 2001b).

Successful establishment requires high seedling survival and growth, which are affected by seed quality. Many countries have adopted seed certification as stipulated in Article 14 of the EU Directive 1999/105/CE, which standardizes seed quality in terms of origin, genetic traits, and purity of seed lots. Accurate seed characterization and good seed management decisions require thorough knowledge of the characteristics of the product. This evaluation procedure entails acorn sampling in order to guarantee reliable data. Seed lot samples must be truly representative of the whole lot, and competent analysts must carry out the testing.

Plant Production and Nursery Practices

Large-scale cork oak planting may have occurred as early as the end of the nineteenth century (Natividade 1950). For example, at Rio Frio, Portugal, 3,600 hectares was planted using cork oak seedlings in wooden boxes, and yet as recently as thirty years ago, seedling production was still unusual in forest nurseries. Instead, acorns were seeded directly despite incompatibility with agroforestry practices and the unpredictable supply of acorns. Over the last fifteen years, however, oak seedlings in containers have become more common, and greater attention has been paid to improving quality and developing seedling certification procedures.

Planning of seedling production is an essential step to achieve quality, and field performance is a critical part of planning (Landis 1993). Nursery managers must be informed ahead of time about the area to be planted, the location, and site characteristics. Furthermore, nursery cultivation regimes can strongly affect the functional characteristics of seedlings (i.e., their quality) and consequently their field performance (Villar-Salvador et al. 2004). This depends on the proper use and timing of cultural practices, including sowing date, type of container, growing substrate, and watering and fertilization regimes (Vilagrosa et al. 1997; Cortina et al. 2004). Both the storage of acorns in inappropriate conditions and the inadequate manipulation of

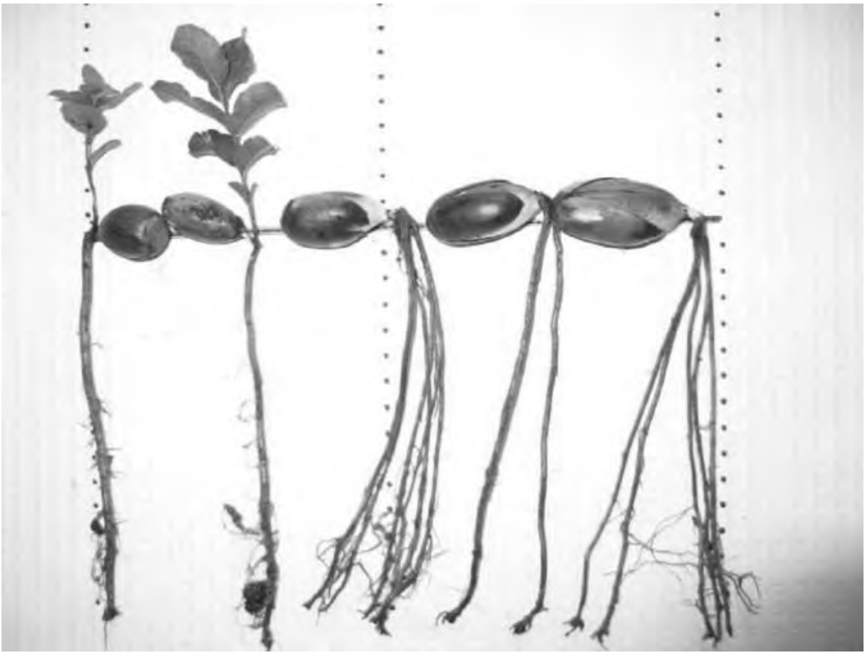

Figure 11.1. Cork oak seedling development with acorns showing typical roots *(left)* and fasciculated root systems *(right)*.

pregerminated acorns result in high failures of seedling emergence, such as 30 to 40 percent losses (Peñuelas and Ocaña 2000). This is often caused by damage of pregerminated acorns at the radicle–shoot junction during sowing. Figure 11.1 shows cork oak seedlings with a typical taproot and seedlings with a fasciculated root system, with two or more main roots rather than a single one, as a result of radicle–shoot breakage. Sowing controlled, pregerminated seed typically yields more than 85 percent seedling emergence and avoids the problem of shoot weakness.

Finally, seedlings with high aboveground biomass and low root:shoot ratios suffer more intense transplant shock, and consequently higher mortality and lower growth in the field (Costa e Silva et al. 2001).

Seedling Age

In traditional tree nurseries, the planning of seedling production is limited because acorns are available for only a short time (typically November and December). However, improved storage techniques allow year-round acorn availability. Another advantage of storage is that it accelerates acorn germination and seedling emergence rates, increases the *relative growth rate (RGR)*, and increases seedling uniformity (Merouani et al. 2001b, 2005).

Sowing acorns immediately after harvest and planting the next autumn leads inevitably to a longer period in the nursery (and additional seedling costs), which may negatively affect their root–shoot equilibrium. Furthermore, fresh acorns show wider variation in the time of germination than cold-stored acorns (Merouani et al. 2001b). This can create serious nursery crop problems related to variable seedling sizes because small initial differences in size can lead to large size differences at the time of shipping and cause difficulties with oak seedling certification (EU Directive 1999/105/CE in Annex VII Part E).

Containers and Substrates

New types of containers for growing seedlings are continuously being developed to reduce handling costs and improve seedling quality. Indeed, container design largely determines the morphological and physiological characteristics of tree seedlings (Aphalo and Rikala 2003; Villar-Salvador et al. 2004; Pemán et al. 2006). Container volume and height affect nutrient availability and space for root development. Container diameter has a direct influence on distance between seedlings, and therefore competition for light, and on the relationship between shoot and root growth, and therefore stem diameter. Although there is no standard type of container in use, 300 cubic centimeters is the most commonly used volume in the Iberian Peninsula (Costa e Silva et al. 2001; Montero and Cañellas 2003a; see Color Plate 13c). In southeastern France, 600–cubic centimeter containers with anticoiling interior ribs are preferred and have proven useful (P. Brahic, personal communication, 2006). Containers coated with copper carbonate may also help produce smaller seedlings and avoid spiraling roots (Pardos et al. 2001). Larger containers induce higher seedling growth (Domínguez et al. 1997; Suárez et al. 1997). However, seedlings cultivated in deep containers acquire several morphofunctional advantages, improving seedling water status under drought conditions (Chirino et al. 2008), although the differences in seedling size often disappear over time in the field because growth is no longer constrained by the amount of space and the substrate provided by the container (Costa e Silva et al. 2001).

The growing substrate provides physical support for the seedling, and it should provide water, nutrients, and air. There are many different types of substrates on the market that have been used successfully for cork oak seedling production (Figure 11.2), including granulated cork, a byproduct of

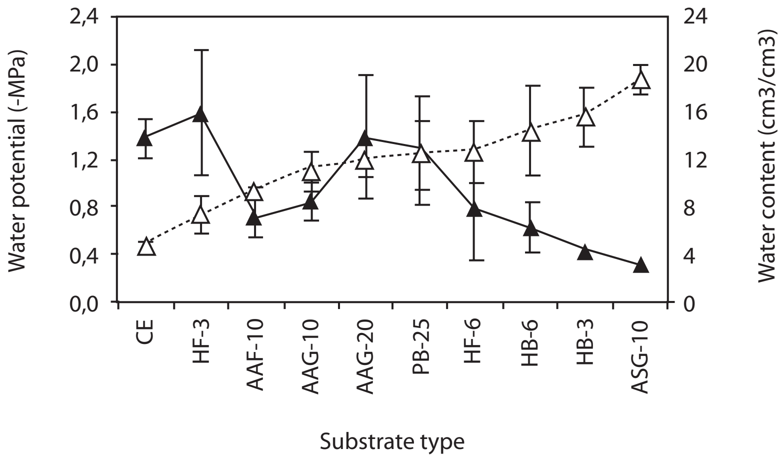

FIGURE 11.2. Changes in water status and substrate moisture content in cork oak seedlings planted in different growing mixes and subjected to a 7-day drying period. Bars correspond to means ± *SE*. AAF, fine atapulgite (10% and 20% v/v application rates); AAG, coarse atapulgite (10% v/v application rate); ASG, coarse sepiolite (10% v/v application rate); CS, control mix (peat and coconut peat, 50:50 v/v); HB, medium hydrogel Bures (0.7% and 1.5% w/w application rates); HS, medium hydrogel Stockosorb (0.7% and 1.5% w/w application rates); PB, pine bark (25% v/v application rate). All amendments were added to the CE mix. *White triangles*, growing mix water content; *black triangles*, plant water potential. (Data from Chirino and Vilagrosa 2006)

the cork industry itself (Costa e Silva et al. 2001; Merouani et al. 2005). Growing substrates may have a significant effect on cork oak morphofunctional traits and field performance that may last for more than three years. In general, the inclusion of substrates that improve water retention and availability, such as peat, promotes higher field performance (Landis et al. 1990; Costa e Silva et al. 2001). However, the use of pine bark and soil organic layers in substrate leads to poor performance, which can be explained by unfavorable water retention properties and difficulties in forming a consistent firm root plug. Field experiments have shown that optimized growing media may increase seedling survival by as much as 30 percent compared with traditional substrates (Figure 11.2).

Adding Fertilizers

Fertilization can accelerate shoot and root growth of seedlings, modify tissue nutrient contents and the amount of available reserves, improve posttransplant rooting and growth capacity, and increase resistance to water stress

(Grossnickle 2000). Several studies have reported a positive relationship between seedling size and nutrient status in planting and field performance (Cortina et al. 1997; Puértolas et al. 2003). We found that heavily fertilized seedlings may double in size, as compared to seedlings receiving no N or P, after ten months in the nursery, whereas the relative amount of biomass allocated to roots did not change. However, cork oaks seedling quality may decline at high fertilization rates. When cork oak tree seedlings were planted in the field, differences in biomass accumulation decreased because part of the aboveground biomass dried in the summer drought. More importantly, differences in size and nutrient content did not generate differences in field survival (Costa e Silva et al. 2001). To date, fertilization in the nursery is not a common practice in cork oak seedling production because growth is initially based on seed reserves, and increased growth can lead to unbalanced plants in the restricted space of small containers over a long nursery growing period. This might be overcome by shortening the production period in the nursery.

Preconditioning Treatments

Seedling hardening or drought preconditioning (i.e., exposing seedlings to periodic stress) has been recommended for acclimatizing nursery seedlings to harsh field conditions. Nevertheless, a recent study with cork oak seedlings found that drought preconditioning had little effect on seedling survival in the field, despite substantial effects on seedling morphology (Chirino et al. 2004).

Nutritional hardening (i.e., reduction in nutrient supply, particularly nitrogen, during the late stages of nursery growth in order to acclimatize seedlings to harsh field conditions) has received less attention than drought preconditioning. Yet seedlings subjected to low N availability may be better adapted to drought because of reduced leaf size and increased allocation of biomass and nutrients below ground (Chapin 1991; Liu and Dickman 1993). Nitrogen availability is often low in degraded Mediterranean soils, and that may limit seedling establishment (Bottner et al. 1995; Martinez-Mena et al. 2002; Valdecantos et al. 2006). Therefore, the depletion of seedling N reserves resulting from a reduction in N application rate could compromise seedling performance in the field. However, a reduction in N supply could favor an accumulation of phosphorus and other macronutrients and improve seedling capacity to withstand low P availability, as is common in many dryland soils (Valdecantos 2003).

Studies of the response of Mediterranean woody species, including cork oak, to N deprivation during their last weeks in the nursery show that foliar N concentration and seedling size are significantly reduced in most species (Trubat et al. 2008). In contrast, the effect of N hardening on seedling survival showed no common pattern. Nitrogen deprivation had a positive effect on survival of seedlings planted under semiarid conditions (Trubat et al. 2008), whereas the effect was not statistically significant in cork oak seedlings planted under dry to subhumid conditions.

Seedling Quality Assessment

Seedling quality, defined as fitness for purpose, is a concept that includes the degree to which trees achieve end-of-rotation goals at a minimum cost (Willén and Sutton 1980). Forest nurseries seek to provide seedling stock for reforestation that can survive prolonged environmental stresses and produce vigorous growth after outplanting. Unfortunately, few studies have been conducted on growth of cork oak seedlings in the nursery in relation to field performance (survival and growth), and no reliable morphological or physiological predictor of plant quality and vitality has yet been identified.

There is an ongoing debate over the optimum seedling size at planting. In the context of the restoration of Mediterranean ecosystems, seedlings should be able to withstand unfavorable growing conditions (transplant shock, summer stress, drought) and still take advantage of favorable weather to grow. Plant investment in root system development is an advantage for field survival because it facilitates water uptake. Conversely, having too many leaves in comparison to roots increases water loss by transpiration without prompt access to water. Nevertheless, high leaf area favors seedling survival as long as it is accompanied by a well-developed root system. In fact, in Mediterranean ecosystems, although soil water may be exhausted from the topsoil during the dry season, enough water is usually available for woody plants in the underlying soil or subsoil, except in extremely dry sites or after severe droughts (see Chapter 6). If roots fail to reach that water because of seedling defects or compact soil layers near the surface, survival is jeopardized. Plant quality indexes, such as relative growth rate (Hunt et al. 2002) and *root growth potential (RGP)*, integrate information about growth processes and are the most reliable parameters available to assess plant quality.

Performance in the field is the ultimate measure of the quality of seedlings used for restoration. Still, the costs of replanting after losses caused by poor seedling quality are so high that often only a small number of seedlings with insufficient growth potential must be identified before plantation to overcome this problem. However, all efforts to produce high-quality seedlings in the nursery will be futile if seedlings are not cared for after they leave the nursery.

Vegetative Propagation

The use of vegetative propagation for cork oak afforestation is not common. This technique is more expensive per plant than seminal production. Furthermore, plant material is not widely available because no comprehensive breeding program has been implemented, and the genetic control of cork is unknown. Bearing in mind that cork oak is a long-lived species and considering climate change scenarios for southwestern Europe and the need to maintain genetic diversity, we believe that the establishment of clonal forests should be avoided. However, studies on vegetative propagation using stem *cuttings* and micropropagation techniques will provide valuable information on cork oak adaptability to changing environmental conditions. If "elite" trees (e.g., tolerant to certain diseases) are identified, these techniques can become appropriate.

Conclusions

Using suitable genetic material by selecting adequate provenances and improving the morphological and physiological quality of reproductive material are necessary steps toward ensuring the success of cork oak plantings, as is the use of appropriate forest reproductive material to offset unfavorable growing conditions. Several innovative nursery treatments lead to improvements in seedling stock quality and performance under field conditions. A key factor is careful planning that includes attention to the entire process, starting from seed collection. The development of long-term acorn storage techniques will facilitate planning and enhance seed and seedling quality. However, there is still a clear need to optimize seedling production in order to reconcile the qualitative and economic aspects of the cork oak restoration and afforestation efforts. Chapter 12 will deal with field techniques used to improve cork oak establishment.

Acknowledgments

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SITE PROFILE 11.1

Aspres and Albères, France

This site is in the eastern part of the Pyrenees, on the Mediterranean coast of southern France, near the Spanish border (French Catalonia). It consists of several patches in which mature mixed forest is regenerating spontaneously.

Geographic and biophysical description	The main location is in the Aspres and Albères formations (15,000 ha), with additional patches in the Têt valley of Roussillon and the Tech Valley (Vallespir). Mean annual precipitation ranges from 500 to 1,000 mm per year. The prevailing winds are the dry and cold Tramontane from the northwest and the humid Maritime from the east. Topography is rugged, and altitude ranges from 0 to 700 m. Bedrock consists of schists, detrital materials of Pliocene (Aspres), and schists, gneiss, and granite (Albères). Accompanying vegetation includes holm oak (*Quercus ilex*), downy oak (*Q. pubescens*), strawberry tree (*Arbutus unedo*), tree heath (*Erica arborea*), rockrose (*Cistus monspeliensis*, *C. salvifolius*), stone pine (*Pinus pinea*), European chestnut (*Castanea sativa*), common smilax (*Smilax aspera*), wild madder (*Rubia peregrina*), broom (*Ruscus aculeatus*, *Calycotome spinosa*), strawflower (*Helichrysum stoechas*), lavender (*Lavandula stoechas*), and false olive (*Phillyrea angustifolia*).
Physiognomic description of the cork oak woodlands and their landscapes, including woodland dynamics	Many pure cork oak forests occur, as well as mixed stands with other oak species. In the absence of active forestry practices, cork oak can be crowded out by other oaks in marginal stands, such as those of the Aspres region. Colonization of abandoned fields or former vines by oaks is also occurring.
History of land uses, land tenure (and socioeconomic drivers), and current land uses, economic activities, and context	Stands were intensively managed in small to medium-sized land holdings from the 18th century until World War II for cork extraction, animal husbandry, and charcoal production. A new wave of tree planting took place at the end of the nineteenth century, on abandoned vineyards devastated by phylloxera root rot. Cork production was abandoned in the 1950s because of competition from Portugal and Spain. Cork extraction was revived in the 1990s, thanks to the rise of cork prices and subsidized projects designed to avoid or reduce the risk of wildfires.
Disturbance regime (fires, pests, overgrazing)	The risk of forest fires has increased since the 1970s, menacing tourist areas and shrublands. This is made worse by low livestock stocking rates, except in strategic zones for forest fire protection, where subsidized grazing is maintained.

	Some cork oak decline has been observed, caused by combined drought and pathogens (e.g., *Platypus cylindrus*, *Diplodia corticola*, *Biscogniauxia mediterranea*). Populations of wild boar (*Sus scrofa*) cause much depredation.
Constraints and conflicts, protective measures, restoration actions, land use regulations, and relevant policies	Recreational hunting, hiking, and gathering of wild berries and mushrooms are increasingly important activities. Forest management, carried out primarily by professional organizations, is not highly intensive. Cork extraction is carried out every 12–15 years, but some problems arise due to bad practices (e.g., tree injuries, cork theft). Some trees have been planted on abandoned old fields and formerly cultivated pastures. Cork oak forests are taken into consideration in local territorial policies.
Current trends and prospects for the future	Cork oak can spread on abandoned lands at low altitudes (<300 m) but tends to suffer in competition with other oaks at higher altitudes (>300 m) or on the plains. Strong pressure exists for housing in areas of contact between urban and forest zones (e.g., the Albères). Cork production is maintained by the presence of local industries in Spanish and French Catalonia.
Source	Renaud Piazzetta, IML (Institut Méditerrannéen du Liège), Vivès, France.

Site Profile Figure 11.1. Argelès-sur-Mer cork oak woodland.

Chapter 12

Field Techniques to Improve Cork Oak Establishment

Jordi Cortina, Marian Pérez-Devesa, Alberto Vilagrosa, Mohamed Abourouh, Mahand Messaoudène, Nora Berrahmouni, Luis Neves Silva, Maria Helena Almeida, and Abdelhamid Khaldi

Chapter 11 detailed best practices in germplasm selection and nursery techniques for active restoration of cork oak woodlands. In this chapter we focus on field techniques. In parts of its range in the western Mediterranean, the surface area covered by cork oak woodlands has been declining (Natividade 1950), and this decline probably is not as recent as it sometimes appears (Parsons 1962), nor is it unique; other Mediterranean oaklands show similar, equally worrisome trends (Pulido 2002). However, concern for the future of cork oak woodlands has fostered vast revegetation and restoration programs in recent years (e.g., Andrade 2003; Berrahmouni et al. 2005). Unfortunately, in addition to a progressive reduction in woodland area, cork oak often shows poor recruitment, the technical term for spontaneous regeneration via seedlings, regardless of the technique used for afforestation and restoration. This endangers the persistence of existing forests and limits the tree's potential to colonize new areas, as noted in Chapter 10. The reasons for low regeneration are numerous and may be site specific. Acorn predation, harvesting and herbivory on seedlings by various animals, unfavorable climatic conditions for seedling establishment, pests, competition, changes in fire frequency, and human-induced changes in forest composition are the main constraints to cork oak recruitment (Natividade 1950; Cabezudo et al. 1995).

Caution is warranted before we can draw any conclusions, however. The aforementioned studies were based primarily on observations rather than controlled experiments, and current knowledge on the driving factors and obstacles to cork oak recruitment is scarce (see Chapter 10). This limits our ability to prescribe successful field techniques for the establishment of cork oak seedlings. In addition, the costs of site preparation, seedling planting, and aftercare may amount to two thirds of overall plantation expenditures. Therefore, technical improvements are needed to help reduce the costs of planting and replanting for afforestation and restoration. In this chapter we review available field techniques to improve cork oak establishment and discuss the ecological bases for selection of available techniques. We focus on afforestation and *active restoration*, via acorn seeding and seedling plantings, because spontaneous regeneration (passive restoration) was discussed in Chapter 10.

Direct Seeding

Direct seeding was the preferred technique for reintroducing cork oak in the past, and it is still frequently used in some areas (Mesón and Montoya 1993). The main benefits, as compared to planting out of nursery stock, are the low cost and the advantage that an acorn sown in situ develops a normal taproot, whereas that of nursery seedlings often must be cut or pruned before being transferred to the field. An unpruned taproot may confer an advantage to cork oak, as for other trees that grow in areas with seasonal drought and that rely on an early exploration of deep soil horizons to ensure establishment (Rambal 1984; Pulido 2002). Acorn predation can be substantially reduced by wrapping individual acorns with a metal screen or hard cloth before seeding or covering the acorn, once seeded, with a small piece of metal screen (Schmidt and Timm 2000; J. Pons, personal communication, 2004). Protecting seeded acorns with tree shelters inserted a few centimeters into the soil may also work (Vilagrosa et al. 1997), provided that tree shelters do not attract large predators, which is sometimes the case.

Direct seeding can be an effective, rapid, and inexpensive forestation technique. However, planting of seedlings is still preferred in most cork oak planting programs, and many people mistrust direct seeding. However, most recorded failures in the use of this technique are probably the result of improper implementation, including poor selection of sites and seeding season, inadequate site preparation, low seeding density, and the use of poor-quality or unprotected seeds.

Seedling Planting

Given all the problems with direct seeding, planting nursery-grown seedlings probably is the best way to ensure cork oak regeneration (see Color Plate 13). However, there are drawbacks with this approach as well. In this section we review major field constraints for the establishment of nursery-grown seed-

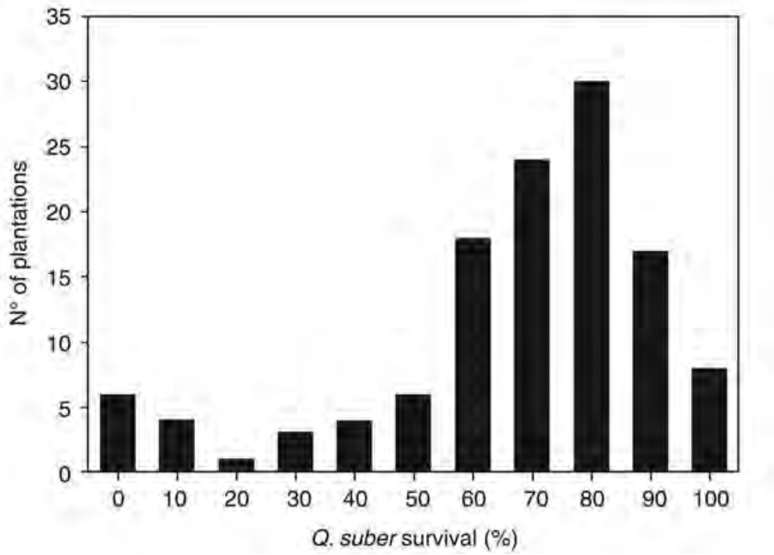

FIGURE 12.1. Frequency of experimental cork oak plantations ranked according to the survival rate of this species after the first summer in the field. Most of the plantings were performed after intense site preparation. (Data from Varela 2000; Oliet et al. 2003; Messaoudène unpublished data; Pérez-Devesa unpublished data)

lings in the field and the techniques developed to overcome those limitations. Seedling survival in the field shows varying results, as shown in Figure 12.1. This may be a consequence of various factors, including improper site preparation, and clearly there is much room for improvement.

Interactions between Extant Vegetation and Introduced Cork Oak

Studies of cork oak seedling density reveal that recruitment rates can be highly dependent on plant cover and community composition (Herrera 1995; Zaidi and Kerrouani 1998; Pons and Pausas 2006; Acácio et al. 2007; Chapter 10). Seedling establishment may be favored by clearing, particularly in *mesic* sites, because shrubs and herbaceous vegetation may compete with introduced seedlings for resources, mainly water and light (Montero and Cañellas 1999). Shrubland clearing may also incorporate organic matter and nutrients into the soil and change microclimatic conditions, temporarily increasing soil fertility.

However, plant–plant interactions are not always negative (Callaway 1995). Many studies have shown that standing vegetation may facilitate seedling performance under Mediterranean conditions (Pulido and Díaz 2005a).

Shading, improved soil fertility, defense against herbivores by spiny nurse plants, and protection from freezing may all play a beneficial role (Maestre et al. 2003; Castro et al. 2004a; Cortina and Maestre 2005). The shift from net positive to net negative plant–plant interactions cannot be easily defined for a particular set of interacting species, however, because the outcomes of the interactions vary spatially and temporally (Maestre and Cortina 2004). This is a major limitation for a straightforward application of scientific advances to restoration practices.

Shrubland clearing, sometimes including uprooting, has been a traditional technique to establish cork oak (Natividade 1950; Lepoutre 1965). Manipulative experiments carried out in Serra d'Espadà (eastern Spain) support the idea that shrubs have a negative effect on the short-term performance of cork oak seedlings (Figure 12.2). However, some studies have shown a negative effect of shrubland clearing on cork oak establishment (Santilli 1998), suggesting that we still lack a full understanding of the interplay between extant vegetation, environmental factors, and cork oak performance.

Other processes beyond plant–plant interactions must also be taken into account in planning for shrubland management (Table 12.1). Natividade (1950) suggested that competing vegetation should be controlled with caution, preserving as much as possible the protective cover of accompanying vegetation and slash. He recommended clearing the shrubland in strips perpendicular to the prevailing slope, preserving some herbaceous cover, a

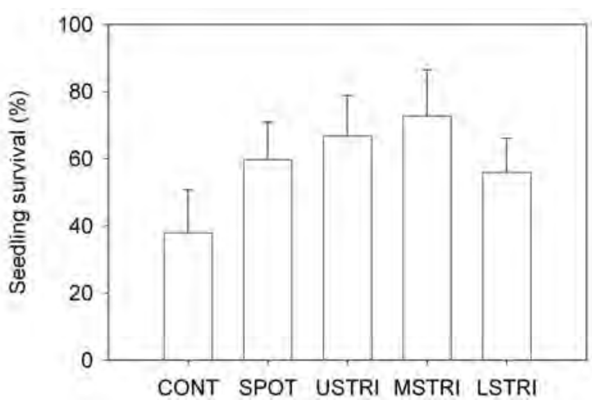

Figure 12.2. Effect of shrubland management on survival rates of cork oak seedlings 16 months after planting and after 2 summers in the field. Seedlings were planted in 40-cm^3 holes with minimum shrubland disturbance (CONT); in 2-m diameter circular clearings (SPOT); and in the upslope, middle, and downslope parts of a 5-m-wide cleared strip (USTRI, MTRI, LSTRI, respectively). Bars correspond to average and standard errors of 3 replicated sites.

TABLE 12.1.

Ecosystem-scale effects of shrubland clearing in cork oak plantations

Positive	Negative
Fire protection	Surface soil alteration
Biomass harvest	Erosion risk
Increased palatable vegetation (improved pasture quality)	Alien species invasion
Decreased competing vegetation	
Less habitat for harmful fauna	

Source: Natividade (1950).

suggestion that has been incorporated into the International Code of Good Practices (Proyecto SUBERNOVA 2005).

The positive or negative outcomes and the magnitude of plant–plant interactions may change depending on the identity of the species and their stage of development (Castro et al. 2004a; Gómez-Aparicio et al. 2004). Some studies have shown that cork oak establishment can be facilitated by the presence of native shrubs and trees, such as mastic, strawberry tree, hawthorn, laurustinus, Butcher's broom (*Ruscus aculeatus*), Mediterranean fan palm, tree heath, *Prunus* spp., and *Phillyrea* spp., and hampered by others, such as rockroses, black wattle (*Acacia mollissima*), and various *Eucalyptus* species that are planted in the region (Natividade 1950; Beaucorps et al. 1956; Santilli 1998; Acácio et al. 2007; Figure 12.3). Most of these studies are based entirely on observation; manipulative experiments considering a range of species and environmental conditions are clearly needed.

A completely different situation arises in open cork oak woodlands (e.g., *dehesas* and *montados*), where isolated trees are surrounded by an herbaceous understory. *Canopy* cover reduces high summer temperatures and thermal amplitude, improving plant water relations and seedling survival (Nogueira 2006). But herbaceous vegetation may outcompete oak seedlings (Pulido and Díaz 2005a), and mowing or seasonal grazing can be necessary, as is the case also for holm oak (Plieninger et al. 2004). In addition, herbivore pressure is commonly high in these ecosystems, representing an additional risk for oak seedlings (see Chapter 3). In well-stocked *dehesas* and other cork oak woodlands, temporary suppression of grazing and cropping may be enough to ensure successful recruitment, as for holm oak (Plieninger et al. 2003, 2004). Planting shrub patches to create safe sites for oak seedlings and using other types of shelters may also be advisable to protect seedlings against herbivory (Pulido 2002). Careful soil preparation may be needed when cork oak establishment is main priority, as will be discussed next.

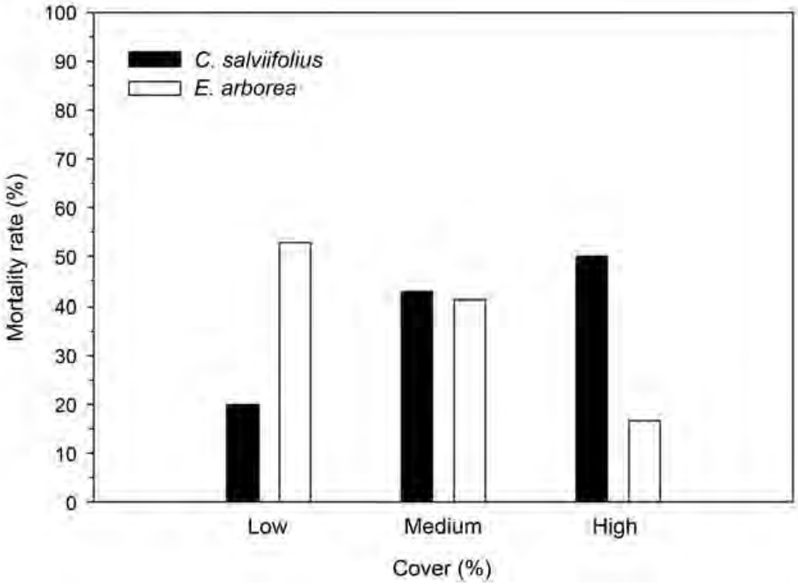

Figure 12.3. Effect of shrub species (*Cistus salviifolius* and *Erica arborea*) cover on cork oak seedling mortality 1 year after planting in a shrubland site in Serra d'Espadà (eastern Spain). Shrub cover was estimated on a 2-m-diameter circle around each 40-cm^3 planting hole. Low, medium, and high cover classes correspond to 0–10%, 10–20%, and >20% cover for *C. salviifolius* and 0–10%, 10–25%, and >25% cover for *E. arborea*.

Soil Preparation and Cultural Treatment

The interaction between unfavorable soil conditions and climatic constraints has been identified as one of the major factors limiting seedling establishment, and the improvement of soil properties has high priority in afforestation programs in environmentally degraded areas in the western Mediterranean (Navarro Garnica 1977). It is not surprising that manipulation of soil conditions has commonly focused on improving soil water availability because water is the most limiting resource for seedlings. Watering has been recommended when feasible (Anonymous 2000). Watering may be more efficient when applied copiously on each cork oak seedling immediately after planting and, if possible, two or three more times during the first two years (M. H. Almeida, personal observation, 2006). *Mulching* with cereal straw or other suitable materials may help reduce direct evaporation and decrease transpiration by hampering the establishment of herbaceous vegetation. This technique may improve seedling survival (Abourouh and Bakry unpublished data) and growth (Favrel and Priol 1998). Runoff concentration may be a suitable alternative to increase water availability in dry sites. Microcatchments (e.g., two ridges, 1 to 1.5 meters long and 0.15 to 0.20 meter high, forming an oblique angle upslope from the planting hole) can be an affordable technique, but its success depends on the quantities of runoff water during the critical period after plantation (Whisenant et al. 1995; Saquete et al. 2006).

Deep soil labor may also be used to improve water infiltration, facilitate plant rooting, improve water status, suppress competing vegetation, and thus improve seedling establishment (Pikul and Aase 2003; Patterson and Adams 2003; Alloza et al. 2004). The establishment of planted cork oak seedlings may be favored by deep soil preparation (more than 0.35 meter or even more than 0.9 meter; Anonymous 2000). Soil preparation can be particularly important for cork oak because this species is highly sensitive to soil properties, including waterlogging (see Chapter 8), and because of the importance of deep rooting in oak establishment. Cork oak is sensitive to excess water. Soil preparation may also help to reduce soil pest attacks (Zaidi and Kerrouani 1998). Harrowing associated with chemicals can effectively control damage from *Melolontha* sp. (Almeida unpublished data).

Protection against Adverse Microclimatic Conditions

Seedling performance can be impaired by excessive radiation and temperature. Reductions in direct radiation and thermal buffering may improve seedling performance. Many types of tree shelters are available for this purpose, and their effects on plant performance vary (Bellot et al. 2002; Oliet et al. 2003). Ventilation is needed to avoid excessive temperatures, allow transpiration, and keep CO_2 concentrations near atmospheric values (Bergez and Dupraz 2000; Jiménez et al. 2005). Cork oak tolerates high temperatures, even when water stressed (Ghouil et al. 2003; Aranda et al. 2005a), suggesting that this species may not be particularly sensitive to changes in maximum temperature inside tree shelters. However, cork oak is strongly limited by low temperatures, particularly in provenances from warm areas (Aranda et al. 2005a), and tree shelters may promote freezing because minimum winter temperatures can be slightly lower inside them (Oliet et al. 2003; Jiménez et al. 2005).

Acclimation to shade may reduce *photosynthetic capacity* in cork oak leaves (Aranda et al. 2005a) and the ability to tolerate drought through *osmotic adjustment* (Pardos et al. 2005). But shade provided by tree shelters may enhance *photoprotection* and reduce *photoinhibition* in summer (Werner and Correia 1996). As a result of improved microclimatic conditions, short-term growth of cork oak seedlings can be enhanced when they are protected with tree shelters (Oliet et al. 2003). Ventilated 60-centimeter-long polypropylene tree shelters, with translucent twin walls reducing as much as 70 percent of incoming photosynthetic radiation, may be the best choice for this species.

The use of tree shelters may have some disadvantages for cork oak establishment because seedlings tend to be slender and etiolated under light-limiting conditions (Quilhó et al. 2003). However, by using translucent tree shelters allowing the passage of high red:far-red ratios of irradiance—a type of irradiance controlling stem elongation—this problem can be alleviated (Sharew and Hairston-Strang 2005). In addition, tree shelters commonly favor aboveground rather than belowground biomass allocation (Dias et al. 1992; Bergez and Dupraz 2000; Jiménez et al. 2005), a trend that could compromise seedling capacity to withstand intense drought. Conversely, tree shelters may control excessive branching and promote straight stems, facilitating cork extraction and improving cork quality. Finally, tree shelters may hamper herbivory by rodents, rabbits, and hares, but they are not as effective against large grazers.

Livestock Management

Grazing on cork oak acorns and seedlings is responsible for low establishment success in many areas (Lepoutre 1965; Pulido 2002), which is why careful and closely supervised livestock management is essential to cork oak woodland health and sustainability. Grazing exclusion can be very effective in improving seedling establishment (Torres and Montero 1992; Montero and Cañellas 2003b). It has been suggested that protection from grazing should last more than ten years to be effective, or up to the age when grazers are no longer a threat (i.e., the age at which trees surpass the critical browsing height) (Marion 1951; Santilli 1998; Montero and Cañellas 2003b). Brush piles around planted seedlings, especially using spiny species, may also deter cattle and deer, as observed in other oaks (Wetkamp et al. 2001).

Conclusions

Many studies indicate clearly that success rates of plantings can be increased substantially by using suitable field techniques. Adequate grazing management, environmental friendly control of potentially competing vegetation, and low-cost techniques to improve soil conditions and increase water availability in the proximity of planted seedlings, such as microcatchments, appear to be the best options to promote cork oak establishment. Having completed the discussion of the ecological and horticultural bases for restoration, including nursery and field techniques, in Part III we discuss the economic aspects of the current predicament and future prospects of cork oak woodlands.

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PART IV
Economic Analysis

In Part I of this book we became acquainted with the cork oak tree and the variety of ecological systems in which it grows. We also learned about the prominent ecological and economic uses and the cultural roles that cork oak woodlands and cork products have long played in the western part of the Mediterranean Basin. It was also made clear that the *dehesa* or *montado*—indeed, all of the traditional cork oak–based land use systems—appear to be at risk, partly because of degeneration of the woodlands. In Parts II and III the scientific state of the art for restoration and active management of cork oak woodlands were presented, with some specific techniques for enhancing the success of cork oak restoration projects in the nursery and in the field. However, there is another menace hovering over cork oak woodlands, in addition to the general decline in natural regeneration, and it is economic in nature, concerning both public and private economies.

In Part IV we address tradeoffs and balances in open cork oak woodlands from an economic perspective. In Chapters 13–15 we present three carefully researched analyses of the costs and benefits of contemporary open cork oak woodland resource base use in Portugal, Tunisia, and Spain. In all three chapters, the authors apply the theory of total economic value as a conceptual framework for measuring the total income of a range of cork oak woodlands. The total economic value approach combines market and nonmarket (environmental services) benefits by using homogenous exchange values for marketed and nonmarket benefits and costs.

Total private and social cork oak woodland forestry benefits are also calculated, based on an agroforestry accounting system approach that organizes the economic data generated in a one-year period, with the aim of measuring total income from resource base use. This accounting system is applied to five cork oak woodland ecosystem case studies, representing a range of highly contrasted situations. To wit, in Chapter 13 the authors report on the private total income supplied by a mixed cork oak and stone pine woodland in the Alentejo region of southern Portugal, the same area highlighted in Chapter 4. Then, in Chapter 14 a similar approach is applied to the economic analysis of a state-owned cork oak woodland in Iteimia, Tunisia, where a household subsistence economy provides contrast with that of the large private land holding in Portugal, a European Union member country, described in Chapter 13. Finally, in Chapter 15 the authors apply an extended *cost–benefit analysis* to measure both private and social incomes changes arising from the planting and renewing of aging open cork oak woodlands in three settings in Spain. This sampling of sites does not cover the entire gamut found in the western Mediterranean region, but it does provide a cross-section and a method to help guide future studies, both in southern Europe and in North Africa. (Please note that all monetary values are given in euros. At press time (January 2009), the conversion rate was 1 euro = 1.3 US dollars).

Rounding out this part of the book, the authors of Chapter 16 provide an up-to-date overview of the manufacture and trade of cork products as they have evolved over the past forty or fifty years, during which the cork industry has become steadily smaller in geographic terms, focusing largely on the Iberian Peninsula. The ramifications of this trend for the cork trade itself and for the future of open cork oak woodlands are addressed specifically.

Among the encouraging factors that favor the survival and adaptive evolution of open cork oak woodlands in the twenty-first century, we shall see that manufacturers have made bold efforts to improve quality and communicate the advantages of natural cork products. But to save the *dehesas* and *montados* from extinction, woodland owners and cork producers must reinforce this praiseworthy effort by manufacturers, something that has been all too rare. Finally, there are clear indications that more public measures will be needed to keep these cultural heritage systems alive and functioning. This is especially true in light of climate change and other global changes affecting all ecosystems on the planet, including cork oak woodlands. These are issues that will be addressed in Part V.

Pablo Campos and James Aronson

Chapter 13

Mixed Cork Oak–Stone Pine Woodlands in the Alentejo Region of Portugal

Inocêncio S. Coelho and Pablo Campos

One of the most unusual Mediterranean landscapes dealt with in this book is the mixed cork oak and stone pine woodland, found primarily in southern Portugal and scattered parts of northease, west, and southwestern Spain. Given that stone pine is widespread in all the warmer parts of the Mediterranean region and that it occurs on the same kind of soils as cork oak, it is surprising that this particular type of mixed woodland occurs in only a small portion of the Iberian Peninsula. It is not impossible that its origin is anthropogenic.

In this chapter we present an economic study of a mixed cork oak–stone pine woodland maintained on a private estate in the Alentejo region of southern Portugal. We analyze costs and benefits to the owner and private income distribution for the woodland owner and his employees. The goal is to determine whether total profitability for landowners is competitive, as compared with alternative nonland investments of similar risk and time horizon frames, given the prevailing management practices of nonmechanical harvesting of cork and pine nuts and chronic overgrazing by domestic livestock, which prevent regeneration of cork oak. In addition, we ask whether the conservation of the mixed woodland is important enough for society and government to underwrite their conservation. The last section of the chapter is devoted to this question and addresses issues that will also be raised in the next two chapters and are central to the book as a whole.

Mixed Cork Oak and Stone Pine Woodland Areas

In 2004 mixed stands of cork oak and stone pine occupied 22,380 hectares in Portugal, which represents a huge increase in stone pine, particularly, since 1985. This is the result of the afforestation programs supported by the

Portuguese application of Common Agriculture Policy (EU 2080/92 regulation) set-aside measures. In the planted stands of mixed woodland, cork oak is dominant, but the primary goal of stone pine management traditionally was timber production, with a final harvest at about forty years, after which time the mixed plantations were generally transformed to pure stands of cork oak. In the second half of the twentieth century, however, the increasing use of roasted pine nuts as human food stimulated the interest of landowners so that harvesting pine nuts gradually became subject to a private property rights regime. (Formerly, pine nut gathering in Portugal was a free-access resource for local people.) There is also growing demand for *private amenities* from woodlands, which economists define as the private exclusive use of environmental goods and services, such as the landowner pleasure of spending weekends and holidays far from the city, surrounded by cork oak woodlands. Today, private amenities are the most important nonindustrial source of private landowner capital income—after cork itself—that owners derive from open cork oak woodlands in Portugal and Spain (Campos and Caparrós 2006; Campos et al. 2007a).

The traditional mixed woodland system in Portugal is practiced mostly on large private estates (100 hectares or more), which occupy about 60,000 hectares in all. The landowner usually manages most forest operations with paid workers (employees) and privately owned machinery. Cork and pine nuts can be sold on the tree as stumpage or at the farm gate after being harvested. Cork and pine nuts are manually harvested. Livestock rearing is often managed by livestock keepers who lease the use of the grazing resources from the woodland owner.

Cork stripping continues to be the primary cork oak management goal. Therefore, the nearly total lack of natural regeneration indicates that in the long term, mixed cork oak and stone pine stands in Portugal, as well as pure cork oak stands (see Chapters 10 and 15), are at risk. To shed light on this precarious situation, in the next two sections we develop a private economic analysis of the current lack of facilitated natural regeneration practices in mixed woodland. For lack of data, we will not attempt to measure the loss of natural capital caused by the death of mature cork oak trees, but this factor should ultimately be taken into account. Furthermore, we disregard livestock activity, for which detailed studies have been published elsewhere (Coelho 2005b; Campos et al. 2007a, 2008b, 2008c; Rodríguez et al. 2005). For lack of data, we also could not directly include the economic value of environmental services to society from mixed woodlands, although this issue is discussed at length at the end of the chapter and in Chapters 14 and 15. Government expenditures on woodland are not also taken into account in our analysis.

Private Economic Benefits and Cost Valuation Methods

The relevance of applying an accounting system that considers the mixed woodland ecosystem, *Hicksian income*, is recognized in the European System of Accounts regulation (Eurostat 1996), and it is only partially applied to European Union woodland and forest "farms" via the Economic Accounts for Agriculture and Forestry (EAA/EAF) (Eurostat 2000). The latter accounting system does not incorporate the value of private owner amenity consumption and the public benefits and costs that accrue to society from the mixed woodland ecosystem. As a consequence, the official statistics on woodland and forest total incomes are incomplete. The shortcomings of the EAA/EAF accounting system have led us to seek a more comprehensive approach (Campos et al. 2008c). In Table 13.1 we explain the specific character of the different market and nonmarket types of economic values included in a total economic value (TEV) of forest total income measurement (Campos 1994; Campos et al. 2005; cf. Pearce 1993).

Because private cost does not include the Portuguese government's direct expenditures on woodland fire control and natural resource depletion mitigation, the private total costs only partially reflect the economic effort needed to manage woodland activities. Thus, public expenditure increases the amount of the private total income because in the absence of such government support, the owner must expend labor and capital on fire prevention and control to mitigate natural and manufactured capital loss by wildfire.

The complete accounting and valuation methods applied in this chapter, and also in Chapters 14 and 15, are available in Rodríguez et al. (2005) and Campos et al. (2008b) and will be explained briefly here. Note that we calculate mixed woodland private total income, taking into account market

TABLE 13.1.

Potential sources of total economic value of cork oak woodlands.

Active uses			Passive uses
Actual uses		Future uses	
Direct	Indirect	Option	Existence values
Often exclusivity or competition in use; either private or public goods.	Environmental services considered as an intermediate output or input for the production of final ecosystem goods and services.	Users' willingness to pay for goods and services for one's own or other people's future benefit.	Collective and individual users' willingness to pay for the future existence of a good or service in danger of extinction, independently of its current or future active use.

Source: Based on Campos et al. (2005:325).

benefits and costs, and extend mixed woodland outputs to include the monetary measurement of private amenities.

Private Benefits and Costs

Private amenities include an owner's exclusive current active access to and enjoyment of his or her land and a number of landowner *option values* and *passive use values*, such as legacy and *existence values* (Campos et al. 2005, 2007a). This "self-consumption" of private amenities is commonly internalized as capitalized market value in the setting of woodland market prices (Eurostat 2002; Campos and Caparrós 2006; Campos et al. 2007a). To measure private amenity income value, we asked owners of pure and mixed woodlands along the Alentejo coast how much income they were willing to forgo in order to maintain their landownership and not sell the property to invest in alternative enterprises. We calculated an average private amenity value of €197/ha (Coelho 2005b; Campos et al. 2007a, 2007b). We shall now present results from an analysis of current private incomes and profitability rates at the Vale Estate, situated in the Alentejo coastal region, on the banks of the Sado River.

Case Study: Vale Estate Woodland

The Vale Estate has a total of 1,793.5 hectares of productive woodland. Most of this (78.7 percent) consists of mixed stands of cork oak and stone pine. In addition, there are 2.6 percent of pure stands of stone pine and 18.2 percent of pure stands of cork oak. Sandy soils prevail, and with less than 500 millimeters mean annual precipitation, stone pine regenerates easily and spontaneously, but not cork oak, for which natural regeneration is often deficient for reasons described in Chapters 6 and 10.

Private Economic Incomes and Profitability Rates

Although we assume that cork production will decline in the future if current cork oak management practices continue unchanged, this is ignored in our economic analysis, whose results reflect an average year. In other words, for the purposes of this study we assumed that outputs and costs are stable, and we calculated total income for Vale Estate in 2003 prices and omitted rates of inflation and capital gains related to land revaluation. Assuming that both these rates are constant, our results are given in real terms. As noted earlier, owners' profits are considered to be commercial outputs derived from sales

TABLE 13.2.

Mixed woodland Vale Estate total private benefits, 2003.

Class	Quantity/ha	Price (€/unit)	Value (€/ha)[a]
1. Sales			411.3
1.1 Cork (kg)	167.300	2.000	334.600
1.2 Pine nut (kg)	61.500	0.475	29.200
1.3 Firewood (kg)	1,000.000	0.025	25.000
1.4 Grazing rent (forage units)	150.0	0.1	15.0
1.5 Hunting rent (ha)[a]	1	7.5	7.5
2. Private amenity (ha)[a]	1	197.0	197.0
3. Subsidies net of taxes			0.93
4. Total benefits (1 + 2 + 3)			609.23

[a]"ha" refers to woodland hectares.

of cork, pine nuts, firewood, charcoal, grazing rights, and hunting rights, as well as subsidies net of taxes on the aforementioned outputs and the self-consumption of private amenities.

Table 13.2 summarizes the total private benefits of Vale Estate in the "average" year of 2003. Cork stripping, private amenities, and pine nut harvesting contribute 54.9 percent, 32.3 percent, and 4.8 percent, respectively, of total woodland benefits (sales, private amenities, and subsidies). The remaining benefits—firewood, *grazing rent*, hunting rent, and subsidies net of taxes—represent only 8 percent of total benefits. Notably, cork accounts for 81 percent of sales.

As for total costs (Table 13.3), more than half (54.8 percent) consists of silvicultural treatments for cork oak and stone pine, including maintenance of footpaths and firebreaks, understory shrub cutting and pruning of young pines, and administration of the farm. The *labor cost* is the greatest portion (81.6 percent) of total cost, with intermediate consumption (raw materials and services) accounting for 4.2 percent and machinery depreciation for 14.2 percent of Vale Estate's total costs. Wage rates for cork stripping (€10.6 per hour) and pine nut harvesting (€2.9 per hour) are, respectively, 2.5 and 0.67 times the average Vale wage rate (€4.31 per hour) paid to temporary and permanent employees on the estate (see Table 13.3).

The total benefit should be the Vale Estate source for paying the costs of intermediate consumption (raw materials and services) and capital consumption (machinery depreciation; 3 percent of total benefits) and labor costs (12 percent of total benefits). The remaining 85 percent of total benefit belongs to the private landowner as business capital income. The Vale Estate owner benefits amount to €519.27/ha and represent 87.67 percent of total income (Table 13.4).

TABLE 13.3.

Mixed woodland Vale Estate total private cost, 2003.

Class	Quantity/ha	Price (€/unit)	Value (€/ha)
1. Raw materials			1.25
1.1 Forestry work			1.25
2. Services			2.51
2.1 Forestry work			1.04
2.2 Cork stripping			0.16
2.3 Pine nut harvesting			1.31
3. Labor costs[a]	17.03	4.31	73.4
3.1 Forestry work	8.9	3.84	34.25
3.2 Cork stripping	1.98	10.63	21.06
3.3 Pine nut harvesting	6.15	2.94	18.09
4. Machinery depreciation[b]			12.8
5. Total cost (1 + 2 + 3 + 4)			89.96
5.1 Forestry work			49.34
5.2 Cork stripping			21.22
5.3 Pine nut harvesting			19.4

[a]Per hour of work.
[b]Includes machinery depreciation for forestry work and cork and pine nut transport to farm gate.

TABLE 13.4.

Mixed woodland Vale Estate private labor, capital, and total incomes, 2003.

Class	Labor income (€/ha)[a]	Capital income (€/ha)	Total income (€/ha)
1. Cork stripping	21.06	313.38	334.44
2. Private amenity		197.00	197.00
3. Pine nut harvesting	18.09	9.80	27.89
4. Firewood		25.00	25.00
5. Grazing rent		15.00	15.00
6. Hunting rent		7.50	7.50
7. Forestry work	34.25	–48.41	–14.16
8. Total (1 + 2 + 3 + 4 + 5 + 6 + 7)	73.40	519.27	592.67

[a]"ha" refers to woodland hectares.

Sales of cork contribute 60.3 percent of total *capital income*, 32 times the income from pine nut harvesting, and the cork stripping wage rate is 3.7 times the pine nut harvesting rate (see Table 13.3). Vale cork is of high quality for natural stoppers, and its price is as high as €2/kg at the farm gate, whereas cork prices in southern Spain often are less than €1/kg.

The mature Vale mixed woodland implies an annual average private investment of €6,620/ha. (The woodland market price is €6,575/ha, and the operating capital is €45/ha.) These figures show that this mixed estate is a human-created woodland resource-based investment, with a low durable human-made operating capital investment. We find that Vale Estate commercial profitability rate (4.8 percent) is competitive, and adding the 3.0 percent private amenity profitability rate, we estimate the Vale total profitability rate to be 7.8 percent. This high short- to medium-term private profitability rate is possible without replacing the mature cork oak's natural mortality. It is shown in Campos et al. (2007b) and Chapter 15 that given the lack of private owner profitability from facilitating natural cork oak regeneration through silvicultural practices, including the planting of cork oak saplings, woodland owners cannot be expected to undertake such practices without subsidies. Therefore, in the final section we develop an appeal in favor of investing public money in mixed woodland conservation, with the aim of contributing to the potential needs of future human generations for cork and pine nut raw material and for *public amenities,* such as public recreation, climate change mitigation, and biodiversity conservation (Campos et al. 2007a, 2008b).

Sustainability and Stewardship of Total Economic Value

Stone pines naturally dominate cork oak in mixed associations and thereby endanger the equilibrium and the sustainability of the mixed woodland ecosystem. Because cork oaks regenerate poorly (see Chapter 10), some intervention is needed to counter the immediate temptation of landowners to allow exclusive renewal of stone pine. Yet the economic incentive of landowners to actively promote balanced regeneration of the two species, or to invest in replanting of cork oak, depends entirely on government subsidies (Campos 1998; Campos et al. 2007b, 2008c). Indeed, recent public policy incentives offered for planting and maintaining mixed woodland stands have contributed to the maintenance and conservation of the mixed woodland ecosystem (see also Chapter 15).

Although the mixed woodland ecosystem, such as the one at Vale, when studied in the context of private benefits has certain peculiarities, woodland management and the apparent tradeoffs between grazing and cork oak regeneration can provide useful insight for those concerned with all cork oak woodlands, both in southern Europe and in northwestern Africa (see Chapters 14 and 15). Livestock grazing plays a major role in the biodiversity and cultural components of all open woodland systems (Díaz et al. 1997; see Chapter 3 and Box 3.2; see also Color Plate 6), and both overgrazing (intensification of use) and undergrazing (extensification of use) can provoke an unstable situation (see Chapter 10). On one hand, unrestricted animal grazing by livestock and wild herbivores inhibits or prevents cork tree seedling recruitment and in the long term can lead to total disappearance of open cork oak and mixed woodlands as a reservoir for carbon storage and sanctuary of heritage and biodiversity values. On the other hand, maintaining livestock in the woodlands helps to combat shrub encroachment (see Chapters 14 and 15). If managed properly, the livestock help maintain high plant biodiversity and increase the value of the mixed and other cork oak woodlands as working cultural landscapes. In this light, sustainable grazing of livestock in open cork oak woodlands is an agroforestry bio-tool that increases the provision of public goods, including mitigation of global warming and biodiversity loss at a local or regional scale, and also helps maintain the economic supply of natural cork for future generations (see Chapters 17 and 18). Both carbon credits and biodiversity credits are beyond the scope of this chapter, but they merit attention for their possible economic value in a mixed woodland setting in the future (cf. Campos et al. 2005).

The mixed woodland ecosystem has great social relevance, yet the private and public benefits it provides are in danger of declining or even disappearing. All those joint private and public economic benefits and nature conservation tradeoffs motivate society as a whole in favor of government incentives and regulations to preserve the mixed woodland ecosystem area, on the basis of compatibility between traditional and new uses (i.e., commercial uses and environmental services).

Forest fires are an ever-present factor in the dynamics of woody vegetation in all Mediterranean climate regions, including southern Portugal. Wild and human-set fires are dissimilar in the mixed woodland and the pure conifer forest, with the incidence of forest fires being smaller in open mixed *montados* than in closed coniferous forests. In woodland ecosystems with open tree stands and shrubs controlled by grazing and by periodic clearing, the risk of catastrophic fires is reduced.

Finally, the mixed woodland case study presented here confirms what we know about the short- to medium-term competitive private profitability of mature Mediterranean pure and mixed cork oak woodlands. But we also know that landowners incur capital losses by renewing cork oak or stone pine (see Chapter 15; Campos 1998; Campos et al. 2007b) through facilitated natural regeneration or actual replanting. Current market failures to anticipate the future scarcity of private mixed woodland ecosystem services could lead to an undervaluation of those commercial and environmental economic benefits. These facts could help explain why market land prices—which should reflect the discounted owner capital income by market long-term private profitability rates—and government direct expenditures and subsidies both fail to anticipate true actual asset value (market and social values) of the mixed woodland with a sustainable tree management scheme. Therefore, if we accept that private owners do not renew their mixed woodlands under actual and future expected market trends, preservation of the rare mixed woodland of southern Portugal becomes a public concern for present and especially future human generations. Chapter 14 describes the householder's subsistence economy in a state-owned cork oak woodland situated in northern Tunisia.

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SITE PROFILE 13.1

Monchique and Caldeirão, Portugal

This site profile includes pure cork oak stands (*sobreirais*) and more intensively managed *montados*, located in patches enjoying protection status, as part of ecological or agricultural special protection areas.

Geographic and biophysical description	This site is located in the Algarve region of southern Portugal. The largest stands are Monchique/Espinhaço de Cão (65,632 ha) and Caldeirão (80,653 ha). Annual rainfall is 500–1,500 mm, in an area of rugged topography and siliceous soils, at altitudes ranging from 100 to 750 m. Accompanying vegetation includes the strawberry tree (*Arbutus unedo*), tree heath (*Erica arborea*), lavender (*Lavandula* sp.), common myrtle (*Myrtus communis*), gum rockrose (*Cistus ladanifer*), oleander (*Nerium oleander*), laurustinus (*Viburnum tinus*), and, rarely, European chestnut (*Castanea sativa*) (in Monchique above 400 m). There are also several oak species present in addition to cork oak, including Algerian oak (*Quercus canariensis*), Portuguese oak (*Q. faginea*), holm oak (*Q. ilex*), and Lusitanian oak (*Q. lusitanica*).
Physiognomic description of the cork oak woodlands and their landscapes, including woodland dynamics	Two types of cork oak stands are present, which differ in terms of their density and composition. So-called *sobreirais* are pure cork oak stands with little or no agricultural exploitation. Strawberry trees are common, as are various shrubs. The other type (*montado*) has much lower tree density and is subjected to ongoing agro-silvopastoral use.
History of land uses, land tenure (and socioeconomic drivers), and current land uses, economic activities, and context	Most holdings in the site are small private properties, with many Tasmanian blue gum (*Eucalyptus globulus*) plantations established in the mid-twentieth century. The sole exception is the 900-ha National Forest, Mata Nacional da Herdade da Parra, in Monchique.
Disturbance regime (fires, pests, overgrazing)	Fires are common, and forest decline is common as a result of *Phytophthora* fungi attacks and inadequate cultural practices to eliminate dead and unhealthy wood. No large herbivores are present, and human pressure is very low.
Constraints and conflicts, protective measures, restoration actions, land use regulations, and relevant policies	These patches are located in ecological or agricultural special protection areas (*Reserva Ecológica Nacional* and *Reserva Agrícola Nacional*). Some reforestation projects have been undertaken with good success. Vegetation protection measures are applied after forest fires in the National Forest at Monchique. Subsidies for reforestation and cleaning forests also exist. Cork stripping takes place every 9–10

	years for cork production in Caldeirão, Monchique, and Espinhaço de Cão.
Current trends and prospects for the future	Cork production averages 130 kg/ha, and the oak population is increasing. Cork production will persist in the future in the large patches, thanks to multiuse value. Hunting and mushroom collecting, especially of chanterelles (*Cantharellus cibarius*), are very important supplements to landowners' income.
Source	José M. D. Rosendo, General Direction of Forestry Resources, Portimão, Portugal

Site Profile Figure 13.1. Serra do Espinhaço de Cão, Lagos.

Chapter 14

Cork Oak Woodland Conservation and Household Subsistence Economy Challenges in Northern Tunisia

Pablo Campos, Paola Ovando, Ali Chebil, and Hamed Daly-Hassen

Cork oak is the most common native tree species in northwestern Tunisia, occurring especially throughout the Kroumerie-Mogod mountain range. Over the past half century, however, cork oak woodlands in this area have been reduced and converted into agriculture and pastureland (Chebil et al. 2009). In 2003 it was officially estimated that cork oak woodlands in Tunisia covered 90,000 hectares (CNT/DGF 2005), which represents a loss of one third from estimates made in the 1950s (Boudy 1952). One key management problem is that the Tunisian Forest Code lists livestock grazing among the usage rights that can be freely practiced by rural inhabitants but does not set periods for grazing exclusion. Unrestricted grazing, increasing demographic pressure, and lack of proper surveillance have led to degradation and natural resource destruction throughout the cork oak woodlands of the country (FAO 2001; Ben-Mansoura et al. 2001; Daly-Hassen et al. 2007).

Despite their declining area, cork oak woodlands continue to play a prominent economic role for rural households and also for the state, which is the sole legal owner of all Tunisian woodlands. Market benefits from the cork oak woodland area derive from multiple final products, including cork, mushrooms, berries, essential oils, wildlife game, and firewood collected for domestic uses (see Chapter 3). Nevertheless, rural households benefit mainly from traditional livestock rearing and subsistence crops grown in small, treeless parcels within or bordering the cork oak woodlands.

In this chapter we analyze natural resource use and the challenges for conservation in cork oak woodlands, in the context of the developing economy of Tunisia. For this purpose, cork oak woodland area includes associated shrubland (hereafter *woodland*). Our analysis focus only on total income supplied by cork oak woodland activities, although we refer also to livestock rearing and crop activities, which are the other two activities in agroforestry (cf. Campos et al. 2008a).

Our main objective is to measure the total income accrued from the current unsustainable woodland use in a specific case study of a state-owned but communally grazed woodland, located in northern Tunisia (Iteimia), and its distribution to local households, the state, and private firms working with cork harvesting, firewood, myrtle, and other woodland products. Second, we estimate the livestock keeper's income loss if current overgrazing is reduced to a sustainable grazing regime in order to facilitate and promote the natural regeneration of cork oak and associated shrub vegetation. This analysis should be useful for householders, nongovernment organizations, and government decision makers concerned with woodland natural resource conservation and restoration management in Tunisia.

We first present the Iteimia case study, in view of current woodland management practices and the actual distribution of woodland resources. Next, we consider the criteria for valuing goods and services derived from woodland use. Third, we measure cork oak woodland total income and discuss how it is distributed to the state, private firms, and local households. Fourth, we discuss the conflicts that arise between a hypothetical woodland conservation policy and local householder's subsistence economy. Finally, our concluding remarks are framed by two perspectives: the need to improve current scientific knowledge of the environmental services provided by Tunisian woodlands and the need to enforce natural resource conservation policy, including local householders' needs and equity tradeoffs.

Case Study: Iteimia

Current Woodland Management

Campos et al. (2008a) estimated a set of economic indicators derived from the agroforestry on-site uses in the *douar* (village) of Iteimia under subsistence farming conditions. Iteimia is located in the Ain Snoussi region of northern Tunisia, a midelevational mountain area with altitude ranging from 400 to 642 meters. This region has a humid Mediterranean climate, with an average annual rainfall ranging from 1,000 to 1,500 millimeters (Oliveira et al. 2004).

The agroforestry area was farmed and managed by 110 households and 508 inhabitants. We conducted our study considering only woodland area. Cork oak area covers 444 hectares, or 72 percent of the overall agroforestry area, with an average density of 583 cork oaks per hectare (Campos et al. 2008b). Shrubland occupies 44 hectares, or 7 percent of the area. The woodland area thus totals 488 hectares and consists of 91 percent cork oak area and 9 percent shrubland. The most common shrub species are mastic, myrtle, and strawberry tree. Subsistence crops are cultivated in small treeless plots bordering the woodlands, making up a total of 127 hectares (21 percent of the agroforestry area).

The agroforestry area belongs to the state, but local inhabitants have specific use rights. The state is represented by the Forest Administration Service of the Ain Snoussi region, which is engaged in natural resource management operations (except for grazing resource use), from which it gets commercial benefits, mainly from cork (which is also entirely owned by the state) and firewood outputs. The Forest Administration profits also, but to a lesser extent, from selling licenses (through the auction system established by the Tunisian government in the area) for wild boar hunting and from selling the right to collect mushrooms and myrtle to private firms, which hire local workers to gather those products (see Site Profile 14.1).

The household subsistence economy in the agroforestry area generates diverse uses of natural resources, especially the freely accessed grazing resources and the collection of woodland goods, such as acorns (see Color Plate 7b), firewood from cork oaks (legally restricted to dead wood lying on the forest floor), and shrub biomass, used for fodder, firewood, charcoal, and shelter (see Chapter 3). Local householders also benefit from seasonal woodland jobs—mainly for men—and the cultivation of subsistence crops. Women and children play a major role in rearing livestock and tending crops. Livestock herds consist of local races and cross-breeds of cattle, as well as goats, sheep, mules, and horses.

The Forest Administration aims to generate woodland capital income (net benefit) to the government and, simultaneously, to develop local householders' subsistence economy while respecting the Tunisian Forest Code regarding forest resource usage rights and restrictions. This allows attempted livestock production improvement through introduction of exotic breeds of hybrid meat and milk cows. Concurrently, the local people use natural resources with the aim of maximizing their household income, given their labor capacity and knowing that alternative job opportunities in the area are scarce. Labor market regulation is weak, and most operations, except cork stripping, occasional sanitary felling of trees, and private firm operations, are performed by household members (self-employed labor).

Private Economic Benefits and Costs Valuation Criteria

We follow the conventional system of national accounts for measuring woodland benefits and costs (Eurostat 2000). Accordingly, Iteimia woodland

TABLE 14.1.

Total benefits from state cork oak woodlands, Iteimia, Tunisia, 2002.

Class	Quantity/ha	Price[a] (€/unit)	Value[a] (€/ha)[b]
1. Cork (kg)	207.800	0.390	81.5
1.1 Summer cork	113.800	0.650	74.0
1.2 Winter cork	94.000	0.080	7.5
2. Firewood (kg)	867.300	0.010	8.9
2.1 Cork oak firewood	397.000	0.014	5.4
2.2 Shrub firewood	470.300	0.008	3.5
3. Charcoal (kg)	49.400	0.260	12.8
4. Grazing rent (forage units)	651.700	0.070	44.4
5. Other woodland goods	21.902	0.360	7.8
5.1 Acorns (collected) (kg)	20.400	0.060	1.3
5.2 Myrtle (t)	0.100	27.450	3.5
5.3 Mushrooms (kg)	1.400	2.050	2.8
5.4 Hunting rent (license)	0.002	97.60	0.2
6. Subsidies net of taxes			–2.5
Total benefits (1 + 2 + 3 + 4 + 5 + 6)			152.9

[a]Exchange rate in 2002: 1.34 Tunisian dinar = €1.
[b]"ha" indicates woodland hectare, including cork oak woodlands and associated shrubland.

benefits are determined by market exchange values (i.e., price time quantity), except for free access grazing resources, whose rental rates were estimated subjectively (Table 14.1). Total costs considered were labor costs (employees and self-employed labor cost), intermediate consumption (raw materials and services), and machinery depreciation. All except self-employed labor costs are also derived directly from known market values (Table 14.2). We also measure householders' total livestock income as the *market accounting residual value* from livestock benefits minus intermediate costs (for details see Campos et al. 2008b).

For woodlands we also assume a subjectively estimated grazing *forage unit (FU)* price and then estimate the grazing rent as the quantity of extracted FUs times assumed price (€/FU). (An FU is the energy equivalent of 1 kilogram of barley.) Consequently, if we assign a positive grazing rent, then it conditions the joint livestock *self-employed labor income*, but the householders' total income derived from livestock husbandry does not change because the hypothetical open-access grazing rent is entirely appropriated by livestock keepers.

Assuming a positive grazing rent, we assign an FU price of €0.07/FU for grazing resources, which is nearly equivalent to 50 percent of the barley FU price at the farm gate (Table 14.1). This implies a household livestock self-employed wage rate of €0.22 per worked hour, assuming the later FU

TABLE 14.2.
Iteimia woodland total cost, 2002.

Class	Quantity/ha	Price[a] (€/unit)	Value[a] (€/ha)[b]
1. Raw materials and services			10.2
1.1 Summer cork			3.4
1.2 Winter cork			0.7
1.3 Firewood			3.1
1.4 Charcoal			2.7
1.5 Other woodland goods			0.3
2. Labor cost (h)[c]	134.2	0.31	41.3
2.1 Employee labor cost (h)	66.2	0.37	24.7
Summer cork	*45.3*	*0.37*	*16.9*
Winter cork	*2.4*	*0.37*	*0.9*
Firewood	*10.2*	*0.37*	*3.8*
Other woodland goods	*8.4*	*0.37*	*3.1*
2.2 Self-employed labor cost (h)	68.0	0.25	16.6
Firewood	*54.3*	*0.11*	*5.7*
Charcoal	*6.5*	*1.56*	*10.2*
Other woodland goods	*7.2*	*0.10*	*0.7*
3. Machinery depreciation			0.5
4. Total cost (1 + 2 + 3)			52.1
4.1 Summer cork			20.4
4.2 Winter cork			1.7
4.3 Firewood			13.0
4.4 Charcoal			12.9
4.5 Other woodland goods			4.1

[a]Exchange rate in 2002: 1.34 Tunisian dinar = €1.
[b]"ha" indicates woodland hectare.
[c]"h" indicates working hours.

price gives a household livestock self-employed wage rate equal to only 60 percent of the average woodland worker wage rate. If no monetary value is assigned to woodland grazing resources, then the livestock self-employed wage rate increases to 82 percent. The latter result is an objective figure and reveals that assumed woodland grazing rent might have been reduced under current conditions of chronic overgrazing, as usually occurs in open access livestock overgrazing regimes (Campbell and Luckert 2001).

Woodland Income

As in Chapter 13, our indicators here are based on an average year, 2002. Annual cork yields are considered in terms of the latest outcomes from a complete stripping rotation cycle of twelve years. However, we recognize that future cork stripping will gradually decline, given the natural regeneration problems that cork oak woodlands in Iteimia and elsewhere are currently facing (see Chapter 10). We estimated total income accrued from open cork oak woodlands natural resource use as the difference between a reduced number of benefits and costs (Campos et al. 2008a). But given that our analysis does not integrate income changes caused by the gradual decline in cork yields and by losses in soil fertility due to excessive grazing or cropping, the estimated woodland total income is probably overvalued. We measured single and total benefit values offered by the current woodland use (Table 14.1). Note that summer cork stripping and grazing rent contributed 47 percent and 29 percent of woodland total benefits, respectively. The remaining woodland uses yielded 24 percent of woodland benefits, of which 5 percent corresponds to a range of products collected by private firms. Woodland uses did not benefit from government subsidies, and taxes on products were low.

Total cost is shown, including individual inputs and tasks (Table 14.2). Raw material and service expenditures are only 20 percent, and machinery depreciation has a negligible value of 1 percent of total cost. By contrast, labor (employees and self-employed) accounts for 79 percent of the woodland total cost. Total woodland income is shown in Table 14.3, distributed among households, the landowner, and private firms working in the area.

Woodland total income consists of 29 percent labor income and 71 percent capital income (Table 14.3). The capital income is shared by the state

TABLE 14.3.

Woodland labor, capital, and total income at Iteimia, 2002.

Class	Labor income (€/ha)[b]	Capital income (€/ha)[b]	Total income (€/ha)[b]
1. Cork	17.8	57.0	74.8
1.1 Summer cork	16.9	51.2	68.1
1.2 Winter cork	0.9	5.8	6.7
2. Firewood	9.5	–4.1	5.4
3. Charcoal	10.2	0.0	10.2
4. Grazing rent		44.4	44.4
5. Other woodland goods	3.8	3.6	7.4
6. Total income (1 + 2 + 3 + 4 + 5)	41.5	100.8	142.2
6.1 Woodland owner		52.8	52.8
6.2 Private firms		3.6	3.6
6.3 Households	41.5	44.4	85.8
Grazing rent		*44.4*	*44.4*
Self-employed labor cost	*16.6*		*16.6*
Employee labor cost	*24.7*		*24.7*

[a]Exchange rate in 2002: 1.34 Tunisian dinar = €1.
[b]"ha" indicates woodland hectares.

(52 percent), private firms (4 percent), and livestock keepers (44 percent), who appropriate the grazing rent. Householders' woodland income makes up 60 percent of total woodland income. This comes from grazing rent (52 percent), self-employed labor costs (19 percent), and employee compensation (29 percent). The state and private firms receive 37 percent and 3 percent, respectively, of total woodland income (Table 14.3).

Conflicts between Woodland Resource Conservation and Householders' Subsistence Economy

Livestock rearing is certainly the most important activity for the local population. No less than 80 percent of householders' agroforestry-based income (self-employed labor income plus grazing rent) comes from livestock rearing. This activity strongly depends on woodland for free-access grazing resources for feeding animals and, to a lesser extent, on forage crops and crop fallows.

We estimate that current grazing resource consumption is 527.8 FU per hectare of agroforestry area (Campos et al. 2008a). Likewise, it is estimated that livestock obtains 80 FU/ha from cropland (OEP 1992) and 651.7 FU/ha from woodland. This latter FU consumption rate comes from areas populated by cork oaks (642 FU/ha) and shrubland (750 FU/ha). These FU values are compared with the edible growth output of FUs in cork oak area and shrubland, which have been estimated to attain 422 FU/ha and 493 FU/ha, respectively (for further details see DGF 1995). Considering the former edible biomass annual growth figures and the distribution between cork oak areas and shrubland, we estimate that the sustainable grazing consumption totals 428.4 FU/ha of woodland. In other words, there is an overgrazing problem, which is estimated to reach an average rate of 223.3 FU per woodland hectare per year. Thus, current annual FU extraction is nearly 1.5 times the estimated edible biomass growth.

As indicated earlier, overgrazing has undoubtedly caused soil and vegetation degradation. Therefore, it seems likely that Iteimia—and similarly managed woodlands throughout northwestern Africa—will gradually lose their value as a productive natural resource. However, this situation could be corrected by enforcing livestock grazing regimes compatible with cork oak woodland tree regeneration while avoiding livestock keeper income losses.

Simulated Comparison

To analyze the potential economic effects of sustainable grazing on householders' income, we conducted a simulation, assuming that supplementary feed could replace the quantity of FUs considered to overshoot the sustainable level of livestock grazing. For doing so, we assumed that herd size and composition remain constant.

If livestock keepers were to reduce their annual woodland grazing to a sustainable level corresponding to edible biomass growth, then cork tree recruitment and woodland pasture resources could be improved in the long term, but household income would decrease significantly. In theory the overgrazing could be offset by supplementary hay, and therefore consumption of pasture resources would decrease from the current 84 to 56 percent of livestock's total energy requirement, according to our simulation. This would imply a grazing rent loss of €15.2/ha of woodland, representing a woodland income loss of 11 percent (Figure 14.1). The average cost of supplementary hay feed in Iteimia is €0.28/FU. This raw material forage unit price is four times higher than our imputed grazing forage unit rent (€0.07/FU). As a result, the substitution of grazing resources for supplementary hay decreases household livestock income by 37 percent. The combined grazing rent and livestock self-employed labor income losses under this scenario lead to a household total income loss of 39 percent (Figure 14.1).

Certainly, this hypothetical approach to estimating the effects of grazing restrictions has several caveats because we ignore what would be the real feedback effects, in terms of herd composition, size, management intensity,

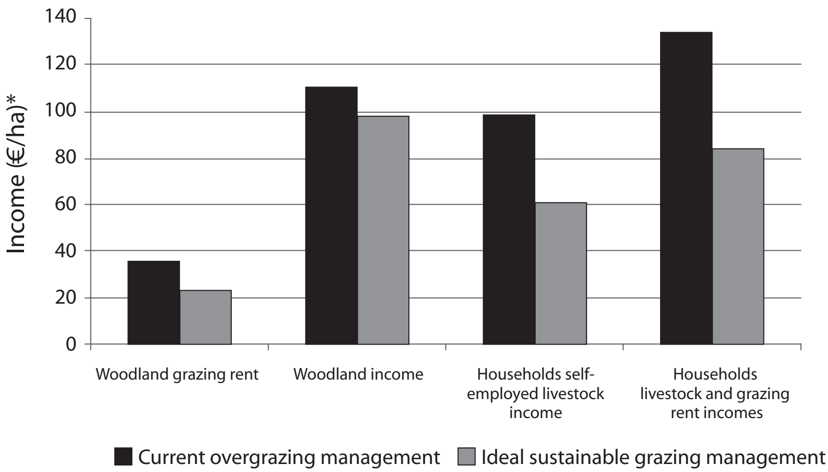

Figure 14.1. Householders' income with overgrazing and under ideal sustainable grazing management in Iteimia, northern Tunisia.

and land use change. This analysis should also consider alternative market opportunities (e.g., a dairy industry) to offset householders' income loss.

Conclusions

Our economic analysis indicates that households are the main beneficiaries of the goods and services generated in the woodland area, obtaining up to 60 percent of total income. This share actually is higher for agroforestry areas, when crop and livestock activities are considered, given that household income accounts for 81 percent of total income. On average, households get an annual woodland income of €480, and it increases to €948 when the agroforestry area is taken into account (Campos et al. 2008b).

Grazing and crops (forages and residues) grown in the agroforestry area are the main sources of livestock feed. As shown, comparing a hypothetically nonovergrazing woodland management scenario entailing supplementary feed with the current lack of tree regeneration management, characterized by chronic overgrazing, shows that householders' total income would decrease but that range conditions would be improved. In this regard, the quantity of available feed could be increased by creating improved grassland areas because climatic conditions are favorable in the area (1,000 mm/year of rainfall). Some parcels have been allocated to local communities for hay cropping in order to decrease overgrazing. A shift in livestock structure was also promoted by the Tunisian Forest Administration, introducing more productive cattle breeds that cannot be fed from forest grazing resources and encouraging local communities to develop new woodland activities in order to diversify and enhance their income. But to date, all attempts by the Forest Administration and local householders to manage woodland grazing in a sustainable ways have failed. Management practices for woodland areas, such as rotation of grazing parcels, surveillance, and control of illegal grazing, should be improved, with the local population involved in decision making about property rights and resource allocation, but these measures will entail changes in Tunisian government forest policy.

Householders' economic opportunities in the area are currently restricted to livestock rearing and subsistence cropping. These villagers rely on grazing resources as the mainstay of their subsistence economy, even though this leads to problems in resource conservation of woodlands and related pasture lands. The government could implement a wide array of steps to increase the income of the local population while reducing woodland degradation. Income losses from grazing restrictions should be compensated for, given the subsistence economy of most or all households. It is reasonable to base this compensation partly on the capital income that the state currently receives from stripped cork and other miscellaneous woodland rents in Iteimia and partly on a transfer compensation mechanism from developed countries when Iteimia households suffer the economic losses of generating global environmental benefits or mitigating environmental losses. Otherwise, it is inequitable that the state, as the woodland owner, benefits from a relevant capital income (similar to a resource rent) from Iteimia woodlands while its investments in local development projects, such as roads, electricity, potable drinking water, housing, education, and health services, are grossly inadequate with respect to basic needs. The compensation scheme should also consider the public benefits of the woodland conservation services provided by local householders' livestock, such as a reduction of the risk of catastrophic woodland and shrubland fires and biodiversity losses.

This study has focused on woodland incomes derived from private goods and services controlled by the state but with the Iteimia householders being beneficiaries of certain natural resource usage rights. Therefore, total private commercial income provides an incomplete picture of the total woodland benefits (see Chapters 13 and 15). Mediterranean woodlands give refuge to exceptional levels of biodiversity, provide watershed and habitat, sequester (or release) carbon, offer historically meaningful landscapes, and are aesthetically pleasing. Neither these benefits nor the cost of losing cork oak woodlands has been taken into account in this study. Consideration of these public values in further studies is essential in order to assess the total sustainable income in Iteimia and similar woodlands.

However, even if these benefits are not considered, their existence and the evidence of gradual cork oak woodland depletion should warrant the creation of a specific program for woodland conservation, paying special attention to mitigating the income losses of livestock keepers from woodland sustainable management in Tunisia and in other Mediterranean countries. In the next chapter we apply a cost–benefit analysis to two land management scenarios in Spanish cork oak woodlands.

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SITE PROFILE 14.1

Maamora, Morocco

This site profile describes what may be the most famous cork oak woodland, the Maamora. A mere century ago, it was a great forest, but today it is much reduced and in need of restoration.

Geographic and biophysical description	The Maamora forest is a distinct geographic, geological, and botanical unit situated in northwestern Morocco, between Rabat and Kenitra to the west, the Kenitra to Sidi Slimane road to the north, the Beht River to the east, and the latitudinal parallel of Rabat in the south. Total area today is only 70,000 ha. Altitude ranges from 30 to 270 m. The climate is subhumid, with warm winters near the coast, and semiarid, with moderate winters further inland. An aridity gradient exists from west to east. The deep geological substratum consists of Miocene marl–limestone formations, Pliocene sands, and an ancient calcareous sand hill system. The soil is sandy, varying in depth from a few centimeters to 2 m, beneath which is found the Maamora red clay. Accompanying plants include Mediterranean fan palm (*Chamaerops humilis*), rockrose (*Cistus salviifolius*), brooms (*Cytisus arboreus* and *C. linifolius*), giant fennel (*Ferula communis*), European frostweed (*Helianthemum guttatum*), thatching grass (*Hyparrhenia hirta*), lavender (*Lavandula stoechas*), narrow-leaved lupin (*Lupinus angustifolius*), Maamora mountain pear (*Pyrus bourgaeana* subsp. *mamorensis*), and rabbit-foot clover (*Trifolium arvense*).
Physiognomic description of the cork oak woodlands and their landscapes, including woodland dynamics	Together with the mountain pear, cork oak is the only native tree in the Maamora forest. Its density varies as a function of the depth of the sand and slope of the clay substrate, ranging from 600 trees/ha to just a few trees here and there. Natural regeneration is absent.
History of land uses, land tenure (and socioeconomic drivers), and current land uses, economic activities, and context	The forest is used principally for cork production and grazing. Exotic woody species, such as maritime pine (*Pinus pinaster*), river red gum (*Eucalyptus camaldulensis*), and black wattle (*Acacia mollissima*), were introduced over the past century for the production of wood and tannin. As a result, the Maamora has been much reduced in size, but it is still the largest managed cork oak woodland in the world.
Disturbance regime (fires, pests, overgrazing)	High human pressure, overgrazing, and stand senescence are all strongly present. Fires occur regularly but vary in size and intensity from year to year.

Constraints and conflicts, protective measures, restoration actions, land use regulations, and relevant policies	Reforestation is under way every year, with satisfying results. Cork stripping is carried out every 10–12 years, principally for stopper production. Other commercial products include mushrooms, aromatic and medicinal plants, lichens, and sweet acorns for human consumption.
Current trends and prospects for the future	Cork production will continue. Recreational activities near the principal cities are becoming increasingly important. Restoration of damaged parts and reconversion to cork oak of areas planted in eucalyptus, pine, and acacia will be more important in the future.
Source	Mohamed Abourouh, Forestry Research Center, Rabat, Morocco

Site Profile Figure 14.1. Maamora cork oak forest.

Chapter 15

Cost–Benefit Analysis of Cork Oak Woodland Afforestation and Facilitated Natural Regeneration in Spain

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Cork oak woodlands in Spain occur mostly in large private estates in the west-southwest (80 percent) and in the northeast (Girona province, 13 percent), and the remaining 7 percent are spread in isolated patches in the central and eastern (Castellón province) parts of the country (see Figure 1.1). The occasional cropping of cereals, which was formerly practiced in many cork oak woodlands, has nearly disappeared over the last three decades (Moreno et al. 2007).

Two trends have emerged with regard to livestock. In the west-southwest, stocking rates and grazing pressure have increased, exacerbating the traditional lack of natural regeneration by cork oaks (Pulido et al. 2001; Chapter 10). In sharp contrast, in the northeast there is widespread abandonment of livestock, which leads to a rapid buildup of excess biomass in the cork oak woodland understory. Thus, cork oak woodlands in the northeast now contribute significantly to carbon sequestration in the short to medium term, except for the fact that they are increasingly decimated by fires. As a result, government expenditures for fighting and preventing wildfires maintain the woodlands as a carbon sink. This leads to an equity problem because ultimately it is affluent people in the cities who are the main beneficiaries of both types of public expenditure.

For some, the lack of natural regeneration of oaks in the cork oak woodlands of the west-southwest of Spain and the biomass problems of the northeast are both undesirable to the public. And in the medium to long term, both trends appear to be unsustainable from a competitive commercial cork productivity perspective. Both unsustainable management regimes appear to generate competitive private profit rates through rising real estate prices, private amenity values, cork harvesting, rental fees for hunting of wild game, livestock grazing, and various government subsidies (Campos et al. 2008c). Nevertheless, the long period of cash losses before the time of first commercial cork stripping in cork oak stands resulting from afforestation or facilitated natural regeneration makes the expansion and renewal of cork oak woodlands economically unattractive to private landowners. If benefits and costs at current market prices are considered alone—that is, in the absence of government or international subsidies—in the short and medium term, those investments generate cash losses (Campos et al. 2007b). Nevertheless, as mentioned in Chapter 14, southern European governments and concerned interest groups state that the predicted decline of cork oak woodland public and private benefits should be offset by increasing public expenditures on cork oak afforestation and natural regeneration (ID 1997; CMA 1999; WWF 2004).

In this chapter we present an extended cost–benefit analysis for evaluating possible capital income changes, from both private and social capital perspectives in the case that either afforestation or facilitated natural regeneration is undertaken as an alternative to the two trends cited earlier. The two land management scenarios presented are commercially oriented. We assume a nonindustrial woodland private owner with a mixed low-risk investor–consumer reasoning process. This implies that private landowner demands commercial returns while enjoying the private amenities derived from the woodland, shrubland, and cropland environmental services.

This cost–benefit analysis was applied in three Spanish cork oak woodland sites with different management schemes: the Aljibe massif in the southwest (Andalusia), the Monfragüe plain in the west (Extremadura), and the Gavarres massif in the northeast (Catalonia). The Aljibe site is located inside the Los Alcornocales Natural Park (see Site Profile 17.1), the Monfragüe site is part of the buffer zone of Monfragüe National Park, and the Gavarres site is a protected natural area.

Cork Oak Woodland, Shrubland, Pasture, and Cropland Management Scenarios

We simulated six idealized sustainable silviculture models for investment scenarios in pure cork oak stands: three of afforestation of bare lands and three of commercially oriented, facilitated natural regeneration. The later entail different kinds of costly interventions, especially at the earliest stages of the cycle (e.g., for removing competing vegetation and preventing the entry of livestock and other herbivores).

We compared these six scenarios with six corresponding noninvestment scenarios, where *noninvestment* refers exclusively to the lack of cork oak forestry treatments. Those alternative scenarios were three bare lands and three aging cork oak woodlands with no treatments to encourage natural regeneration. These twelve forecast models are well adapted to the current technical and economic conditions of the three study sites. Indeed, the idealized silviculture models are based on actual data for cork oak growth and cork yields at Monfragüe, Aljibe, and Gavarres sites.

The six investment scenarios include a series of cork oak forestry treatments to be completed over the entire productive cycle of afforestation or of a facilitated natural regeneration. The main prescribed treatments are twenty years of grazing exclusion only in Aljibe and Monfragüe, because there is no livestock grazing in the Gavarres site. In addition, at all three sites, treatments include structural tree pruning, selective thinning, shrub clearing, and regeneration felling, which consists of cutting a large percentage of aging cork oak trees in such a way that on-site seeding under the tree canopy is encouraged without completely forgoing cork extraction. This is made possible by leaving the most productive trees standing until the final clear-cut of remaining mature trees takes place (for details see Campos et al. 2007b). According to the silviculture models analyzed, cork stripping takes place every nine years in Aljibe and Monfragüe and every twelve years in Gavarres after the first cork oak stripping, which takes place when trees are twenty-six years old in Monfragüe, twenty-eight years in Aljibe, and forty-four years in Gavarres. In all three cases, the first stripping takes place when the trees reach a circumference of 60 centimeters at breast height.

To simulate afforestation investment scenarios, we assumed that the current vegetation cover, where new plantations are being carried out, is unproductive shrubland in Aljibe, pastureland in Monfragüe, and marginal cropland in Gavarres. The ideal silvicultural models start with afforestation using cork oaks, followed by the application of the aforementioned forestry treatments. In the three investment scenarios based on facilitated natural regeneration, we assumed that the current vegetation is aging cork oak woodland at all three study sites, where trees are 144 years old in Aljibe and Monfragüe and 151 years old in Gavarres. In this case, our silvicultural models start with regeneration felling treatment on the senescent woodland, followed by the application of pruning, thinning, and shrub clearing as needed.

For the three facilitated natural regeneration scenarios, the corresponding nonrenewal scenarios were the aforementioned aging cork oak woodlands. In this case, however, the regeneration treatment is not applied at the time that regeneration felling should, in theory, be carried out. Under these noninvestment scenarios, the cork oak will disappear in the future, as we assume that livestock grazing in Aljibe and Monfragüe and marginal crops in Gavarres are the private owners' main commercial interests. It is expected that in Aljibe and Monfragüe, cork stripping will cease after a few decades, as a direct consequence of declining tree numbers and cork productivity, resulting eventually in the complete disappearance of cork oak and a return to shrubland and pastureland uses, respectively. In the case of Gavarres, however, we assumed that the noninvestment scenario would reduce commercial cork productivity, with a subsequent abandonment of commercial cork-oriented treatments and a return to cropland use after the unproductive cork oak stand is cleared.

Present Discounted Values of Capital Income from Cork Oak Investment and Noninvestment Scenarios

In our forecast models, landowners obtain private capital income from the sale of cork, firewood, cropland rents, grazing, and hunting rents, as well as government net subsidies and private amenities (i.e., nonmarket, self-consumption services internalized in woodland market prices). The landowners, visitors, and society as a whole all benefit from the social capital income derived from private capital *income at market prices* (without consideration of net subsidies) and from the public environmental capital income (i.e., public environmental benefits minus government expenditures). For the latter income, we incorporated three public environmental incomes: the recreation services provided for visitors, natural habitat conservation (joint option and existence values) services for visitors (only at Aljibe and Monfragüe), and cork oak woodland carbon sequestration services at all three sites. Furthermore, we assumed that government subsidies and taxes would influence current private capital income gain and loss, respectively, but not modify the current social capital income of cork oak woodlands.

We further assumed constant prices corresponding to real (sales, net subsidies, and costs) or estimated (private amenity and public environmental benefits) market prices in 2002. Even so, we analyzed the sensitivity of results to variations on 2002 cork prices ranging from ±25 percent to ±50 percent. In order to aggregate both commercial and environmental benefits in a homogeneous manner, we used simulated *exchange prices* for private amenity, recreation, habitat conservation, and carbon sequestration services (Campos et al. 2008c).

Private and Public Benefit Exchange Values

Except for private amenity value, woodland private benefits were drawn as direct market exchange values (i.e., price time quantity) (Table 15.1). The values attributed to hunting rent reflect the amount that landowners would be paid for leasing their estates for developing big (Aljibe and Monfragüe) or small game (Gavarres), net of costs and taxes. The grazing rent reflects the market prices for leasing 1 hectare of cork oak woodland, shrubland, or pastureland, for supplying edible food for livestock grazing (Campos et al. 2007b).

The commercial benefits that landowners obtain from bare lands before cork oak afforestation in Aljibe and Monfragüe derive from grazing and hunting. In Gavarres, landowners obtain revenues from leasing land for cropping and from renting hunting rights (Table 15.1).

Private amenity includes owners' exclusive on-site enjoyment (current active use) plus a number of landowner option values (future active use) and passive uses (existence values) (Campos et al. 2007a; see Table 13.1). The private amenity value was measured by three *contingent valuation surveys* ap-

TABLE 15.1.

Commercial and environmental benefit prices in Aljibe, Monfragüe, and Gavarres (2002 €/unit).

Class	Aljibe	Monfragüe	Gavarres
Commercial benefits			
1. Summer stripped cork (kg)[a]	1.10	1.18	1.18
1.1 Virgin cork (kg)	0.24	0.27	0.30
1.2 Reproductive cork (kg)	1.17	1.22	1.28
2. Winter cork (kg)	0.10	0.06	0.15
3. Firewood without bark (kg)	0.03	0.02	0.04
4. Grazing rent (forage units)	0.09	0.10	
5. Hunting rent (ha)	38.10	42.10	9.00
6. Dry cropland rent (ha)			79.80
Environmental benefits			
1. Private amenity (ha)	209.30	100.20	225.40
2. Public visitor services (ha)	11.00	23.00	n.a.
2.1 Recreation (ha)	5.10	10.50	
2.2 Conservation (ha)	5.90	12.50	
3. Carbon (t C)	23.00	23.00	23.00

[a]Average summer stripped cork price is estimated considering the share of virgin and reproductive cork obtained at each site.
n.a., not available.

plied to a sample of cork oak woodland owners in Los Alcornocales Natural Park, Monfragüe district, and the Girona province. We assumed that the private amenity value was the same for all the land uses considered at each study site (Table 15.1), although we recognize that this might not be realistic. The monetary amounts that public visitors of Monfragüe and Aljibe were assumed to be willing to pay for recreational use, as an increase in the cost of the visit, and for habitat conservation as a contribution to a voluntary fund, came from two contingent valuation surveys.

In the near future, carbon emission reductions and sequestration in cork oak woodlands will have market value, and therefore owners may profit from selling carbon credits derived from cork oak afforestation and even from avoiding deforestation. However, this was not the situation when this study was carried out. Accordingly, carbon sequestration was considered here simply as a public service, and its monetary value was set to correspond to the global damage cost avoided by mitigating 1 ton of carbon for the period of 2000–2010 (Table 15.1). Like all of the numerous estimates of the *marginal cost* of damage of increasing atmospheric CO_2, this assumption is subject to great uncertainty. Thus, we estimate the sensitivity of results to carbon prices ranging from €0/t C to €100/t C.

Private and Public Cost Measurement

Private total costs considered were those of the system of national accounts: labor costs, intermediate consumption (raw materials and services), and fixed capital consumption (human-made capital depreciation). These costs partially reflect the economic effort of managing the three cork oak woodlands, given that government agencies, both national and regional, assume public expenditures that affect the provision of the accounted private and public benefits. From various government agencies we collected data on the effective government expenditures in 2002 in Aljibe and in Monfragüe (no data were available for Gavarres) for fighting wildfires and providing information and other minor services to recreational visitors, which were equally distributed over the entire area of those two sites.

Capital Income Change Present Discounted Values

The economic analysis of investment scenarios, compared with their corresponding noninvestment scenarios, was performed on the basis of private and social capital income change estimates at present discounted values. We assumed that a nonindustrial private owner would seek to maximize her or his private capital *income at factor costs* (i.e., including government subsidies net of taxes and at present discounted value). Concurrently, from the societal perspective, we assumed the goal of obtaining the greater social capital income at market prices and present discounted value.

We assumed that the sustainable ideal silvicultural management of either afforestation or a facilitated natural regeneration would lead to a permanent commercial cork oak woodland stand. Thus, the afforestation and facilitated natural regeneration productive cycles are followed by an infinite sequence of identical natural regeneration rotations (cycles) at a fixed time interval, over which period the owner repeatedly incurs cork oak natural regeneration treatment costs.

We applied cost–benefit analysis tools to estimate the present discounted values of the all future streams of private and social capital incomes surrounding the analyzed land use management scenarios (Campos et al. 2007b). The stream of private benefits and costs was discounted using the estimated real profitability rates that landowners get from bare land uses before afforestation at each study site. This represents the private opportunity cost of capital for land investment at the study sites. The estimated annual private profitability rates were 4 percent in Aljibe, 5.5 percent in Monfragüe, and 6 percent in Gavarres. The public (environmental) capital income was discounted assuming an imputed 2.5 percent annual social *discount rate*, although a sensitivity analysis to social discount rates ranging from 1 percent to 7 percent was also provided.

We estimated the present discounted values of capital income gains (if positive) or losses (if negative) as the difference between capital incomes present discounted values, obtained from afforestation and facilitated cork oak woodland natural regeneration investment scenarios and the capital income's present discounted values, generated by bare land uses and aging cork oak noninvestment scenarios. In the next sections we will use the term *income* to refer to the capital income's present discounted value.

The private and public agents' cork oak investment rationales described in the next sections are based on the net present capital income changes (gains or losses) measured in Aljibe, Monfragüe, and Gavarres for twelve compared scenarios.

It must be noted that livestock, crop, and game activities do not affect directly the afforestation and facilitated natural regeneration cost–benefit analysis, but these activities indirectly influence the cost–benefit analysis via the values of grazing, cropland, and hunting rents.

Cork Oak Afforestation and Facilitated Natural Regeneration under the Current Private Owner Investor–Consumer Perspective

Over the last decade, the European Union and the Spanish government have strongly encouraged cork oak afforestation on abandoned pastures, shrublands, and croplands under European Regulations 2080/92 and 1257/99 (Ovando et al. 2007). In 2002, these government aids were established to encourage investment in cork oak afforestation through a five-year plant maintenance payment and a twenty-year compensation for grazing exclusion. According to our studies, planting with cork oak a shrubland in Aljibe and a pastureland in Monfragüe became the preferred options for private investors accepting profitability rates equal to or lower than 4.0 percent and 5.5 percent, respectively. The Aljibe and Monfragüe private capital income gain at factor cost was equal to €1,006/ha and €52/ha, respectively (Table 15.2). In Gavarres, however, afforestation led to a capital income loss of €3,084/ha for a private investor who normally demands a profitability rate of 6 percent, when compared with growing annual crops on the same piece of land (Table 15.2).

TABLE 15.2.

Capital income changes from cork oak afforestation and facilitated cork oak woodland natural regeneration in Aljibe, Monfragüe, and Gavarres sites (2002 €/ha).

	Cork oak afforestation		Facilitated cork oak natural regeneration	
Class[a]	Private capital income at factor costs	Social capital income at market prices	Private capital income at factor costs	Social capital income at market prices
Aljibe				
Investment scenario (A)	7,929	–2,726	7,112	2,143
Noninvestment scenario (B)	6,923	5,811	11,861	8,005
Capital income change (A – B)	1,006	–8,537	–4,749	–5,862
Monfragüe				
Investment scenario (A)	3,218	–811	4,742	2,776
Noninvestment scenario (B)	3,166	3,636	9,529	9,407
Capital income change (A – B)	52	–4,447	–4,787	–6,631
Gavarres				
Investment scenario (A)	6,382	162	8,695	5,957
Noninvestment scenario (B)	9,466	5,383	11,076	9,724
Capital income change (A – B)	–3,084	–5,221	–2,381	–3,767

[a]Discounting rates of 4% in Aljibe, 5.5% in Monfragüe, and 6% in Gavarres were applied for discounting private benefits and costs, and public benefits and costs were discounted using a social discount rate of 2.5%.

Private capital income associated with facilitated cork oak natural regeneration (investment scenario) results in a worse private economic alternative than letting an aging cork oak woodland deplete (noninvestment scenario) (Table 15.2). Current government aids to facilitate cork oak natural regeneration management, as contrasted with afforestation, are insufficient to make this an attractive investment option for private owners (Table 15.2).

Afforestation and Facilitated Natural Regeneration under Current Societal Preferences

At all three study sites, investment scenarios for afforestation and facilitated natural regeneration generated social capital income losses (Table 15.2). These results are not very sensitive to variation in the social discount rate used for estimating the present discounted values of future public benefits and costs (Figure 15.1).

Given that we assume that private amenity, current visitors' recreation, visitors' habitat conservation concerns (i.e., visitor option and existence values), and government expenditures have the same values for all land uses at each site, it follows that social capital income changes are entirely due to private commercial capital income changes at market prices (i.e., independent of government subsidies and taxes on products) and carbon emission reduction or mitigation values. Private capital income strongly depends on cork sales, but as Figure 15.2 shows, social capital income changes are sensitive only to variations in market prices for cork and carbon mitigation. In the

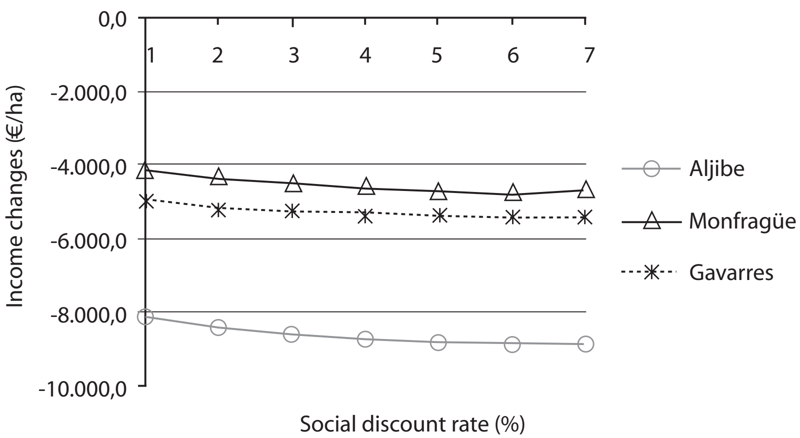

FIGURE 15.1. Sensitivity analysis of social capital income changes to social discount rates in cork oak afforestation scenarios.

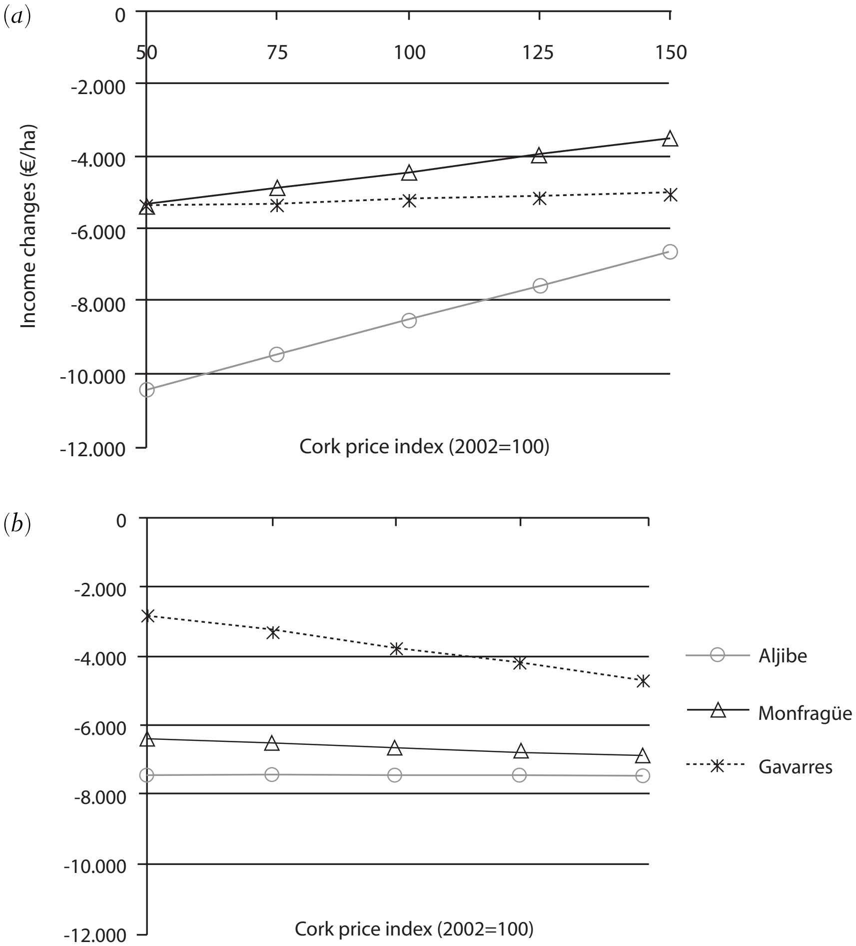

Figure 15.2. Sensitivity analysis of social capital income changes to cork prices in *(a)* cork oak afforestation and *(b)* facilitated cork oak natural regeneration scenarios.

afforestation scenarios, this is due to the long lag time before cork of commercial interest is obtained. Although changes in cork prices affect both natural regeneration investment and noninvestment scenarios (note that an aging cork oak stand with no regeneration treatments still produces cork for some decades; Campos et al. 2008c), investment scenarios would imply social capital losses even if cork prices increased by 50 percent.

Carbon income could be a relevant public economic value for cork oak afforestation and natural regeneration projects only if its price reached a value several times higher than the current €20 t C avoided social damage service. Thus, the slow cork oak growth rate penalizes the short-term benefits

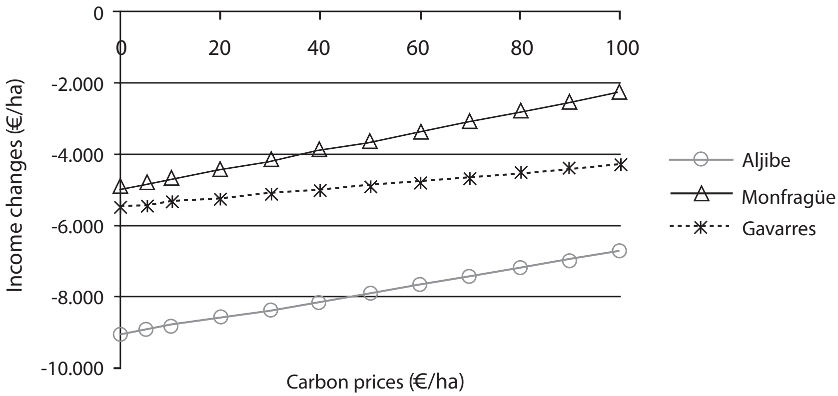

FIGURE 15.3. Sensitivity analysis of social capital income changes to carbon prices in cork oak afforestation scenarios.

accrued from sequestering carbon, even if higher carbon prices (greater than €50/t C) are assumed (Figure 15.3). However, native cork oak woodlands store carbon for longer periods and bestow higher biodiversity and scenic values compared with afforestation with fast-growing species.

Conclusions

Cork oak afforestation is an expensive alternative that, at present, requires strong government subsidies, especially because of the long time lag between planting and obtaining cork of commercial interest. Thus, both cork oak afforestation and facilitated natural regeneration alternatives are expensive and involve an opportunity cost related to grazing resource use, cropping, and cork yields (Campos et al. 2008c).

At present, government afforestation aid provides sufficient incentives to encourage private owners in Aljibe and Monfragüe to invest in cork oak afforestation. However, in Gavarres, those incentives are insufficient to provide an attractive alternative to cropland instead of cork oaks.

In contrast with afforestation aid, insufficient government aid is given for restoring aging cork oak woodlands in the three study sites. This could be a government policy failure because recent studies suggest that restoration and sanitary treatments on existing wooded Mediterranean oak stands might be preferable, in terms of biodiversity conservation and carbon release mitigation, to the artificial creation of new stands (Campos et al. 2006).

Given the limitations of current societal preferences, afforesting bare lands with cork oak and facilitating the natural regeneration of aging cork oak woodlands both lead to social capital income losses as a result of the willingness to pay revealed in the marketplace and stated in contingent valuation surveys by visitors to the woodlands (Table 15.2). We recognize that the individuals' willingness to pay for habitat conservation might not prevail in a situation of increasing risk of irreversible biodiversity losses. From an ethical perspective, however, the precautionary principle should prevail for all policy decisions related to preserving an endangered ecosystem such as cork oak woodlands. In other words, in the presence of uncertainty regarding future biological diversity loss with the current decline of aging cork oak woodlands in the Mediterranean region, government criteria to provide incentives for cork oak conservation should not be based only on the positive or negative changes in social capital income. Instead, woodland conservation, enhanced management options, and, wherever needed, restoration should be supported by government (and the European Union) on the basis of *society-tolerable cost*.

Furthermore, in the context in which our cost–benefit analysis was carried out, it is worth noting that market values of cork oak woodlands may be the result of short-sighted agents' behavior because the slow disappearance through age of a significant number of cork oak stands might drive up the price of the surviving stands in the future, as compared with bare lands without tree cover, in the same areas. Therefore, it is possible that the current market or environmental values estimated in this study for private commercial incomes, private amenity, and public environmental income, at present discount values, undervalue the real private and social capital incomes that cork oak woodlands will offer in the future. The final chapter in this section reviews the current state of the manufactured cork industry and trade and considers prospects for the future.

Acknowledgments

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Chapter 16

Manufacture and Trade of Cork Products: An International Perspective

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Chapter 5 focused on the physical properties of cork and the history of the cork sector. Here we focus on the economics of cork manufacture and trade, especially since the late twentieth century.

Relationships between people and the cork oak tree have evolved over many centuries in tandem with technical change. The first breakthrough was the discovery, in the seventeenth century, of cork's usefulness as a stopper for bottles with liquids, such as the sparkling wines of Champagne. The second great change was the invention of agglomerate cork at the end of the nineteenth century, which greatly increased the variety of cork products and their applications, especially as insulating material for domestic and industrial uses (see Chapter 5 and Color Plate 3).

Both innovations increased demand for cork and stimulated the manufacturing industry's development. Silviculture of cork oak stands, which provided raw material with obvious commercial value, spread over the entire "subericola world" in the western Mediterranean Basin (Natividade 1950), in parallel with the stopper industry, normally performed in workshops and highly dependent on skilled workers. Later, with the invention of agglomerate cork, these workshops became less prominent because much higher capital inputs were needed to make it. Thereafter, machines and factories began to lead the production process.

Until the end of the nineteenth century, the cork industry developed in cork-producing countries (Portugal, Spain, France, and Italy) and other countries (the United States, the United Kingdom, Germany) where raw cork was absent. This, together with growing market demand, led to growth of international trade in cork products, which was encouraged or discouraged by specific protectionist policies.

The appearance of synthetic materials as substitutes for natural cork in the mid-twentieth century was the third great wave of technical innovation. Unlike previous changes, this one has had negative consequences for the cork business in most of its former applications and outlets because it is now obliged to focus mainly on bottle stoppers, and even here it suffers strong competition. Most developed countries that once engaged in cork manufacture have lost interest in this activity, which has now come to be concentrated in the Iberian Peninsula.

The current situation of the cork industry is not good. Although there have been large corporations, such as Armstrong Cork and Amorim, this industry is not dynamic because it is very dependent on a natural resource and suffers from low capitalization, limited labor productivity, and a preponderance of factories smaller than the minimum size needed for efficiency. The industry is generally located in rural areas and often appears to be concentrated in industrial districts (Aveiro, Portugal; Baix Empordà and San Vicente de Alcántara, Spain; Calangianus, Italy; Delmenhorst, Germany). The absence of backward integration is another factor promoting conflicts between forest owners' and manufacturers' interests, which in turn hinders the improvement or restoration of cork oak woodlands.

However, the main characteristic of the cork business has always been its international dimension. Therefore, this chapter focuses on this aspect and its possible effects on the future of cork oak stands. The analysis concentrates on countries and on the last century. And we use the Standard International Trade Classification's terms (*raw cork*, *semimanufactured products*, *natural cork manufactures*, and *agglomerate cork manufactures*) and the following aggregates: *unmanufactured cork* (raw cork + semimanufactured products), *manufactured cork* (natural cork manufactures + agglomerate cork manufactures), and *cork products* (unmanufactured cork + manufactured cork).

The Iberization of the Cork Business: 1920s to 1970s

The great boost that the arrival of agglomerates gave to the cork industry withstood the effects of the two world wars and the interwar period, but it ended with the development of synthetic materials, which replaced cork in many applications. This development led to two major changes: the decline of the cork industry in countries that were net importers of unmanufactured cork and the Iberization of the cork business, that is, the concentration of production, industry, and commerce in the Iberian Peninsula.

By 1960, the number of companies and employees, as well as production and import of unmanufactured cork, had declined dramatically in all importing countries, which Sampaio and Leite (1987:266) attributed to the "unbearable increase of the wages" and the "constant rise of the marine freightage." Similar causes led to decline in France and Italy, where producers were no longer competitive with Portugal and Spain. By possessing abundant raw cork and a cheap workforce, the latter countries had advantages in an industry in which the unmanufactured cork itself and workers' wages represent three quarters of production costs (Normandin 1979; Sampaio 1982; Idda and Gutierrez 1984; López 1995). However, some non-Iberian companies maintained their activity by replacing cork with other materials, such as the Armstrong Cork Company, which changed its name to Armstrong World Industries Inc., and several companies in Germany (Mehler 1987; Hess 2002; Kaldewei 2002). Across the Atlantic, the decline of the cork industry in the United States was noteworthy. Around 1930, this industry was the first in the world, both in production scale and in capacity of technical innovation (Faubel 1941; Jiménez 2009).

The second change—the Iberization of the business—has been clearly advantageous for Portugal, which has displaced Spain from the preeminent position it had occupied since the eighteenth century (Zapata 2002). The Portuguese ascent began in the 1930s, increased during the Spanish Civil War, and was consolidated by 1950s, when the Spanish cork industry was still in the grip of the inward-looking and interventionist policy of the first period of the Franco era. Since then, Portugal has been the unquestionable leader of the three facets of the business, fully overcoming the former backwardness of its industry as compared to other manufacturing countries.

One reason for the Iberization has been the strong reduction in product diversification that agglomerate cork offered and the consequent return to the stopper industry, whose products are now almost exclusively dedicated to sealing high-quality wine bottles. The cork industry depends much more on the wine industry than vice versa because wine is also sold in other packages that are not sealed with cork stoppers. At any rate, Iberization is equivalent to localization in the major wine-growing regions of the world (close to the "subericola world"), in which demand for bottled wine has increased in recent decades.

Other reasons for Iberization are related to the cork industry's features. Activities that use spatially concentrated natural resources are risky for countries that are net importers of unmanufactured cork. These countries try to produce manufactured products (e.g., for insulating and coating) by using readily obtainable materials. Likewise, not many technology- and capital-intensive industries can be located in backward countries, which will export their stoppers and other similar commodities to the entire world.

Consequently, given the conditions in which the cork industry has existed for several decades, it seems that the optimal location of such activity is the Iberian Peninsula. This area meets the classic requirement of proximity to raw material and final consumption. It is also a region where external economies, coming from a long manufacturing and commercial tradition, operate.

However, Iberization has been accompanied by a drastic decrease in the size of the cork business in the Iberian countries. The number of factories and jobs and the scale of production and foreign trade have all decreased over the past century (Zapata 2009). Thus, for instance, the percentage of cork products as a fraction of all exports in Spain was 8 percent in 1927 and is 0.2 percent today. For Portugal, the figures are 7 percent in 1920 and 3 percent today (Branco and Parejo 2008).

Manufacture and Trade of Cork Products in the Last Thirty Years: The International Scene

The changes initiated in the mid-twentieth century, leading to the Iberization of the business and the primary importance of bottle stoppers, have been consolidated in the last thirty years, as shown in figures for Spanish exports of manufactured cork products. At the beginning of the twentieth century, stoppers represented nearly 100 percent of Spanish manufactured cork exports; by the 1920s, they represented only 40 percent. Over the next five decades, the figure hovered around 60 percent; in the 1980s, it rose to 72 percent; and in the 1990s, it reached 80 percent (Parejo 2002). Because the proportion of manufactured cork products other than stoppers is very small (López 1995), the industry is becoming monoproduct based, which greatly increases its vulnerability.

Figures 16.1 and 16.2 show the strong decrease in cork imports and exports' values, which in the 1990s were about half of those in the 1960s. In the evolution of the exports (Figure 16.1), it is important to note the similarity of the total exports curve to those of Portugal and Spain and the decrease in exports from both countries. The marked decline of activity in United Kingdom is also notable. In the evolution of the imports (Figure 16.2), Others, such as France, Germany, and the United States, stand out as main importers. But the most significant fact is the rapid increase of import activity in Portugal and Spain, which attained about the same volume as the major importers in 2000.

Tables 16.1, 16.2, and 16.3 show data that complement Figures 16.1 and 16.2. Table 16.1 shows the relative importance of each producer country in

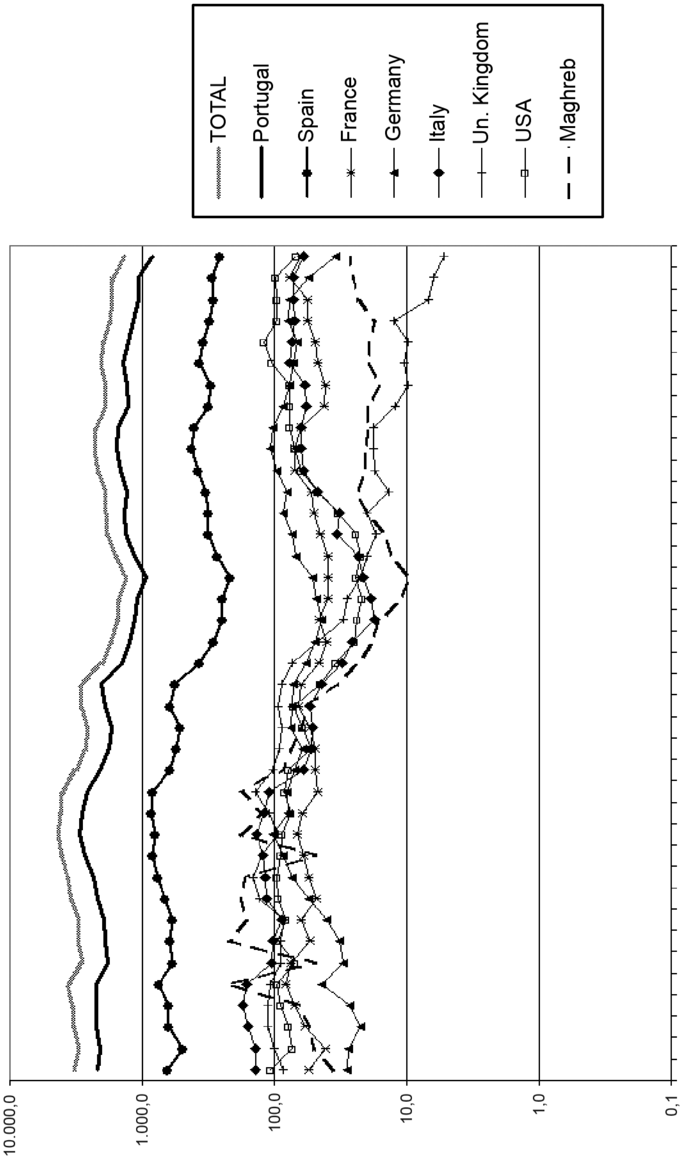

Figure 16.1. Exports of cork products by several countries, 1962–2000 (in millions of 2000 cork U.S. dollars). (Unpublished data from the doctoral thesis of F. M. Parejo, based on United Nations sources; "cork U.S. dollars" are U.S. dollars that have been deflated with the synthetic cork deflator by Zapata 2006)

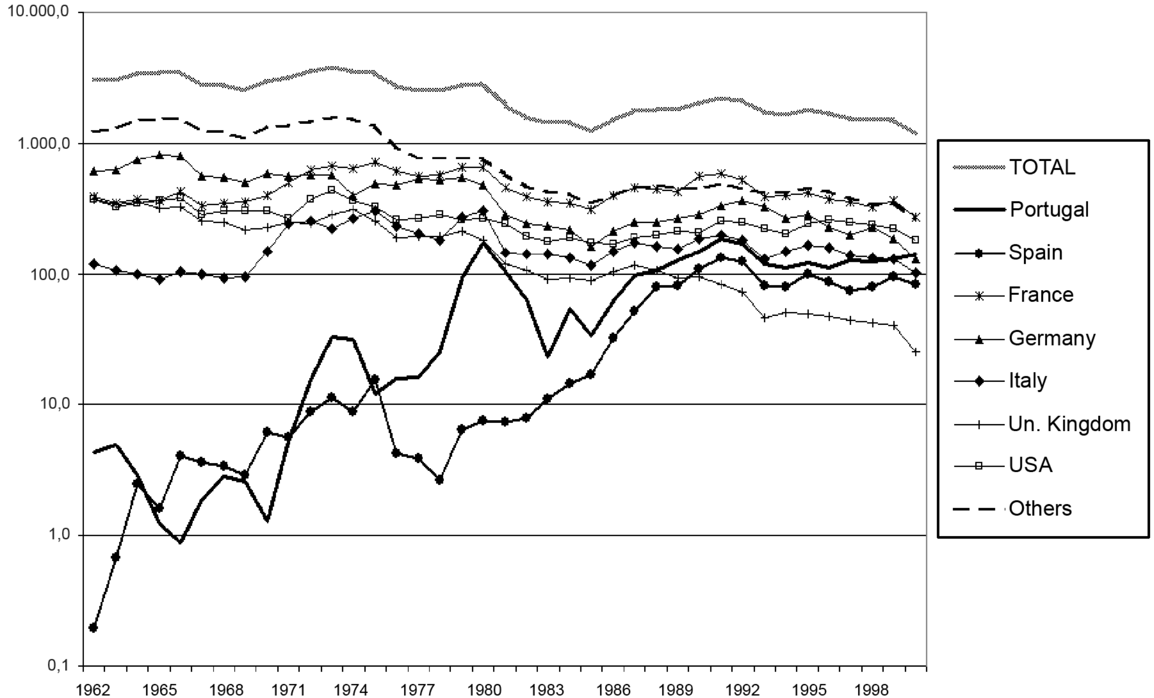

FIGURE 16.2. Imports of cork products by several countries, 1962–2000 (in millions of 2000 cork U.S. dollars). Others = combined totals of Argentina, Australia, Austria, Belgium, Brazil, Canada, Chile, China, Finland, Japan, Mexico, the Netherlands, New Zealand, Norway, South Africa, Sweden, and Switzerland. (Unpublished data from the doctoral thesis of F. M. Parejo, based on United Nations sources; "cork U.S. dollars" are U.S. dollars that have been deflated with the synthetic cork deflator by Zapata 2006)

TABLE 16.1.

Export and import shares of cork products, 1962–2004 (percentage of total for all countries, measured in current U.S. dollars).

	Export shares			Import shares		
	1962–1964	1982–1984	2002–2004	1962–1964	1982–1984	2002–2004
Portugal	67.5	72.3	64.4	0.1	5.3	11.6
Spain	18.3	16.3	20.1	0.0	0.4	10.1
France	1.6	2.6	4.0	11.6	23.4	22.1
Germany	0.8	2.9	2.5	20.6	15.7	9.9
Italy	4.6	1.3	3.8	3.4	9.2	8.7
United Kingdom	3.1	2.2	0.3	11.1	6.4	1.5
United States	2.6	1.5	3.1	10.8	11.2	15.1
Maghreb[a]	1.5	0.9	1.8			
Others[b]				42.4	28.4	21.0
Total	100.0	100.0	100.0	100.0	100.0	100.0
Iberian Peninsula[c]	85.9	88.6	84.5	0.1	5.7	22.2
European countries				46.8	60.4	63.9
Old wine-producing countries[d]				15.1	38.3	52.5
New wine-producing countries[e]				16.9	19.1	28.6
New wine-producing countries (excluding United States)				6.1	7.9	13.5

[a]Surely underestimates; includes Algeria, Tunisia, and Morocco.
[b]Combined totals of Argentina, Australia, Austria, Belgium, Brazil, Canada, Chile, China, Finland, Japan, Mexico, the Netherlands, New Zealand, Norway, South Africa, Sweden, and Switzerland. The original source does not give data about Australia in 1962, New Zealand in 1962 and 1963, and South Africa in 1962–1964 and 1982–1984.
[c]Portugal and Spain.
[d]France, Italy, Spain, and Portugal.
[e]Argentina, Australia, Chile, New Zealand, South Africa, and United States.
Source: Unpublished data from doctoral thesis of F. M. Parejo, based on United Nations sources.

international trade. Although there have been few changes among the exporters, the changes among importers are numerous.

In exports, the data for the Iberian Peninsula—origin of 85 percent of exports—overshadow the rest. These data are a clear sign of Iberization (evident at the beginning of the 1960s) and of the different degrees of involvement of Portugal and Spain: About 80 percent of Iberian exports are from Portugal. In the remaining countries, what is remarkable is the low level of their shares (less than 5 percent) and the insignificant percentages listed for Maghreb (Algeria, Morocco, and Tunisia), which are surely underestimates.

The import shares show a pronounced and steady decrease of "Others," Germany, and the United Kingdom. Simultaneously, as a consequence of specialization in stoppers, there was an increase of import shares in the

TABLE 16.2.

Structure of cork exports in several countries, 1962–2004 (unmanufactured and manufactured cork as percentages of the total of cork products in each country, measured in current U.S. dollars).

	1962–1964		1982–1984		2002–2004	
	Unmanufactured	Manufactured	Unmanufactured	Manufactured	Unmanufactured	Manufactured
Portugal	45.4	54.6	13.8	86.2	6.5	93.5
Spain	38.6	61.4	33.8	66.2	40.5	59.5
France	39.6	60.4	9.3	90.7	5.3	94.7
Germany	6.9	93.1	3.9	96.1	3.1	96.9
Italy	22.5	77.5	7.4	92.6	6.2	93.8
United Kingdom	1.3	98.7	6.9	93.1	12.3	87.7
United States[a]	15.1	84.9	15.8	84.2	3.1	96.9
Maghreb[b]	86.6	13.4	27.4	72.6	18.7	81.3

[a]Data for 1965 are included in 1962–1964.
[b]Surely underestimates; includes Algeria, Tunisia, and Morocco.
Source: Unpublished data from doctoral thesis of F. M. Parejo, based on United Nations sources.

wine-growing countries—both old and new ones—which in 1962–1964 took in only 32 percent of the imports but in 2002–2004 reached 81 percent (or, if the United States is excluded, 21 percent and 66 percent, respectively). So as the share of the old wine-producing countries (France, Italy, Spain, and Portugal) has increased more quickly than the share of the new ones, a marked Europeanization of demand and consumption of cork products has taken place, also reinforced by the entry of Portugal and Spain into the European Union in 1986. The result of all these changes has been a reduction in the international dimension of the cork business.

In Table 16.2, relative to exports' structure, the most important information concerns countries producing unmanufactured cork, whose figures are a sign of their respective specializations. Because of its high export share, Portugal is of major interest. Its cork industry was undeveloped in the 1960s, but forty years later this country has become the world's main cork industrial power. In contrast, the Spanish data show less specialization in manufacturing and more export of unmanufactured cork, mostly going to Portugal, which reveals another aspect of inequality in the Iberization (Parejo 2006).

Regarding Maghreb, where reported figures are clearly incomplete, change is in the air. In recent years, both unfavorable and favorable elements have been apparent in the cork business (Valette 1992; Goussanem 2000; Abid et al. 2002). For one thing, the survival of ancestral property and use rights concerning cork oak trees, very different from those in European countries, are partially responsible for low productivity, poor forestry practices, and the generally poor condition of the woodlands themselves. The legacy of both colonial and postcolonial periods (see Chapter 5) has not been kind to cork oak stands, nor have the use of industrial equipment ill suited to current production capacity and the absence of external economies, such as those on the Iberian Peninsula. The favorable elements include many recent silvicultural improvements in cork oak woodlands; the building of new factories supported by North African and European investments, both public and private, to take advantage of low labor costs; an increase in export capability, linked to its limited internal market; and growing specialization in the production of agglomerates.

In Table 16.3, countries are described in terms of import structure. All countries except Portugal and Spain had high percentages of unmanufactured cork in 1962–1964, because their industries were still active, and very high percentages of manufactured cork in 2002–2004, a sign of the cork industry's decline in these countries. Italy suffered a decline, but its cork activities have been restructured and have become more concentrated since the 1970s in the district of Calangianus, Sardinia (ISTAT 1984, 1994).

TABLE 16.3.

Structure of cork imports in several countries, 1962–2004 (unmanufactured and manufactured cork as percentages of the total of cork products in each country, measured in current U.S. dollars).

	1962–1964		1982–1984		2002–2004	
	Unmanufactured	Manufactured	Unmanufactured	Manufactured	Unmanufactured	Manufactured
Portugal	87.7	12.3	97.4	2.6	73.6	26.4
Spain	75.5	24.5	9.6	90.4	29.9	70.1
France	36.9	63.1	5.8	94.2	4.4	95.6
Germany	38.5	61.5	10.5	89.5	1.9	98.1
Italy	59.6	40.4	27.3	72.7	18.2	81.8
United Kingdom	28.5	71.5	9.8	90.2	10.0	90.0
United States	54.4	45.6	20.8	79.2	0.9	99.1
Others[a]	51.2	48.8	25.9	74.1	7.2	92.8

[a]Others = combined totals of Argentina, Australia, Austria, Belgium, Brazil, Canada, Chile, China, Finland, Japan, Mexico, the Netherlands, New Zealand, Norway, South Africa, Sweden, and Switzerland.

Source: Unpublished data from doctoral thesis of F. M. Parejo, based on United Nations sources.

Portugal and Spain are both producers and net exporters of unmanufactured and manufactured cork. Yet there are marked differences between. Portugal has a high percentage of unmanufactured cork, reflecting the strength of its industry, which absorbs almost all internal production and is obliged to import additional quantities. Spain presents the opposite situation. Its low percentage of unmanufactured cork and its high proportion of manufactured cork reflect the weakness of its industry: The country manufactures only a part of the unmanufactured cork it produces, and its manufacturing production must be complemented with imports.

In short, the international division of labor in the cork business has experienced numerous changes in the twentieth century and currently is very different from that of the mid-twentieth century. Today, the international dimension of the business is very small. Supply is concentrated in the Iberian Peninsula, much more in Portugal than in Spain. And because of the contraction of the productive diversification that agglomerate cork stimulated, demand increasingly comes from traditional wine-growing countries, including the Iberian ones. Thus, the cork business is now enclosed more than ever in the tiny "subericola world."

Conclusions

Do the changes in the cork industry and trade in recent decades favor the preservation of cork oak trees? There is no clear answer to this question. Some facts seem to be in favor and others against preservation.

Among the latter are the decrease in size of the cork business and its foreign trade and the reduction in the number of supplying and demanding countries for cork products. Likewise, the reduction in productive diversification and the need for stopper specialization do not favor preservation. These changes are converting cork into a monoproduct industry whose vulnerability increases as competition from stoppers made with other materials increases. These factors probably have contributed to the stagnation or decrease in the area of cork oak woodlands and the amount of raw cork production in the last fifty years (Mendes 2002; Voth 2009).

Among the factors that favor preservation, manufacturers' bold efforts to improve quality and defend the advantages of cork products must be highlighted. But this endeavor should be echoed by woodland owners, something that has rarely happened. Yet the involvement of raw cork producers is indispensable for the cork business, whose macroeconomic importance has declined drastically, to become widely acknowledged as a sustainable economic activity. Such involvement would reinforce the position of cork in the market against complementary or substitute products.

Finally, it is difficult to predict the effects that the rapid changes taking place in the production, marketing, and consumption of wine in the world will have in the medium and long term (Anderson et al. 2004). However, if the new producers and consumers of wine are outsiders to the "subericola world" and are gaining ground over traditional ones, the cork stopper probably will be used to seal only a small proportion of wine bottles—possibly at the top end of the market—and only as long as the glass wine bottle continues to be used.

Part V presents four chapters focused on the challenges cork oak woodland managers will face in the future.

Acknowledgments

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PART V

Challenges for the Future

Cork oak woodlands face an uncertain future. They are subject not only to land use changes driven by local conditions in North Africa and Europe and by European Union agricultural policies but also to global changes and market trends. In the final part of the book we address some of the hottest scientific and policy topics of our day, including climate change and its impact on ecosystems and the notion of payments for ecosystem services. We also draw attention to the relevance of the work presented in the previous four parts of the book on a global scale, as is now possible thanks to the Millennium Ecosystem Assessment (MA 2005a, 2005b). From 2001 to 2005, more than 1,360 experts worldwide pooled their knowledge and resources to produce the monumental documents widely known as the MA. Their findings provide a state-of-the-art scientific appraisal of the condition and trends in the world's ecosystems, the services they provide, and the scientific basis for action to conserve and use them sustainably. Their work continues on the global level and encourages those developing proactive strategies for managing individual ecosystems, in order to adapt to and mitigate climate change and desertification threats while fighting the loss of biodiversity.

In Parts I, II, and III we provided a state-of-the-art survey of scientific knowledge, providing the bases for practical strategies and techniques for restoration and adaptive management of cork oak woodlands anywhere in the western Mediterranean region. We also showed how these strategies and techniques could be of interest to everyone actively engaged in restoration and management of other woodland and forest ecosystems. Next, in Part IV we presented an economic analysis for some cork oak woodlands, with many indications of the complex array of factors affecting policy and land use decisions in the region. In the site profiles presented throughout the book, we have also seen many discussions of socioeconomic issues on the site scale. We saw that, like many other Mediterranean ecosystems and landscapes, cork oak systems are of value to people for many reasons that range from utilitarian goods to hunting, recreation, and tourism; to biodiversity conservation; and, indeed, to the intangible value of cultural identity with a given landscape.

Now, in Part V we draw back a bit and provide a very broad perspective. In Chapter 17 we present an overview of conservation value and an application of the rapidly emerging notion of ecosystem services as they apply to cork oak woodlands, both in southwestern Europe and in northwestern Africa. As is true everywhere, a clear research goal for the future must be to apply environmental and ecological economics tools to the valuation of biodiversity conservation and ecosystem services of cork oak woodlands and derived cultural systems. This valuation will have great impact on management and planning.

Next, we discuss climate change from the perspectives provided by empirical evidence of the physiological response to rising temperatures and CO_2 (Chapter 18) and by a detailed ecosystem vulnerability modeling approach that can provide a bridge between the complex relationships of ecology and economics and the models used in vulnerability assessments and optimization strategies (Chapter 19).

Finally, in Chapter 20 we bring together all the elements and perspectives discussed in this book in order to develop and compare some simple land use scenarios and discuss alternative strategies, in light of all we have seen in the course of our grand tour. We hope this will help land managers and decision makers adapt management in such a way as to combine conservation, sustainable use, and restoration of cork oak woodlands and of other ecosystems and landscapes.

James Aronson, João S. Pereira, and Juli G. Pausas

Chapter 17

Ecoregional Planning for Biodiversity Conservation

Nora Berrahmouni, Pedro Regato, Mohammed Ellatifi, Hamed Daly-Hassen, Miguel Bugalho, Sahraoui Bensaid, Mario Díaz, and James Aronson

Under Annex I of the European Union (EU) Habitats Directive, cork oak woodlands and the cultural landscapes in which they occur are recognized as having high biodiversity and therefore as being important to conserve (see Color Plates 4a and 9). But what does this mean, and what should be done about it in a rapidly changing and increasingly complex world? The ecoregional conservation or ecosystem approach, adopted by the Convention on Biological Diversity (CBD) in 2000 and endorsed by the World Summit on Sustainable Development in 2002, can help to achieve this goal. Ecoregion conservation is a strategy originally developed by the World Wide Fund for Nature (WWF, also known as the World Wildlife Fund) that aims to conserve the species, habitats, and ecological processes in representative "functional landscapes," a term for large territorial units used by the International Union for Conservation of Nature (IUCN), WWF, The Nature Conservancy, and other conservation organizations. In practice, this means seeking to reconcile biodiversity protection with sustainable activities that allow people to continue making a living while maintaining environmentally robust and resilient conditions at the landscape scale. In this chapter we look more closely at how this can be achieved specifically for cork oak landscapes.

Biodiversity Value and Ecosystem Services

As a direct result of human management, functional cork oak landscapes present a wide array of forest or woodland, shrubland, and open habitat components. These tapestry-like cultural landscapes are biologically rich, even by Mediterranean standards, and home to many rare, endemic, and endangered species. For one thing, open patches in cork oak woodlands are unusually rich in vascular plant species (see Chapter 3 and Box 3.1). Diaz-Villa et al. (2003) recorded 135 species on a 0.1-hectare plot in a cork oak woodland in Andalusia, one of the highest known plant diversities in the world at this scale. To cite just one example related to woody plants, the Sicilian zelkova (*Zelkova sicula*, Ulmaceae) is a small deciduous tree or large shrub found only in one relictual, recently discovered population of 200–250 small individuals in the cork oak woodlands close to the town of Syracuse, in southeastern Sicily (Fineschi et al. 2004). Like the other Mediterranean endemic in the genus, *Z. abelicea*, which is only found in Crete, *Z. sicula* is included in the IUCN Red List of endangered species.

For animals, the story is perhaps even more compelling. Throughout the Iberian Peninsula, for example, cork oak landscapes provide habitat for the few remaining populations of the critically endangered Iberian lynx (*Lynx pardinus*; see Color Plate 9a) and many large resident and migratory birds, including the few remaining pairs of Spanish imperial eagle (*Aquila adalberti*), black vulture (*Aegypius monachus*), and black stork (*Ciconia nigra*), as well as 60,000 to 70,000 wintering common cranes. In North Africa, the highly endangered Barbary deer (*Cervus elaphus barbarus*), the last surviving African deer, is currently found only in the cork oak woodlands on either side of the border between Tunisia and Algeria (see Color Plate 9b).

Cork oak woodlands also harbor nearly a hundred other animal species, listed in the annexes of the EU Habitats and Birds Directives, including species that are only rarely found elsewhere (Box 17.1). For example, the Maamora forest of Morocco is the home of at least 160 bird species (Thevenot et al. 2003). In addition, cork oak woodlands host a large number of migratory and wintering birds from northern Europe. They also support more diverse communities of herbaceous plants, butterflies, and passerines than nearby dense woodlands, grasslands, or arable areas (Díaz et al. 1997; Díaz 2008).

In addition to supporting biodiversity, cork oak woodlands provide important ecosystem services in all four of the categories established by the Millennium Ecosystem Assessment (MA 2005b), as shown in Table 17.1.

Challenges for Conservation

Despite all the services they provide, the current status of cork oak woodlands is alarming. In North Africa, cork oak woodland cover has decreased in the twentieth century, whereas in southern Europe (except for France) it has increased because of new plantations (see Figure 1.2). Globally, cork oak

Box 17.1. Animal Communities

Mario Díaz

Forests and woodlands are more than groups of trees. Hundreds of plant species interact with thousands of animal species and the environment, giving rise to forest structure and function. Some species or species groups of animals are known to have prominent roles in the regeneration cycle of oaks as herbivores or seed dispersers, and they respond to disturbances, such as fire, fragmentation, or forest clearing, in specific ways and depend on cork oak forests for their long-term survival. Patterns of distribution and abundance of these species are thus causally linked to the function and conservation of cork oak forests.

Herbivores and seed dispersers influence the long-term dynamics of oak forests by increasing or decreasing the natural recruitment of oak populations (Pulido and Díaz 2005b). Herbivores and granivores, such as caterpillars (several species of butterflies and moths, especially *Tortrix* spp., *Catocala* spp., and *Malacosoma neustria*); ungulates, such as wild boars and deer (*Cervus elaphus* and *Capreolus capreolus*); and predispersal and postdispersal acorn predators, such as weevils (*Curculio* spp.), moths (*Cydia* spp.), and woodpigeons, reduce the reproductive potential of individual oaks. Acorn dispersers, on the other hand, move and hide acorns far from the mother plants, increasing their probability of successful establishment. Prominent seed dispersers of cork oaks are European jays (Pons and Pausas 2007c), several mice species, such as wood mice (*Apodemus sylvaticus*) and Algerian mice (*Mus spretus*) (Pons and Pausas 2007a), and one species of dung beetle (*Thorectes lusitanicus*) (Pérez-Ramos et al. 2007). Seed dispersers of cork oaks are also seed predators that hoard acorns for future consumption; they act as dispersers if some hoarded acorns are not recovered (or pilfered) or if acorn cotyledons are recovered after seedling emergence and seedlings survive after cotyledon removal (Sonesson 1994).

Oak forest disturbance has strong effects on several animal groups. Fire favors open-habitat species of birds and small mammals, such as black wheatears (*Oenanthe leucura*) and Algerian mice. These species are then replaced by shrub specialists, such as small *Sylvia* warblers (*S. undata*, *S. melanocephala*) and wood mice. As the forest develops, larger carnivorous mammals, such as genets (*Genetta genetta*), and forest birds, such as tits (*Parus* spp.) and chaffinches (*Fringilla coelebs*), occupy cork oak stands after the next fire (Prodon et al. 1984; Real 2000; Torre and Díaz 2004; Díaz et al. 2005). From a biogeographic perspective, Mediterranean species linked to open and shrubby habitats are replaced by Eurosiberian species as forest develops (Blondel and Farré 1988). Fragmentation reduces bird and small mammal species richness, favoring generalist species, such as

Box 17.1. Continued

mice or some finches, against forest specialists, such as tits, warblers, and some shrews (Santos and Tellería 1998). Finally, forest clearing and shrub removal for creation and maintenance of *dehesas* tend to increase species richness of butterflies and passerine birds, as well as total species richness, by promoting the coexistence on narrow spatial scales of species linked to both forest and open habitats (Tellería 2001; Díaz et al. 2003; Díaz 2008).

Last but not least, cork oak forests harbor many animals that are protected under the Birds and Habitats Directives of the European Union, including nearly a hundred species in the Iberian Peninsula alone (Díaz et al. 2006). Some small species are found nearly exclusively in cork oak forests, such as the large spider (*Macrothele calpeiana*) (Galante and Verdú 2000), the northward-expanding white-rumped swift (*Apus caffer*) (Martí and del Moral 2003), and relict sedentary populations of blackcaps (*Sylvia atricapilla*) (Pérez-Tris et al. 2004). Large species of conservation concern, such as black vultures, Spanish imperial eagles, and Iberian lynxes, tend to use large undisturbed oak forest patches and patches of other forest types to nest or rest, whereas they depend on nearby open habitats, such as *dehesas* and grasslands, as hunting grounds (Carrete and Donázar 2005). Overall, very few of these species depend exclusively on cork oak forest; rather, they use mosaic landscapes where undisturbed forest and open habitats coexist at several spatial scales (Díaz et al. 2003, 2006).

TABLE 17.1.

Ecosystem services of cork oak woodlands according the terminology of the Millennium Ecosystem Assessment.

Service	Description	Examples
Provisioning	Products obtained from ecosystems	Food (acorns), fodder, firewood, cork, other nontimber forest products
Regulating	Benefits obtained from regulation of ecosystem processes	Soil conservation, water retention, watershed protection, erosion control, fire risk prevention, carbon sequestration
Cultural	Nonmaterial benefits obtained from ecosystems	Cultural heritage (landscape amenity), recreation, tourism
Supporting	Services necessary for the production of all other ecosystem services	Soil formation, nutrient cycling, primary production

Source: MA (2005b).

woodland health and resilience have decreased, and cork oak populations are aging because of a lack of natural regeneration (see Chapters 10 and 20).

In North Africa, almost all cork oak woodlands are state owned and managed by forestry directorates. Governance problems and unfair conditions, in terms of commercial rights and access to the forest products for local communities, are to blame for degradation. At present, although local communities benefit from the use of products and services for subsistence and, in most cases, through informal markets (i.e., access to grazing and acorn collection are free and not regulated), most of the monetary benefits from cork oak woodlands go to the authorities. Because cork is a state-owned product, only the few members of communities who work as harvesters obtain income from the harvesting operations, which makes only a small contribution to their annual income (e.g., the daily wages of local workers in Morocco is 50–80 dirham, i.e., €5–8). Under these circumstances, it is not surprising to find overexploitation and illegal harvesting of products and services that are normally free of access for subsistence to local communities. In addition, these conditions lead to trade through informal or illegal markets (e.g., illegal exploitation and trade of cork oak acorns in the Maamora forest to Spain and Portugal, to feed black pigs) or even the conversion of forests to cannabis cultivation (in the Rif mountains of northern Morocco; see Site Profile 10.1).

In Portugal and Spain, where most cork oak land areas are privately owned, an increase in cork oak cover occurred in the mid-1990s, due to cork oak planting on marginal lands, supported by EU subsidies. However, even in Iberia most cork oak stands are suffering high mortality levels and decreases in habitat quality, thus mirroring the situation in all five other countries where they occur. Thus, both the embedded biodiversity and the ecological services they provide are declining dramatically or at risk of doing so in the near future (see Chapter 20).

The loss in cork oak woodland biodiversity is the consequence of a number of interrelated threats, including pressure on natural resources, conversion to fast-growing plantations and other uses, poor forest management practices, fires, desertification, land abandonment (mostly in southern Europe), and, throughout the region, runaway urban development in coastal areas. These threats, all potentially exacerbated by climate change, affect the health of cork oak woodlands, increasing their vulnerability to diseases, pests, and catastrophic fires. They are driven by a combination of underlying factors related to poor management capacity, inadequate national and EU policies, and various market drivers (Figure 17.1).

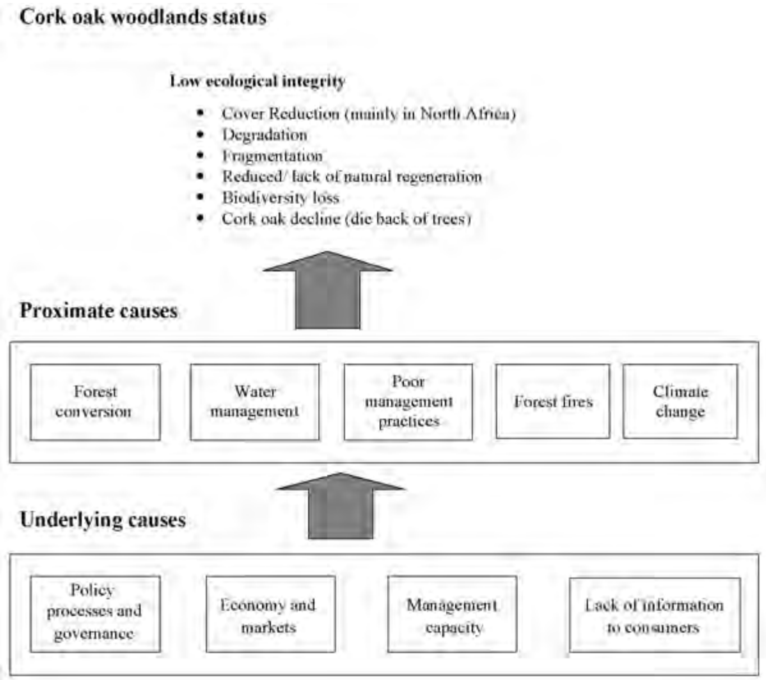

FIGURE 17.1. Simplified root causes conceptual model. (Modified from WWF MedPO 2004)

Addressing these drivers requires collaboration between the conservation community, government institutions, cork oak woodland owners, users, managers, industries, researchers, communities, and consumers.

In 2004, WWF launched a strategic program to actively promote ecoregion conservation in cork oak woodlands by addressing management, markets, and policy-related issues that represent root causes of biodiversity loss and habitat degradation in these threatened cultural landscapes. During its first phase, this program focused its activities in four cork-producing countries (Portugal, Spain, Morocco, and Tunisia) and one consumer country (the United Kingdom). In the second phase, this program will expand its activities to other cork-producing and consumer countries. In the following sections we discuss the challenges to be addressed in order to reverse current trends.

Protection Challenges: Is the Current Protected Areas System Adequate for Cork Oak Woodland Conservation?

One of the main approaches for biodiversity conservation is the establishment and effective management of representative protected areas. We present the protection status of cork oak woodlands in the countries involved in the first phase of this kind of program. (Expanding this program to other countries, including Italy and France, is planned in the second phase.)

In Morocco, cork oak woodlands are present in two national parks (Tazekka and Talassemtane) and in a network of nineteen government-recognized sites of biological and ecological interest, which are all candidates for becoming protected areas in the near future. According to estimates, the eight most important sites (including the two national parks) with cork oak woodlands cover an estimated total of 54,570 hectares (Hammoudi 2002; Ellatifi 2005).

In Algeria, the total area of cork oak stands under protection is 38,140 hectares (i.e., 16.6 percent of total national cork oak woodland current cover), distributed in seven national parks; the largest portion by far is in the national park and biosphere reserve of El Kala (34,000 hectares), which also hosts the last remaining Algerian population of the endangered Barbary deer (see Color Plate 9b).

In Tunisia, the largest cork oak woodland area under legal protection (790 hectares) is included in the national park of El Feija. This represents 30 percent of the total area of the park, which was created specifically for the protection of fauna, mainly the endangered Barbary deer. However, as part of its recently adopted strategy to protect cork oak woodlands, the Tunisian General Directorate has set the objective for the coming years to achieve United Nations Educational, Scientific, and Cultural Organization classification for the best-preserved cork oak woodlands of northwest Tunisia, in the Kroumirie Mogod mountains, as a Man and Biosphere Reserve.

In Spain, the situation is better: 32.5 percent of cork oak woodlands are protected (WWF/ADENA 1998), and the country harbors the largest protected cork oak woodland anywhere, Los Alcornocales Natural Park, which is about 170,000 hectares in size (see Site Profile 17.1). Moreover, 170,544 hectares of dense stands are classified as Sites of Community Interest (M. del Río Gaztelurrutia, personal communication, 2007).

In Portugal, by contrast, the national network of protected areas (national and natural parks) covers only 2.1 percent of the cork oak woodland area. However, this figure is 20.4 percent of total cork oak woodland area when the Natura 2000 network is considered. The Natura 2000 sites of Monfurado

(23,946 hectares) and Cabeção (48,607 hectares) are good examples of areas that were classified because of cork oak woodlands. These data are based on the Portuguese forest inventory of 1995 (F. Catry, personal communication, 2007).

However, the protected area system generally, and specifically in the case of cork oak woodlands, remains inadequate in terms of design, extension, connectivity, management, and integration within regional planning programs. Cork oak protected areas are generally small and isolated. Furthermore, in many of these countries active conservation measures are seldom implemented, even in conservation areas. Because of a lack of financial mechanisms, the Natura 2000 network in Europe is not effectively implemented. Restoration activities and natural regeneration enhancement are absent or entirely insufficient to compensate for the ongoing loss of mature cork oak stands, through disease, senescence, and lack of regeneration (see Chapters 9 and 10). Moreover, to improve the design and management of protected area systems (including cork oak woodlands), there is an urgent need to assess the vulnerability of the current protection systems to climate change and develop adaptation strategies to cope with this threat.

Therefore, it is clear that old-fashioned protected areas cannot be the only tool for protection of cork oak woodlands. Instead, a more flexible conservation approach is needed that integrates protection objectives as part of participatory planning processes and sustainable land uses within large territories. Biosphere reserves may constitute a concrete application of the ecosystem or landscape approach; if well designed and managed, they allow connectivity across large territories and promote sustainable resource use and resilience to threats, such as climate change. Two examples of large areas, where the aim is to balance conservation and sustainable development needs, are the 424,400 hectares of cork oak and holm oak woodlands in the Sierra Morena Biosphere Reserve, in Spain, and the Inter-continental Mediterranean Biosphere Reserve (894,135 hectares), straddling the Gibraltar Strait in northern Morocco and southern Andalusia, where cork oak woodlands dominate.

Management Challenges Inside and Outside Protected Areas

In only a few cases do the managers of cork oak woodlands have detailed management plans. The Los Alcornocales Natural Park in Andalusia (southern Spain) (see Chapter 15 and Site Profile 17.1) is a notable exception. Where they do exist, park management plans in the region are only rarely implemented and may be obsolete. In North Africa, this is due to a lack of human, technical, and financial resources. In North African and European countries alike, these problems are compounded by policy and market issues. Generally, the management scale is not appropriate because it is not well connected to wider land use and development planning processes. This is true mainly in the development of fire prevention and grazing management plans. Any isolated prevention or mitigation action cannot be effective if it is not designed and planned jointly with landowners on a larger scale beyond the private land boundary. For instance, in Portugal, with the support of a technical commission after the catastrophic fires of 2003 and 2004, the Portuguese General Directorate of Forest Resources put in place a new landscape planning scheme to restore the burnt forest areas. This scheme, called Zona de Intervenção Florestal, aims to address forest management planning at larger scales (i.e., landscapes beyond landowners' boundaries).

Frequently, the management of cork oak woodlands is not based on a balanced use of all goods and services or on good knowledge of values, such as ecosystem services. In addition, there is a real lack of management knowledge and capacity and a lack of incentives and necessary investments, preventing forest managers, private landowners, and local communities to apply sound forest management practices.

Policy Challenges: Policies Competing with and Ignoring Human and Landscape Dimensions

A recent study on current management practices supported by EU subsidies in southern Portugal demonstrated that they can have negative impacts on cork oak landscapes (WWF MedPO 2005). EU subsidies have led to more homogeneous and artificial landscapes, causing a significant loss of habitat and of landscape heterogeneity in large areas. Indeed, EU subsidies have tended to support high grazing pressure, mechanized shrub clearance, and infrastructure building, often leading to degradation of cork oak woodlands (WWF 2006). In addition, conservation policies, such as the various protected area systems and Natura 2000, generally are not implemented effectively. Indeed, the current model of governance of the cork oak woodlands (and other forests) in North Africa does not favor the adoption of alternative models for development that could empower local communities and provide them with incentives for a more rational, economically viable, and sustainable use of cork oak woodlands. Policy and management decisions often are based on an incomplete views of forest benefits that capture only the market value of cork, with no consideration for other nontimber forest products (NTFPs) or nonmarket values (e.g., biodiversity and soil conservation). In addition, most of the monetary benefits from cork oak forests of North Africa countries go to the authorities. For example, according to the Moroccan Forestry Law, 80 percent of the revenues generated by harvesting and management of forest products are to be invested in the welfare of the communities in and around the forest area. Unfortunately, this law is very seldom applied, and in most cases all benefits end up in the hands of external actors.

Market Challenges

The economy of most managed cork oak woodlands is based mainly on cork production and on livestock. In North Africa, the commercial exploitation of cork has declined, and livestock management usually is highly informal, that is, uncontrolled. The price of animal products does not take into consideration the real costs of management and production, which amounts to a failure to internalize costs. Other potential goods and actual services, such as the informal and nonregulated exploitation of NTFPs and grazing rights for livestock, are not marketed even though they may be linked to informal markets.

Another increasingly important issue is the dwindling market share of cork bottle stoppers in the wine industry. More than 70 percent of cork's market value comes from the production of cork stoppers (Natural Cork Quality Council 1999), which is under increasingly strong competition from plastic stoppers and screw caps. Unless this commercial value is maintained, especially in the market for high-quality bottle stoppers, there is a high risk that conversion of cork oak woodlands to other uses (e.g., agriculture, urbanization) or land abandonment will be rapidly generalized to many currently managed cork oak woodlands (mainly in Iberia), increasing their vulnerability to fires.

Another challenge facing rural communities and landowners is the development of their entrepreneurial skills to use opportunities in the green and natural products market to develop businesses, based on a multipurpose use of cork oak woodlands. One community rising to the challenge is the Hinojos Communal Woodland in Andalusia, whose owners have based their 2001–2011 management plan on the production of cork and pine nuts, beekeeping, livestock grazing, timber, and recreation, generating an average annual income of more than €3.5 million (more than US$5 million) (Berrahmouni et al. 2007). This is without counting many nonmarket values, such as informal recreation, biodiversity conservation, and carbon sequestration.

Reconnecting Environmental, Social, and Economic Interests through Landscape Conservation Planning

To respond to the challenges cited in this chapter and conserve cork oak woodlands as adaptive, resilient, multipurpose systems, there is a clear need to integrate sustainable local economic development with biodiversity conservation and active restoration. Conservation planning at a landscape level, based on ecoregion conservation principles, is the best tool to ensure the integration of conservation and socioeconomic needs (WWF MedPO 2004). In southern Portugal, for example, WWF launched a participatory landscape planning process in 2000, in collaboration with local nongovernment partners in the framework of the project "Green Belts against Desertification" (WWF MedPO 2002). This process involved biodiversity and socioeconomic assessments, geographic information system mapping of biodiversity and socioeconomic indicators, threat and root cause analyses, identification of core conservation areas, corridors, and buffer zones, and development of a vision and conservation action plan for the Southern Portugal Green Belt (Figure 17.2).

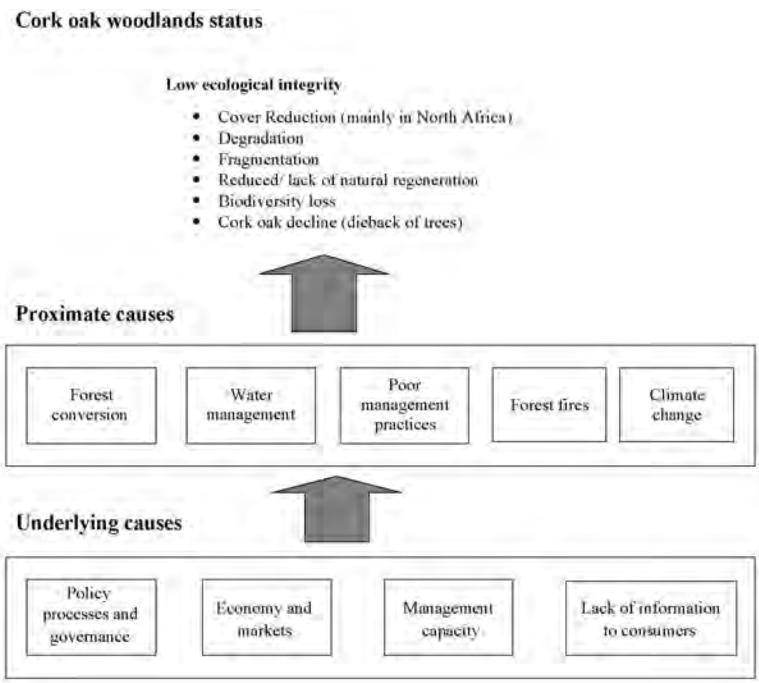

Figure 17.2. Southern Portugal Green Belt. Source: Oliveira and Palma 2003.

Good Practices: Preserving and Regaining Forest Multifunctionality

To drive good practices on the ground for cork oak woodlands, innovative tools and approaches are available at different levels, including a few described in this section.

Forest Stewardship Council Certification

The Forest Stewardship Council (FSC), an international organization devoted to promoting responsible stewardship of the world's forests (see www.fsc.org), has set international standards for responsible forest management and accreditation of independent organizations to certify managers and producers who meet these standards. This management must be environmentally appropriate (maintaining biodiversity, productivity, and ecological processes), socially beneficial (benefiting local societies and providing incentives to sustain forest resources), and economically viable (profitable without harming forest resources, ecosystems, or local communities).

To date, more than 40,000 hectares of cork oak woodlands, including both private and public lands in Portugal, Spain, and Italy, and four cork companies' chains of custody (COCs; i.e., the paths taken by raw materials, processed materials, and products, from the forest to the consumer) have been certified by the FSC. Moreover, FSC cork stoppers are now available and are used by three wine producers and bottlers (in South Africa, the United States, and Spain), who in turn certified their COCs under FSC.

Forest Landscape Restoration

Forest landscape restoration (FLR) is "a planned process that aims to regain ecological integrity and enhance human well-being in deforested or degraded landscapes" (Mansourian et al. 2005:3). Developed jointly by IUCN and WWF, FLR is more than simply tree planting; it searches for the best ways to reestablish forest functionality at the landscape scale. Interventions include the rehabilitation and management of degraded forests, enrichment planting, the promotion of natural regeneration, ecological restoration of degraded ecosystems, establishment of corridors between protected areas, and the development of income-generating activities based on sustainable use of natural resources (Mansourian et al. 2005; cf. Aronson et al. 2007). To implement this approach, WWF and its partners have initiated pilot projects to develop, demonstrate, and practice FLR in cork oak landscapes of southern Portugal and the Rif mountains of northern Morocco. These pilot projects are based mainly on building the capacity of local landowners, managers, communities, and nongovernment organizations (NGOs) to produce native plants from cork oak forests in tree nurseries, testing different ecological restoration techniques in sample plots, and lobbying government actors and managers to implement these best practices and scale them up through larger cork oak areas.

Markets: Building a Sustainable Cork Oak Landscape Economy

As emphasized earlier, the health and resilience of cork oak woodlands reside in their diversity. Creating and formalizing markets for a broader range of sustainably managed goods and services would result in a more balanced use of resources and make the economy of this cultural system more adaptive in a rapidly changing world. NGOs can play an important role, through communication and lobbying. For example, WWF is working to promote products from sustainably managed cork oak woodlands, aiming at driving best management practices in the following ways:

- Encouraging the cork industry to ask suppliers (cork landowners and managers) to obtain FSC certification for their cork oak woodlands.
- Encouraging the wine industry (producers and retailers) to take action and demonstrate their environmental and social responsibility by demanding FSC cork.
- Encouraging local communities (landowners and users) to diversify their economic opportunities through the sustainable use of a wide range of goods (mainly NTFPs) and services (i.e., responsible tourism opportunities) under good governance and a fair and equitable sharing of benefits. There are published examples of biodiversity conservation and the management and marketing of various NTFPs (e.g., mushrooms, honey, aromatic and medicinal plants, pine nuts, and carob) working side by side (Berrahmouni et al. 2007).

Capacity Building: Investing in Building and Strengthening the Capacity of All Actors

To address the problems driving the degradation and loss of cork oak woodlands, there is a clear need to review national forestry education schemes and introduce innovative concepts for sustainable management and biodiversity conservation of cork oak woodlands and the development of sustainable markets, based on responsible management of natural resources.

There is also a need to build the capacity of management agencies and academic institutions, especially in North Africa, to acquire and apply the necessary knowledge and tools for biodiversity conservation and its integration in the management of cork oak woodlands. Concurrently, building the capacity of national and local NGOs will enable them to function as facilitators between foresters and local communities. Indeed, NGOs are invaluable in assisting forest managers in planning, developing the skills of local communities, and seeking markets for local products.

Conclusions

Cork oak woodlands have made a real contribution to culture and livelihoods and are of primary importance for biodiversity conservation in the western Mediterranean (Berrahmouni et al. 2007). Unfortunately, today they are facing complex problems and challenges. In Mediterranean basin forests generally and in cork oak woodlands in particular, the stands are under increasing pressure, caught in a spiral of degradation leading to the loss of both cultural and natural heritage. Innovative conservation approaches, such as ecoregional conservation at a landscape level, if well applied, could provide a greater opportunity to conserve the biodiversity of these landscapes while addressing environmental, social, and economic issues. The cork and wine industries and the building sector worldwide have a key role to play by promoting FSC certification of cork oak woodlands and products. Large-scale and collaborative efforts should be made to increase the resilience of these woodlands to current pressure and future threats. Last but not least, working to conserve cork oak woodlands would support the commitments that all seven governments of the western Mediterranean have made under the CBD, particularly the program of work on protected areas (www.cbd.int/protected/). In Chapter 18 the subject is climate change, yet another challenge that cork oak woodlands and the people who depend on them must face.

Acknowledgments

We thank Stephanie Mansourian, Christelle Fontaine, and Catherine Roberts for helpful comments on the manuscript.

SITE PROFILE 17.1

Los Alcornocales Natural Park, Spain

This park is home to the largest extant cork oak forest in the world and probably the best protected. Unlike the Maamora (Site Profile 14.1), this formation is largely natural in appearance and ecology.

Geographic and biophysical description	This is a continuous mixed oak forest of about 90,000 ha, which covers the southern tip of the Iberian Peninsula up to the Strait of Gibraltar, in the Andalusia region. Topography is rugged, with elevations ranging from near sea level to a maximum elevation of 1,092 m. Substrates are Oligo-Miocene sandstones giving rise to sandy and acidic soils in the uplands, and more loamy to clayey soils are abundant in the lowlands. The climate is subhumid. Annual precipitation ranges from 700 to 1,300 mm depending on altitude and wind exposure. Winters are wet and mild; summers are warm and dry, although moist sea winds and fogs are frequent in the coastal areas.
Physiognomic description of cork oak woodlands and their landscapes, including woodland dynamics	Evergreen cork oak forests cover most slopes, and semideciduous Algerian oak (*Quercus canariensis*) are more abundant in moister, deeper, and more fertile soils of valley bottoms. The understory is highly diverse in both species number and life forms, with tall shrubs including *Phillyrea latifolia*, *Arbutus unedo*, *Viburnum tinus*, heaths (*Erica scoparia*, *E. arborea*), broom (*Genista triacanthos*), gorse (*Ulex borgiae*), and vines (*Smilax aspera*, *Hedera helix*) or climbers (*Lonicera periclymenum* subsp. *hispanica*), some of which are narrow endemics. Riparian forests are refuges for several Tertiary relicts (e.g., *Rhododendron ponticum*) and ferns. On dry and clayey soils of the lowlands, a sclerophyllous woodland, dominated by wild olive (*Olea europaea*) and mastic (*Pistacia lentiscus*), alternates with open pastures.
History of land uses, land tenure (and socioeconomic drivers), and current land uses, economic activities, and context	These cork oak forests have been managed by private owners and by local, regional, and Spanish governments over the last two centuries to optimize cork production. In this area, about 16,000 metric tons of cork is harvested every year. Other resources are lowland pasture for free-range cattle, game—especially red deer (*Cervus elaphus*) and roe deer (*Capreolus capreolus*)—for recreational hunting, and pine nuts from stone pine (*Pinus pinea*) plantations. Since 1989, the area has been protected as Los Alcornocales

	(meaning cork oak woodlands) Natural Park, with about 25% of the land under public management, to foster local ecodevelopment.
Disturbance regime (fires, pests, overgrazing)	Fires are frequent, with an average 15- to 25-year fire return interval, particularly near coastal urban areas. Oak decline, associated with past cork management practices, root fungi infestations, and prolonged periods of drought, can be locally important.
Constraints and conflicts, protective measures, restoration actions, land use regulations, and relevant policies	Sustainable use of woodland resources is in theory regulated by natural park managers. However, subsidized over grazing by livestock and shrub understory clearing and over population of deer, promoted by gamekeepers, conflict with oak regeneration. Reforestation of oak decline patches, culling of deer populations in public lands, and large-scale fencing for the exclusion of large herbivores are management policies that are now being recommended and, in places, implemented.
Current trends and prospects for the future	Market price of cork is the main driver of management, but the future of this industry is uncertain. Biodiversity maintenance and other ecosystem services are increasing in value. Overbrowsing and aridification due to global climate change could reduce cork oak regeneration and modify vegetation structure and function in the future. Under natural forest dynamics, cork oak tends to be replaced by Algerian oak in many mixed stands.
Source	Teodoro Marañón, Institute of Natural Resources and Agrobiology, National Research Council, Seville, Spain

Site Profile Figure 17.1. Sandstone crests and cork oak woodlands near Alcalá de los Gazules (Cádiz, Spain).

Chapter 18

Facing Climate Change

João S. Pereira, Alexandre Vaz Correia, and Richard Joffre

Like other long-time natives of the Mediterranean region, cork oak is accustomed to a highly variable climate, both between and within years. However, since the 1970s the frequency of droughts in the Mediterranean basin has increased significantly, and a long-term process of aridification seems to be under way as part of the generalized trend of global warming. By the end of the twenty-first century, mean air temperature in the region is expected to rise by 2 to 4.5°C above the present average, and total precipitation may decrease by as much as 20 percent in summer and up to 10 percent in winter, in the southern Mediterranean (IPCC 2007). For example, longer dry seasons are expected in the western and central parts of the Iberian Peninsula, with a marked decrease in spring and summer precipitation, as has been occurring since the early 1960s (Paredes et al. 2006).

There have been many climate change episodes in Earth's recent history (Flannery 2005), and like other long-lived organisms cork oak has had to withstand and adapt to climate change many times in the past. During the recent Quaternary glaciations, cork oak may have survived in scattered refugia from which postglacial recolonization originated (see Chapter 2). Some 10,000 years ago, when the climate warmed and the current seasonal pattern of rainfall became established, the trees that make up contemporary Mediterranean vegetation advanced to new territories. Indeed, several lines of evidence, especially fossil pollen studies, confirm that changes in cork oak distribution took place in direct correlation with changes in climate (Riera-Mora 2006).

The current rate of climate change is much faster than most past episodes, and it is occurring in an environment highly modified and dominated by people. Furthermore, the Mediterranean basin appears to be one of the primary climate change hotspots, meaning that for a given level of global change, the regional climate of a hotspot will change more than in other places (Giorgi 2006). In the future, cork oak seedlings may experience climatic conditions substantially different from those of recent centuries. Should we plan and manage solely in terms of prevailing conditions, or should we try to adjust proactively to one of several future climate scenarios?

In this chapter we provide experimental evidence concerning the response of individual plants to atmospheric conditions that may be of help in confronting management decisions at the levels of individual properties, whole landscapes, and ecoregions. In addition to the plant's response to elevated CO_2, under conditions of low and high availability of nitrogen—the major element of plant nutrition—we also consider the effect of the anticipated increase in length of the summer drought, which may exacerbate the effects of combined stresses of drought, heat, and high light intensity, as seen in Chapter 6. This effect must be evaluated both at the level of individual plants and at the landscape scale. Some of the complexities of dealing with the latter will also be addressed in Chapter 19.

Rise in Atmospheric CO_2 Concentration

A prime indicator of global change is the rise in atmospheric CO_2 concentrations recorded in the last 150 years. However, in addition to being one of the major greenhouse gases, CO_2 is also the substrate for photosynthesis. The immediate response of a plant to CO_2-enriched air is to increase its carbon assimilation rate and decrease its transpiration, or loss of water. Unfortunately, this does not last long. Experiments with trees grown under elevated CO_2 have shown that although light-saturated photosynthesis is initially stimulated, a 10 to 20 percent reduction of photosynthetic capacity takes place after several growing seasons (Medlyn et al. 1999). That means that the potential for CO_2 fertilization is not fully realized after a long-term acclimation to elevated CO_2.

How did cork oak respond under similar conditions? In an extended exposure experiment, cork oaks were grown for four years in elevated CO_2 (700 parts per million) and in ambient CO_2 (350 parts per million), with two nitrogen supply regimes: a high-N regime (i.e., no N limitation, 8 mM of N in the nutrient solution) and a low-N regime (1 mM). These N regimes mimic soil heterogeneity (e.g., from fertile valleys to barren hilly slopes). The effect of elevated CO_2 was highly dependent on plant nutrition (Maroco et al. 2002). The plants grown with high N and elevated CO_2 accumulated significantly more biomass than plants grown at ambient CO_2. There was no significant effect of elevated CO_2 for plants grown under low-N regimes (Figure 18.1). The larger biomass accumulation under elevated CO_2 and high N was attributed to the higher photosynthetic capacity and the stimulus to produce more leaves resulting from abundant N supply. Under low N, the short-term effects of CO_2 enrichment on leaf area and biomass accumulation were lost in the long run.

This means that in cork oak, as in most trees, the benefits of a CO_2-enriched atmosphere may be insignificant when other limiting factors, such as low soil nutrients or drought, prevail (Medlyn et al. 1999). However, a consistent tree response to elevated CO_2 is partial stomatal closure, meaning improved water use efficiency (i.e., plant production per unit water transpired).

Rising Temperatures

Rising air temperatures strongly affect plant growth (e.g., carbon balance and phenology) and ecosystem processes. Let us now consider the expected impacts on individual cork oaks.

In general, rising summer temperatures may have negative effects on the carbon balance of trees through an increase in plant respiration relative to carbon uptake and assimilation. In addition, stomatal closure caused by water deficits may lead to overheating and functional damage in leaves, as explained in Chapter 6. Although cork oak tolerates prevailing Mediterranean summer conditions (hot and dry), it may be affected by extremely hot weather episodes, which may become more common in the future. Higher temperatures in autumn and winter may benefit cork oak by reducing the limitations on photosynthesis related to low temperatures. A secondary flush of shoot growth in autumn may be stimulated.

Climate change may also indirectly affect cork oak through soil processes. Because low temperatures inhibit the decomposition of organic matter, soil warming in winter may increase the rate of nutrient mineralization, increasing plant productivity, which is often limited by poor nutrition. However, the medium-term outcomes are hard to predict if rainfall distribution becomes more irregular. For example, when rain comes after a long rainless period, rewetting the soil stimulates heterotrophic respiration and organic matter mineralization (Jarvis et al. 2007). The nutrients released may be washed away if they are not absorbed by fine roots. Although cork oak may develop fine roots in a matter of days upon rewetting of the soil (N. Ribeiro, personal communication, 2007), some nutrients will still be lost because most fine roots are lost during the dry period. More sporadic rainfall has been occurring in the western Mediterranean over the past three decades (Paredes et al.

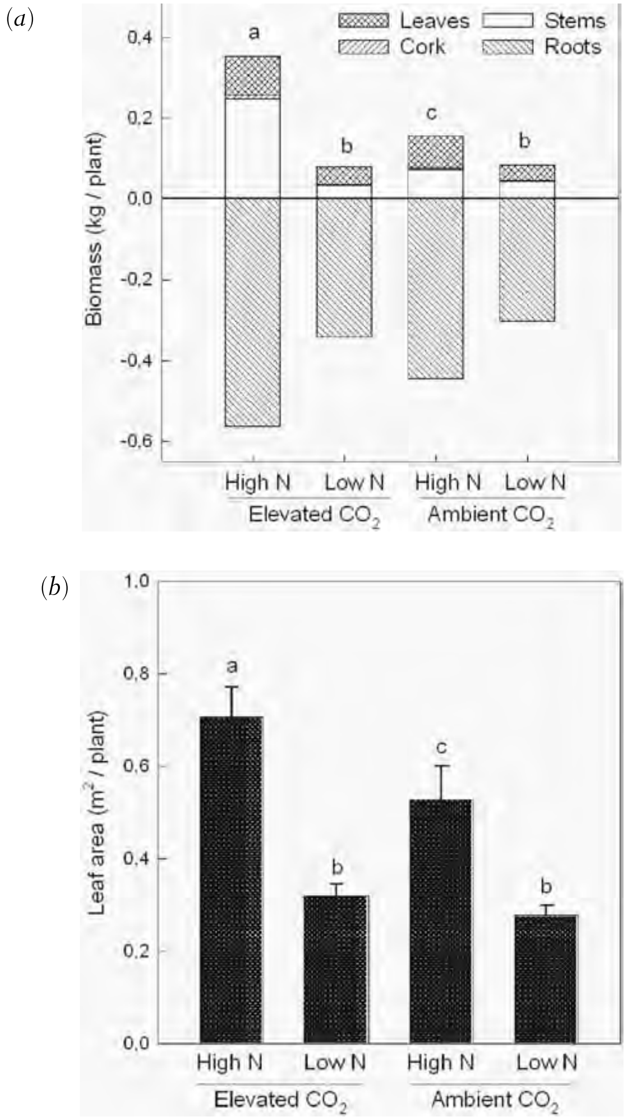

Figure 18.1. Effects of long-term (4-year) exposure to elevated CO_2 (700 ppm) and ambient CO_2 (350 ppm) on *(a)* biomass accumulation and *(b)* leaf area of cork oak under different nitrogen fertilization regimes: high N (8 mM) and low N (1 mM) in nutrient solution. Differences between bars labeled with different letter suffixes are statistically significant. (Original data in Maroco et al. 2002)

2006). We can only assume that this not only increases the severity of plant water stress but also increases the rate of nutrient losses from the soil.

Effects on Communities and Ecosystems

As mentioned in Chapters 1 and 3, and indeed as is obvious to even a casual observer, cork oak trees play a key role as “framework” trees in the ecological communities where they occur. If they change their behavior, they can unleash a cascade of effects at the community and ecosystem levels. For example, in cork oak woodlands, ectomycorrhizal fungi are known to play a role in enhancing the acquisition of resources by the host plant (see Chapter 7). These fungal communities may change in response to drought and soil warming, modifying in turn their functional role in nutrient uptake. Nevertheless, very few field experiments have addressed how the expected changes in climate might influence these ectomycorrhizal communities.

Changes in temperature may also induce uncoordinated shifts in the phenology of interacting organisms. That could lead to drastic changes in community composition and food webs. In the case of attacks by pests and diseases (see Chapter 9), the impact of climate change is difficult to anticipate because it depends on the net result of complex interactions, including direct effects on the physiology and phenology of hosts, pests, and pathogens and indirect effects on the abundance of natural enemies, mutualists (e.g., insect vectors of tree pathogens), and competitors. The susceptibility of cork oak to pests and diseases appears to have increased in recent decades, perhaps as a result of the combined effects of drought and infection on tree physiology (Desprez-Loustau et al. 2006).

At present, *Phytophthora cinnamomi* is a major root disease agent affecting cork oak and probably is associated with the general decline of the species throughout Iberia (Brasier 1996). Infection by the pathogen is favored by warm and wet conditions. Daily minimum temperatures below 12°C inhibit root infection in cork oak, limiting pathogenicity in the winter, and dry soil conditions inhibit root infection during the summer because the flagellate zoospores need free water in the soil to disperse effectively. This results in a short period of optimal climate conditions for root infection under present climate conditions because soil flooding only occurs for very short periods—a few days—in spring and autumn. In winter, when flooding is more common, low temperatures limit the potential for infection. An increase in temperature therefore may expand the operative period into the winter season, increasing infection potential beyond actual levels and reducing the tree’s resistance to prolonged droughts. Studying the effects of climate warming on

Phytophthora cinnamomi in Western Europe, Bergot et al. (2004) concluded that higher annual survival rates of the pathogen that may occur in future warmer climate scenarios could lead to a potential expansion of the high—disease risk zones for English oak and northern red oak (*Quercus rubra*) along the Atlantic coast of France. In the Mediterranean region the threat will remain unabated, eventually expanding north whenever feasible.

Effects at the Landscape and Regional Scales

Cork oak trees are drought resistant and resilient, thanks to their deep rooting ability (David et al. 2007), and it may take a succession of dry years for water deficits to reach a breakdown threshold and result in tree death. In the savanna-like systems (e.g., *montados* and *dehesas*; see Chapter 3), the balance between woody and herbaceous vegetation may be regulated by water availability. Eagleson (1982) developed a theory about the pattern of plant water use at various time scales, suggesting that in savannas a formation of grasses and woody plants is the only stable equilibrium state. Such an "ecological optimality" hypothesis leads to the prediction of an optimum tree density that is stable with respect to perturbations and metastable with respect to climatic variability. Joffre et al. (1999) showed that present tree density in the *montados* and *dehesas* of southwestern Iberia, with average annual precipitation below 700 millimeters, coincided with the ecohydrological equilibrium sensu Eagleson. This seems to result from the coincidence between long-term management objectives and ecohydrological optimality, that is, the control of tree density by water availability. Fluctuations in water resources caused by climate change may provoke a disruption of this long-term equilibrium.

A secondary consequence of increasing aridity suggested by climate change scenarios is an increased risk of fire, created by more severe or more frequent cycles of wetting and drying. Rural exodus and agricultural land abandonment may exacerbate this risk because they will mean that many cork oak woodlands will turn into highly flammable and impenetrable forests or shrublands. Although cork oak is well adapted to fire, increased fire frequency and intensity, combined with other stresses, such as drought and bark stripping, are reducing rates of postfire survival. Thus, fire prevention measures (e.g., control of fuel buildup) will be necessary, but they must be tailored so as to be compatible with soil conservation and natural regeneration goals.

Adjusting the broad geographic distribution of a species to a changing climate is a key feature for survival. Future climate scenarios seem to favor cork oak migration to higher latitudes and altitudes where is not abundant today. Such trends were documented for holm oak in Spain (Peñuelas and Boada 2003). As shown in Chapter 10, cork oak acorns can move quite a distance from their place of origin. However, the rate of climate change may overwhelm the species' capacity for migration and lead to local extinction, especially in fragmented landscapes, where the distance between source stands and suitable new habitats exceeds natural migration distances (Jump and Peñuelas 2005). In such cases, human intervention may be necessary to preserve the species and the cultural landscapes of which it is a major part. This concurs with the conclusions drawn from the economic studies presented in Part IV of this book.

To survive in variable environment, trees may have the ability to change phenotype in response to changes in the environment, an ability known as phenotypic plasticity. However, cork oak is a conservative resource user and has low phenotypic variation (Valladares et al. 2002). Although no studies are available for cork oak, local populations may show some capacity for in situ adaptation to climate change (i.e., genetic change), as other tree species do (Jump et al. 2006). However, this response probably is not enough to allow trees to persist in all their current locations under the pressure of rapid climate change. Nevertheless, changes in the genetic nature of tree populations will condition the genetics of reproductive materials to be used in restoration (Chambel et al. 2005).

Conclusions

As we have seen throughout this book, the management of agroforestry systems based on cork oak is undergoing changes imposed by socioeconomic conditions that encompass a whole range of human uses. Furthermore, climate change scenarios suggest an aggravation of environmental conditions for cork oak, namely increasing aridity with greater unpredictability of rainfall. New management practices and paradigms that can accommodate rapidly changing conditions are needed. Improving restoration techniques entails not only a clear definition of objectives but also a strategy that may include promotion of natural regeneration to allow genetic variability and the possible selection of drought-tolerant genotypes, as well as future evolution toward equilibrium with a new environment. Given the rate of climate change and the sluggish reaction of trees, assisted migration toward more favorable environments will be needed. Careful planning of plantations and selection of appropriate genotypes may combine with natural regeneration to stimulate a stress avoidance migration, provided that corridors to prevent habitat fragmentation are available. Public support for cork oak woodlands will be needed to help them adapt and survive. In Chapter 19 the authors describe vulnerability assessments of cork oak woodlands, using the Pixel-Oriented Growth (PIXGRO) model, specific to the Mediterranean region.

Chapter 19

Simulating Function and Vulnerability of Cork Oak Woodland Ecosystems

John Tenhunen, Ralf Geyer, João M. B. Carreiras, Nuno de Almeida Ribeiro, Nguyen Q. Dinh, Dennis O. Otieno, and João S. Pereira

As we saw in Chapter 18, human activities and the inherent variability in climate make the evaluation of climate change impacts on managed ecosystems uncertain. Therefore, it has been proposed that computer-assisted vulnerability assessments should be carried out to assess risk, define critical thresholds with respect to stability, and establish reliability in providing ecosystem services under different environmental regimes (Pielke et al. 2004; Bravo de Guenni et al. 2004). Bravo de Guenni et al. (2004:500) defined vulnerability as "the characteristic of a person or group or component of a natural system in terms of its capacity to resist and/or recover from and/or anticipate and/or cope with the impacts of an adverse event." Therefore, assessing vulnerability involves physical, biological, and human dimensions. Although vulnerability with respect to water resources is a critical issue (Kabat et al. 2004), especially in arid and semiarid regions, attention must also be given to plant production, focusing on *gross primary productivity (GPP)* as a key variable determining ecosystem function and therefore useful products and ecosystem services that may be at risk (cf. Krysanova et al. 2004).

For cork oak woodlands, the concept of vulnerability has meaning only if value is placed on continued production from these ecosystems, that is, if the current goods and services provided by these ecosystems are given a high value. Under this premise, cork oak woodlands are vulnerable with respect to climate change and to the abandonment of management practices critical for maintaining landscape structure (e.g., neglect of recruitment of young trees into the existing standing tree populations; see Chapter 10). They are also vulnerable with respect to any imbalance in fire protection or grazing intensity that increases tree mortality.

Function and Productivity as Related to Vulnerability Assessments

The primary goods obtained from cork oak woodlands are the main reason they are maintained even though other land use options exist (see Chapter 15). Thus, plant production, including partitioning between trees and herbs, and its sensitivity to climate change or to local disturbances are key factors in evaluations of ecosystem vulnerability. Ecosystem simulation models that estimate carbon dioxide uptake in GPP and, subsequently, GPP-dependent changes in biomass are useful for evaluating the overall function of these ecosystems and how they would respond to different climate change scenarios. Simulation models may also help quantify the potential yield of useful products under such scenarios and hence the economic viability of managed systems.

Water availability is one of the prime drivers of GPP and ecosystem function. The structural maintenance of cork oak woodlands requires adequate water, provided by rainfall, to support growth and maintenance of the adult trees and regeneration cohorts during the extended Mediterranean summer (Figure 19.1). Joffre et al. (1999) showed that the cork oak woodland may be viewed as having two separate but interacting ecohydrological components. First, the trees act as cylinders inserted into the landscape that penetrate to several meters in depth through the soil, as defined by the root system (see Chapters 1 and 6). These cylinders develop via biological processes to relo-

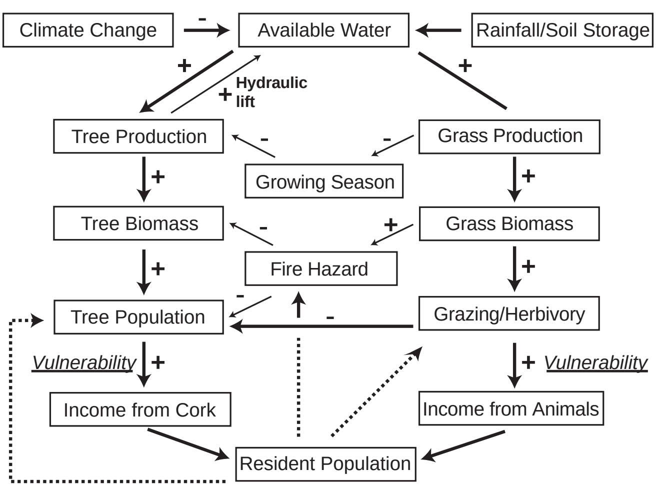

FIGURE 19.1. Diagram indicating the natural *(solid arrows)* and human influences *(dashed arrows)* on production and the resulting vulnerability of cork oak woodlands. Plus and minus signs indicate positive and negative influences of one factor on another.

cate nutrient stocks, increase soil carbon content, change bulk density and porosity, and thereby increase soil water holding capacity (Joffre and Rambal 1988). Additional complexity occurs where trees access the water table (David et al. 2004) because root systems move water via hydraulic lift. In contrast, the herbaceous component of the ecosystem may be considered as a 20- to 50-centimeter-thick blanket covering the ground between trees. This part of the ecosystem stores less water per unit area than trees, but high productivity occurs there during the spring, when soil moisture and weather are favorable for rapid herb growth.

Quantifying microclimate, physiological processes, biomass development, and water fluxes associated with the three-dimensional distribution of trees and understory elements remains a major challenge. In this chapter cork oak woodlands are treated as two separate components: trees and herbaceous plants (see Figure 19.1). This simplified treatment allows us to formulate a spatially explicit, landscape-scale model to describe the influences of water availability and climate on GPP and carbon flows in the vegetation mosaic. The spatial context is important because management measures and policies are best applied across whole landscapes and within regions. However, although models of ecosystem-scale function alone are inadequate to inform policy and management decisions, they do provide a means by which the complex relationships studied in ecology and the natural sciences may be linked to economic models and vulnerability assessments. Initial attempts to develop such a bridging tool will now be described and illustrated with a trial run carried out for a site in Portugal.

The Pixel-Oriented Growth Model for Mediterranean Woodlands

The Pixel-Oriented Growth (PIXGRO) model illustrated in Figure 19.2 was developed to describe the physiological response of vascular plants growing in a Mediterranean savanna-type vegetation with a pronounced tree stratum and an herbaceous understory (Tenhunen and Kabat 1999; Reichstein et al. 2002; Adiku et al. 2006).

Each stand location or pixel of the map (Color Plate 15a) is identified in terms of percentage tree cover, in order to weight the relative contributions of tree and herbaceous strata in gas exchange and biomass production. Canopy conductance, transpiration, evapotranspiration, GPP, plant respiration, and soil CO_2 efflux are calculated with the single-layered core process model Process-Based Pixel Net Ecosystem CO_2 Exchange ($PROXEL_{NEE}$) included in PIXGRO (Figure 19.2). The tree component was considered to have a constant *leaf area index (LAI)*, as determined for individual trees in the field

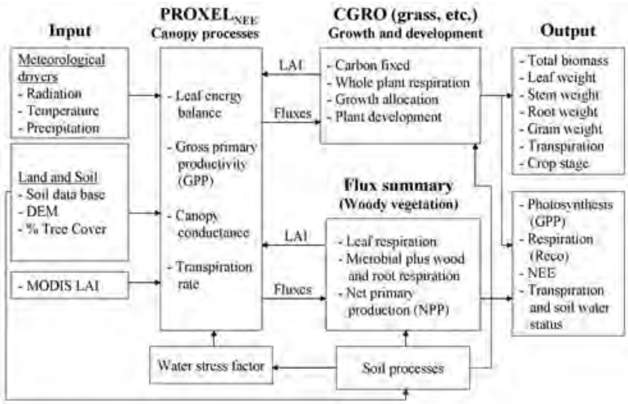

FIGURE 19.2. Schematic diagram of the Pixel-Oriented Growth (PIXGRO) simulation model to describe water balance and carbon flows in oak woodland ecosystems. The model has two components: the submodel Process-Based Pixel Net Ecosystem CO_2 Exchange ($PROXEL_{NEE}$), which simulates canopy gas exchange (e.g., photosynthesis and transpiration), and CGRO, which simulates herbaceous plant growth, partitioning, change in leaf area index (LAI), and plant development. An application of the two components for simulations of barley gas exchange and plant growth is described by Adiku et al. (2006). MODIS, Moderate Resolution Imaging Spectroradiometer; PROXEL, Process-Based Pixel.

(about 3.0 for individual crowns at the test site Herdade de Mitra near Evora, Portugal), but the aboveground herbaceous component changes in structure during the season, as described with classic growth algorithms.

An advantage of the PIXGRO model is that it simulates vegetation gas exchange behavior dependent on rooting depth, taking into account differences in water availability during drought. In the context of the model, herbaceous vegetation extracts water from a small storage reservoir (30 centimeters in depth), and the canopy and growth routines react sensitively to changes in soil matrix potential in this soil volume. Trees extract water from a 1.5-meter-deep soil cylinder (see also Kurz-Besson et al. 2006; Otieno et al. 2006; and Chapter 6).

Ecosystem Carbon Flows

Study of the carbon flows through an ecosystem has long been recognized as a useful method for assessing ecosystem health. Thus, it is essential that carbon flow patterns are correctly described by simulation models and properly validated with field data (see Valentini 2003). For example, experimental evidence showed a close relationship between GPP of the Mitra site on a yearly basis and the total amount of foliage present at each moment, as measured by leaf area duration (Pereira et al. 2007).

Observed responses of the tree and herbaceous components of cork oak woodlands are reproduced in simulations with the PIXGRO model. The predicted behavior at Herdade de Mitra, with respect to CO_2 uptake in 2002, is depicted in Figure 19.3. GPP is determined by the seasonal course of photosynthesis by both trees and herbs, in response to radiation, temperature, and soil water availability. While the herbaceous understory begins to grow after the rains in autumn, herbaceous leaf area remains low because of temperature limitations. As temperatures rise in spring, CO_2 uptake increases because of greater activity in tree leaves, but there is an even stronger increase in the activity of the herbaceous canopy.

In early summer, water stored in the upper soil layers is rapidly depleted, and with growing water deficits, the herbaceous vegetation restricts photosynthesis via stomatal closure; as drying continues, the annual herbs and some perennials die. The annual pattern in GPP follows LAI deployment, with high carbon uptake in spring, a strong decrease after dieback or death of the herbs in summer, and renewed uptake in autumn. Patches with trees exhibit a decrease in GPP after mid-May, as soil water becomes limiting. By midsummer, a slowing down of tree and soil microbial activity, in response to soil drying, leads to *net ecosystem CO_2 production (NEP)* rates approaching zero. The end-of-summer rains cause a burst in *ecosystem respiration* as soil microbes mineralize accumulated organic matter (Pereira et al. 2004; Jarvis et al. 2007). With further rains, the herbaceous annuals begin to develop anew, and the annual cycle is completed.

Adding the GPP components for trees and herbs proportional to their percentage cover at the Mitra site led to an acceptable simulation of the patterns and values, compared with direct (eddy covariance) field measurements (Pereira et al. 2007). In the simulation, however, the initial maximum obtained was higher than that obtained from measurements, possibly because grazing herds reduce herbaceous LAI over a long period in the spring. In late spring, GPP decreases abruptly to zero in the simulation, whereas in reality dieback of the herbaceous vegetation occurs gradually. Increases in GPP as a result of regrowth of the herbaceous component in autumn are reasonably well predicted. Overall, the simulation estimates an annual GPP for the composite landscape of 940 gC/m^2, whereas measurements indicated a great variability (765 ± 275 gC/m^2/year), due to several droughts between 2003 and 2006, with a maximum of 1,140 gC/m^2/year in the normally wet year of 2006

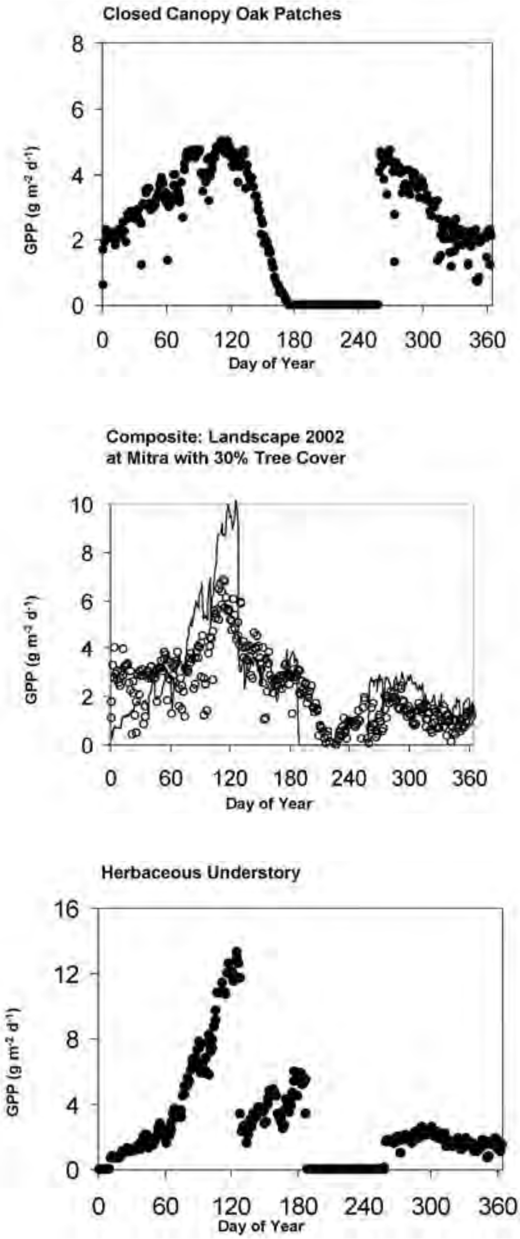

Figure 19.3. Simulation with the Pixel-Oriented Growth (PIXGRO) model of gross primary productivity (GPP) for patches of the herbaceous and tree components at Herdade de Mitra in 2002 and for the entire ecosystem, assuming a tree cover of 30%. Considering the entire ecosystem, the solid line indicates simulation results, and the circles indicate daily flux measurements.

(Pereira et al. 2007). The trees fixed 27 percent of the total, with 73 percent captured by the herbaceous vegetation. Subsequently, GPP drives cork production and accumulation of herbaceous biomass for exploitation in grazing.

Ecosystem Performance at Landscape and Mediterranean Basin Scales

Joffre and Lacaze (1993) and Carreiras et al. (2006) developed satellite imagery–based estimates for tree cover and tree density in cork oak woodlands. Landscape patterning in tree cover for the Herdade de Mitra site is shown in comparison to aerial photography in Color Plate 15a (A, B).

Using this depiction of tree distribution, water balance changes and GPP fluxes of the tree and herbaceous vegetation components may be determined as a function of time and for each pixel on the map. Predicted maps for total ecosystem evapotranspiration and aboveground biomass production of herbaceous vegetation in 2002 are shown in Color Plate 15a (C, D).

With current model settings, tree cover is inversely related to total ecosystem evapotranspiration and aboveground herbaceous biomass production. PIXGRO estimates a slightly lower water use annually by trees than by herbaceous vegetation. Herb production is directly related to water use of the understory and therefore increases as tree cover decreases. The PIXGRO model can be applied at even larger scales (e.g., over the entire Mediterranean basin). In such an application, the identified woodlands may change strongly in herbaceous species composition and in whole ecosystem functioning, leading to greater uncertainty in predictions. Nevertheless, results are shown for the years 2002 and 2003 in Color Plate 15b.

The year 2002 was very similar to average conditions over the previous thirty years and serves as a proxy for normal climatic conditions; however, 2003 was drier and hotter than normal throughout most of Europe (Ciais et al. 2005) but near normal in terms of precipitation in southwest Iberia. In response to greater water deficits, the average evapotranspiration and GPP for all Mediterranean woodlands decreased by about 20 percent. The largest effects occurred along the Spanish eastern coast, in southern France, and in coastal Italy and Greece (about 60 to 70 percent of the 2002 GPP in 2003). Western Iberia was much less affected.

Conclusions

Assessing the vulnerability of cork oak woodlands entails understanding the relationships between management choices and ecosystem responses. In particular, process-based models describing vegetation response to changing climate are needed to understand and quantify GPP in these ecosystems. This is a key variable in vulnerability assessments because it determines functioning and the level of many ecosystem services and goods, such as cork production. PIXGRO may be used to estimate an index, based on GPP, that is used to modify empirical tree growth parameters and cork production (i.e., it includes increments in tree size and number over time, as well as allocation of resources within the tree, including the growth of cork layers). The challenge remains to determine whether such an index is generally valid, whether variation in GPP leads to a linear influence on growth, and, if not, then how such a relationship may be described.

The ability to quantify GPP over large areas, via the application of remote sensing technology, will help extend analyses to the regional scale. Simulations with models, such as PIXGRO, will provide outputs that together with economic and management models can address vulnerability with respect to a given supply of ecosystem goods and services. However, vulnerability assessments must go further and include additional dimensions, as illustrated by Stohlgren (2004) (cf. Chapter 20). For truly useful assessments, models must be extended to simulate the changes in water and carbon balances associated with human activities, namely land abandonment, fire risk, and excessive grazing. The last chapter of this grand tour, Chapter 20, will summarize the challenges facing cork oak woodlands and suggest some strategies for finding a viable way forward.

Acknowledgments

We thank all the colleagues who participated in stimulating discussions of the links between carbon and water cycles in Mediterranean-type ecosystems and contributed their data for this exercise. This work was supported by the EU "Mediterranean Terrestrial Ecosystems and Increasing Drought: Vulnerability Assessment" project, organized by Franco Miglietta, and the CarboEurope-IP "Assessment of the European Terrestrial Carbon Balance" project integration component, chaired by Martin Heimann.

Chapter 20

The Way Forward

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Cork oak trees and woodlands have been managed and cherished by generations of people of many different Mediterranean cultures and in many different ways. Their resilience in a sometimes hostile environment, their economic importance, and their nonmonetary, or nonmarket, aesthetic and cultural values make these cultural woodland systems an outstanding example of the kind of mutually beneficial relationship that is possible between people and the rest of nature. Today, the fate of the cork oak tree and of the ecosystems and landscapes where it thrives depend in large part on pragmatic issues of land use and economic tradeoffs. But the way people think and feel about the tree and the landscapes is important too. Here as everywhere, ethics, cultural values, and identity play a big role in the way people act, along with short-term economic considerations.

Before the twentieth century, there was no single-purpose silviculture for cork oak, but rather multipurpose, multiuse management was carried out under conditions of local self-sufficiency. There was an embeddedness that now seems lost and far away to most of us in our urbanized societies. This cultural and socioecological integration made cork oak woodlands less vulnerable to fluctuating market values. Changes in the demand for cork or other specific products, discussed at various points in this book, are now leading to rapid changes in management and land value. Yet those multiple uses, adapted over time in a wide range of regional and local contexts, explain why we still see such a large variety of cork oak woodland systems and landscapes today. That multiplicity of socioecological contexts and long-nurtured management systems can provide clues, strategies, and tools for future management scenarios in a rapidly and radically changing world. In this final chapter we review what has gone wrong and then discuss the way forward to meet the challenges of the future, creatively and adaptively.

Cork Oak Decline

Once established, cork oaks are naturally resilient and readily withstand the vagaries of the Mediterranean climate and a host of potential catastrophes. However, over the last century this has changed. Resilience has declined, thanks to human imprudence. In the late nineteenth and early twentieth centuries, excessive tannin extraction after bark stripping caused large-scale mortality and was probably one of the main causes of the long-term decline of cork oak woodlands described in several previous chapters (cf. Montoya 1988). But the declining well-being of cork oak trees endangers whole ecosystems and, indeed, whole landscapes we may well call heritage landscapes because they are derived from ancestral agro-silvopastoral systems. Also at risk are the biodiversity itself and the goods and services these heritage ecosystems provide to people. Given the added influence of present climate change and the likely scenario of gradual drying in Mediterranean basin, the risks and hazards seem to be getting worse.

Although cork may provide some fire protection (see Chapter 1), the occurrence of wildfires after bark stripping is a particularly serious threat for cork oak tree survival (Pausas 1997). In the parts of southern Europe where active management and exploitation of cork are disappearing, along with agricultural abandonment and rural exodus, secondary ecological succession is taking place. This means colonization and spreading of shrubs and the generation of an excessively high fuel load of very flammable vegetation. Moreover, for the last forty years throughout the western Mediterranean, the rainless periods of summer have gradually become longer, extending into the spring and combining with hot weather (Paredes et al. 2006), greatly increasing wildfire hazard (Pereira and Santos 2003; Pausas 2004). In North Africa, for the time being, wildfires are limited because of high land use intensity. However, overuse and overgrazing are getting worse, leading to the blockage of natural regeneration of cork oak and other trees (see Chapters 3 and 10) and galloping desertification.

A prominent result of the recent decline, north and south of the Mediterranean, is that a growing number of cork oak trees and groves are orphaned in increasingly fragmented and dysfunctional landscapes, characterized by agricultural abandonment in some areas and overly intensive use in others. Too much exploitation and too little both spell potential disaster for cultural cork oak woodlands. So what can be done to counter these worrisome trends, in

Europe and North Africa, in the larger context described by the Millennium Ecosystem Assessment (MA 2005a, 2005b)?

Europe

From 1988 to 2006, the European Union made an ambitious effort to monitor tree crown conditions throughout Europe, under the direction of the Federal Research Centre for Forestry and Forest Products (UN/ECE and EC report on Forest Condition in Europe; Lorenz et al. 2000, 2007). In southern Europe, approximately 100 plots and 1,500 cork oak individuals were included in the study. For the whole dataset, cork oak defoliation dramatically increased since 1990 and remains high to the present day. In comparisons with similar tree species (e.g., cork oak and holm oak) growing under the same climatic conditions in southern Europe, the trends of worsening defoliation in conditions are almost parallel (Lorenz et al. 2000, 2007). This suggests the dominant role of water stress as a major cause of defoliation, possibly followed by diseases (see Chapter 9).

Forest cover is generally increasing throughout Europe (FAO 2006a). In the case of cork oak stands, there are conflicting trends. Whereas afforestation of agricultural lands led to a gross increase in area in some regions, there have been losses due to decline, forest fires, or land use changes. For example, in Portugal the national forest inventories detected a gross increase in cork oak area of 5 percent in 1995, as compared to the area three decades earlier, but there was a 10 percent loss between 1995 and 2005 as a result of forest fires in 2003 (Tomé et al. 2007). However, over the next few decades part of these burned forests may well recover and then be classified once again as cork oak woodland in the national forest inventory. At the same time, tree density is decreasing in cork oak woodlands; for example, stands with less than forty trees per hectare increased from 10 percent of the cork oak area in 1995 to 30 percent in 2005 (M. Tomé, personal communication, 2007). In Machuqueira do Grou, Portugal (see Site Profile 4.1), the recorded rate of mortality indicates that stand density decreased by 17 percent over the last ten years (N. A. Ribeiro, personal communication, 2007). In Spain, forest inventories indicate a slight but significant increase in the area of cork oak stands, just as in Portugal, but there was also an increase in both basal area and number of trees, indicating denser forests.

The area covered by cork oak is probably expanding slightly in places where new plantings are being undertaken (e.g., in Andalucía and Portugal) and where agriculture has been abandoned and rainfall and soil fertility are sufficiently high to allow natural regeneration (Pons and Pausas 2006;

Chapter 10). In fact, in moderately grazed stands recruitment occurs in most years (Pons and Pausas 2006; Pausas et al. 2006). However, long-lasting recolonization is highly dependent on land use in the expanding fringes of cork oak populations.

North Africa

The current surface area occupied by cork oak in Algeria, Morocco, and Tunisia is probably less than 30 percent of its potential area (Charco 1999) because of overgrazing and poor management (see Chapters 14 and 17; cf. FAO 2001). Increasing drought and persistent overexploitation both promote decline. The result varies in relation to the technological and socioeconomic conditions and availability of resources, but in general overexploitation of resources is much stronger in northwestern Africa than in southern Europe. This is part and parcel of a much broader set of problems affecting North Africa and, indeed, much of the developing world. It consists of a spiral of environmental degradations and desertification intimately related to overpopulation, poverty, and poor distribution of goods and services. In the absence of sustainable land use systems and adequate government aid, ongoing forest clearance and outright desertification are proceeding at a rate of about 2 percent a year (Marchand 1990; López-Bermúdez and García-Gómez 2006), which is just about the same rate at which agricultural lands are being abandoned in southern Europe.

In other words, the western Mediterranean and, indeed, the region as a whole (Blondel and Aronson 1999) represent a very coherent microcosm of world problems with the north–south contrast referred to already, plus the growing population and pollution problems north and south and the menace of major climate change and aridization, as we saw in previous chapters. That being said, how can we go forward? What practical things can be done? In the remainder of this chapter, we will explore the possibilities.

Cork Oak Woodland Products

Cork oak woodlands produce two high-quality, high-cost products for world markets: natural cork and black pig ham. As pointed out in Chapters 5 and 16, increasing dependency on the wine bottle stopper market is worrisome because this sales outlet is facing stiff competition from alternative materials. This constitutes a real threat for the survival of cork oak woodlands because they may lose their economic viability if the bottle stopper market for cork slumps drastically. But, as complements to the consistently high commercial value of high-quality cork products, new marketing and distribution campaigns highlighting the advantages of cork and various forest certification instruments (see Chapter 17) can help maintain the value of cork production and hence the maintenance of healthy cork oak woodlands. Indeed, natural cork stoppers have lower environmental impacts in terms of carbon dioxide emissions and pollution (i.e., stoppers thrown away) than aluminum and plastic closures for wine. In fact, cork stripping does not kill the trees, and the amount of cork harvested is almost negligible compared with ecosystem carbon flux (e.g., the mass of cork harvested is only 2–5 percent of the net primary productivity of the trees during the cork production period, 9 to 12 years). As a consequence, cork harvest barely affects ecosystem carbon balance, and ecosystem carbon sequestration should be credited as an asset in cork production.

Meanwhile, other products are gaining ground. In particular, the recent opening of overseas markets for high-quality cured ham, derived from the ancestral race of rustic black pigs raised in Spanish *dehesas* and Portuguese *montados*, brings higher value to acorn crops produced in these agroforestry systems. The rapidly growing demand for this cured ham may easily surpass current levels of production, opening the way for the expansion of black pig husbandry in *dehesas* and *montados* and generating interest in expanding the surface areas of this system.

If the economics of the exploitation of a given *dehesa* or *montado* system are positive, in terms of cork stripping and associated grazing or hunting rents, the problem is to find technical and administrative solutions for sustainable management to ensure regeneration. However, if the cost–benefit ratios are disadvantageous under current market conditions, new public policy and legislation will be needed to conserve or restore cork oak woodlands in the public interest (see Chapters 15 and 17). This is true in northern Africa and in southern Europe.

Apart from the two top products already mentioned, natural cork and black pig ham, other products and services are obtained from cork oak woodlands, as reviewed in various chapters of this book (e.g., Chapters 5 and 14–17). One of these that is gaining importance is recreational and tourism value, both for locals living in nearby cities and for international tourists. In Spain, in particular, the amounts of money that visitors are willing to pay for recreational use of cork oak forests and woodlands, including *dehesas*, is increasing (see Chapter 15). This may soon surpass the monetary value of conventional market products traditionally obtained. The same recreational value could also emerge in some North African cork oak woodland regions, especially near the Mediterranean coast, as agrotourism and nature-based tourism increase.

By contrast, the recreational value of *montados* is uncertain in Portugal, as well as Italy and France, except in the eastern French Pyrenees. Because of the process described in Chapter 16, in Portugal there is still much emphasis on cork, followed by cattle (including organic farming) and, more recently, pork. Edible mushrooms (e.g., truffles) are important here and there. Hunting is important too. The future of tourism, as a direct benefit of the cork oak woodlands of France and Italy, is also unclear but should not be neglected. The Mediterranean basin is the world's number one tourist destination, and there is an increasing demand for rural tourism, agrotourism, and sustainable ecotourism, as well as "geotourism," which combines natural history and historical and cultural components. Cork oak woodlands clearly have great potential in this regard.

Management Options

Cork oak ecosystems and landscapes are in transition between traditional forms of land use and new social demands, both environmental and productive. The challenge is that any alternative management option should not reduce future options. Because the main causes of ecosystem degradation are local and driven by socioeconomic factors, management alternatives should also be local. For instance, in northeastern Spain the high value of private amenity use (see Chapter 15), together with a general process of abandonment of management practices and domestic grazing, with insufficient colonization by natural herbivores, led to an "unnatural" situation of undergrazing, with huge accumulation of fuels in the understory, increasing fire risk. The challenge here is to maintain the heritage landscape value of cork oak woodlands while keeping fire risk at a manageable level. Indeed, controlling wildfires is clearly a major issue for management of all southern European forests and woodlands.

Therefore, cork oak woodlands must be managed and restored with respect to fire risk. In the extreme case of managed *dehesa* and *montado* systems, fire risk is very low because of the horizontal and vertical discontinuity of fuels. Fuel distribution in the landscape should be designed to reduce the risk of wildfire propagation. Tree density (e.g., using structures as firebreaks and ecotones), understory fuel control, and grazing management are effective fire prevention measures for cork oak woodlands. Consideration of spatial factors in restoration projects is poorly developed to date. The challenge is to match habitat suitability to fire prevention principles. Spatially explicit models of fire propagation, together with habitat quality spatial distribution through geographic information systems, provide tools at the project scale to advance in this direction (Pausas 2006; Duguy et al. 2007; Pons and Pausas 2008). For this, as for reducing stocking rates, appropriate environmental policies, public investments and subsidies, and financial institutions are going to be needed.

Protecting the *dehesa* or *montado* from excessive grazing, by seasonally excluding seedlings or stands from grazing until the tree canopy escapes the reach of herbivores, is a successful technique in some areas managed as natural parks. However, *dehesa* and *montado* systems today range primarily from heavily managed agro-silvopastoral systems, with high short-term economic returns, low biodiversity, and low resilience, to seminatural, high biodiversity, silvopastoral systems, with low use pressure, low economic return, and higher resilience. A middle way is needed. Multipurpose sustainable use of these woodlands should promote high-value herbivores, with low stocking rates that would favor high species richness in the herbaceous layer, and also allow spontaneous cork oak recruitment. Of course, oak tree recruitment is neither regular nor frequent even in natural or seminatural woodlands. Successful recruitment occurs only after rare periods of exceptionally favorable weather, and such periods may be critical for regeneration in cork oak woodlands.

Conservation and Restoration

There are difficulties in ascertaining the potential distribution of cork oak today and in the future. The present area has been artificially expanded and maintained for centuries but also disturbed, fragmented, and degraded by people. However, one simple and obvious response to global warming and regional aridization would be to anticipate and, indeed, encourage the expansion of cork oak woodlands to more mesic climate regions, ideally adjacent to current woodlands, so as to facilitate gene flow and other biological movements and migrations. This seems especially appropriate in the case of populations growing in the driest portions of the current distribution area of cork oak and for isolated populations, such as those found in many places in the Iberian Peninsula and North Africa (see Figure 1.1). This option is limited and will be regulated by evolving land use patterns and market conditions and, in some areas, by the lack of appropriate soils in neighboring wetter regions. As suggested in Chapter 17, ecoregional land use planning will be a key instrument for assisting cork oak migration as an adaptation measure. But policy decisions will be needed uphill of any such efforts.

Some large and overexploited cork oak woodlands, such as the Maamora, the largest existing managed cork oak woodland in the world, should also receive special international protection and attention, in a management model combining the concerns of the three international conventions that were signed at the 1992 Rio de Janeiro World Summit on Sustainable Development (the United Nations Framework Convention on Climate Change, the Convention on Biological Diversity, and the United Nations Convention to Combat Desertification) and sustainable economic use. Indeed, these conventions—the "three Cs"—are intimately interlinked and should be seen as a cluster, as was clearly expressed at Rio and recalled recently by Pagiola and Platais (2007).

As noted, acorn production, dispersal, and germination are critical bottlenecks in cork oak migration, such that recruitment of new mature individuals typically takes several years. Therefore, passive, low-cost restoration strategies and temporary grazing exclusion in sites set aside for self-regeneration are fundamental in planning. This is especially critical in small woodland remnants threatened by excessive fragmentation. However, in areas lacking seed-bearing cork oak trees in the vicinity or effective acorn dispersers, active restoration through plantation or seeding is needed. Although regeneration per se may be of little interest to many landowners—except for sentimental reasons—forest management certification will require measures to guarantee the sustainability of the cork oak populations. Furthermore, such activities may enhance both tourism-related benefits to landowners and their personal enjoyment and satisfaction. Nevertheless, public money will need to be invested on the basis of the externalities and services provided by cork oak woodlands to society.

Coping with Uncertainty

In southern Europe, most land use projections for the coming decades indicate that there will be extensive abandonment of arable land (Rounsewell et al. 2006; Figure 20.1). These projections were based on socioeconomic scenarios of greenhouse gas emissions in the framework of the Intergovernmental Panel on Climate Change (IPCC). The large cultivated areas expected to be abandoned offer great opportunities for forest expansion and carbon sequestration. However, the recent dramatic rise in cereal prices worldwide was not sufficiently considered in the "business as usual" IPCC socioeconomic scenarios that led to the prediction of land abandonment. If sustained, those price increases may change the picture dramatically, both in southern Europe and in arable portions of North Africa.

Ecosystem and landscape restoration projects intrinsically face high uncertainty, and in today's world this applies to conservation and other forms of land management as well. The highly variable and unpredictable nature of Mediterranean climate, uncertainties about soil conditions in afforestation, competition with extant vegetation, mycorrhizal interactions, grazing pressure, and the risk of pests and diseases, all make the fate of restoration actions highly uncertain. Furthermore, decisions to restore at a broad scale require a major and long-term commitment, and they typically involve multiple stakeholders and objectives, which compound the issues related to uncertainty. Finally, climate change projections are introducing still more uncertainty at a regional scale, and harsher conditions are expected in a general framework of aridization for the western Mediterranean (see Color Plate 16; Ulbrich et al. 2006).

One specific element of optimizing adaptation potential for species is the careful selection of genotypes in reproductive materials, to cope with variability and water stress. This is a critical step in the entire restoration process that has been underemphasized to date. But more challenging issues must be taken up at the policy and planning level. The emerging science, business, and practical restoration of natural capital (see Aronson et al. 2007) and the World Wide Fund for Nature (WWF)–IUCN approach of forest landscape

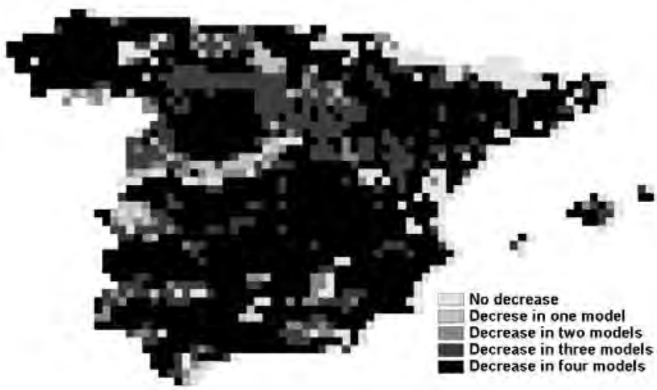


FIGURE 20.1. Projection of areas in Spain with decreasing crop land surface in the 2080 horizon, from climate models hda1, hda2, hdb1, and hdb2. In the hydrological discharge (HD) model, A and B are different climatic scenarios. The A1 and A2 families have a more economic focus than B1 and B2, which are more environmental; the focus of A1 and B1 is more global than that of the more regional A2 and B2. (Elaborated from European Union project Aquatic and Terrestrial Ecosystems Assessment and Monitoring, Vallejo and Alloza 2007, unpublished)

restoration (Mansourian et al. 2005) provide elements of a road map for this general task. However, much work will be needed locally, regionally, and internationally to put these ideas into practice in the context of the cork oak woodlands.

The Millennium Ecosystem Assessment (MA 2005a) suggests that proactive strategies for managing ecosystems of all kinds are needed in order to increase adaptation and mitigation to climate change and desertification threats while also fighting the loss of biodiversity (i.e., the "three Cs" of the 1992 Rio Conventions). In other words, pursuing any one of the "three Cs" in isolation may yield good results, but working on all three simultaneously should lead to far greater, longer-lasting results.

As Blignaut et al. (2008) noted, four enabling factors will determine the success or failure in the quest for synergy between the "three Cs": management tools and techniques, scientific knowledge, policy environments, and functional institutions. The first two of these factors have been discussed in various contexts in this book. With regard to the policy environment, clearly much more is needed, as is the case for functional institutions also. It now appears that various groups of investors could contribute to the conservation and restoration of representative, emblematic, and strategic cork oak woodlands, linked with the general economic development of the local people, by paying the communities to "farm" for nature's services. This could take the form of carbon credits or, better still, the newly emerging biodiversity and sustainability credits, as well as direct payment for ecosystem services, such as watershed and soil cover protection and reduction of fire hazards (Pagiola and Platais 2007).

Although cork oak woodlands are threatened by overexploitation, pests, wildfire, and climate change, proactive management and conservation measures are feasible in the current context of growing environmental awareness and concern for our collective future. When well managed, these socioecological systems harbor a great deal of biodiversity and a number of unique species and landscapes of heritage value. Well-managed trees and pastures (sown or improved) may durably stock or sequester large quantities of carbon to slow anthropogenic climate change and help in the struggle against desertification. Multiple uses may not be as profitable as specialization in the short term, but they may provide greater resilience and robustness in the face of rapid changes and an uncertain future. It is thus possible to envision public support for cork oak woodland restoration, as was the case in the late nineteenth century and the first half of the twentieth century, when several Mediterranean countries invested a huge amount of resources in ambitious afforestation plans for mountainous areas. A number of projects taking place around the world exemplify the strength of a strategy for achieving the interlinked goals of combating desertification, protecting biodiversity, mitigating the consequences of climate change, and promoting the sustainable development of human communities. We hope this book will help advance those goals both regionally and globally.

Color Plate 1. Tree characteristics: *(a)* Trunk with virgin bark, *(b)* detail of the bark after extraction, *(c)* acorns, *(d)* foliage and acorns, and *(e)* catkins (male flowers). Photos: *(a)* J. G. Pausas, *(b)* E. Chirino, *(c)* F. Selvi, and *(d, e)* F. Catry.

(*a*)

(*b*)

Color Plate 2. Cork harvesting: *(a)* Bark stripping and *(b)* piles of bark. Photos: *(a)* R. Piazzeta and *(b)* D. Crespo.

(*a*)

(*b*)

(*c*)

(*d*)

Color Plate 3. Cork traditional and modern products: *(a)* Beehives, *(b–d)* bottle stoppers of different qualities. Photos: *(a)* J. Cortina, *(b, c)* Associação Portuguesa de Cortiça, and *(d)* Copyright Institut Català del Suro.

(*a*)

(*b*)

Color Plate 4. *(a)* The herbaceous layers of some *dehesa* and *montado* open woodlands have been improved through the sowing of biodiverse legume-rich permanent pastures. *(b)* Evidence of the multiuse of these woodlands as a source of cork and grazed improved pastures. Photos: D. Crespo.

(*a*)

(*b*)

Color Plate 5. *Dehesa* and *montado* open woodlands cropped with *(a)* cereals and *(b)* legume fodder. Photos: D. Crespo.

(*a*)

(*b*)

Color Plate 6. *Dehesa* and *montado* biodiverse legume-rich sown permanent pastures used by *(a)* pigs and *(b)* sheep. Photos: D. Crespo.

(*a*)

(*b*)

Color Plate 7. *(a) Montado* open woodland in south Portugal: *(b)* Women collecting acorns in the Maamora forest, Morocco. Photos: *(a)* F. Catry and *(b)* © World Wildlife Fund/Meriel Robson.

(*a*)

(*b*)

Color Plate 8. Dense cork oak forests: *(a)* Los Alcornocales Natural Park (south Spain) and *(b)* Algeria. Photos: *(a)* J. Cortina and *(b)* A. Gasmi.

(*a*)

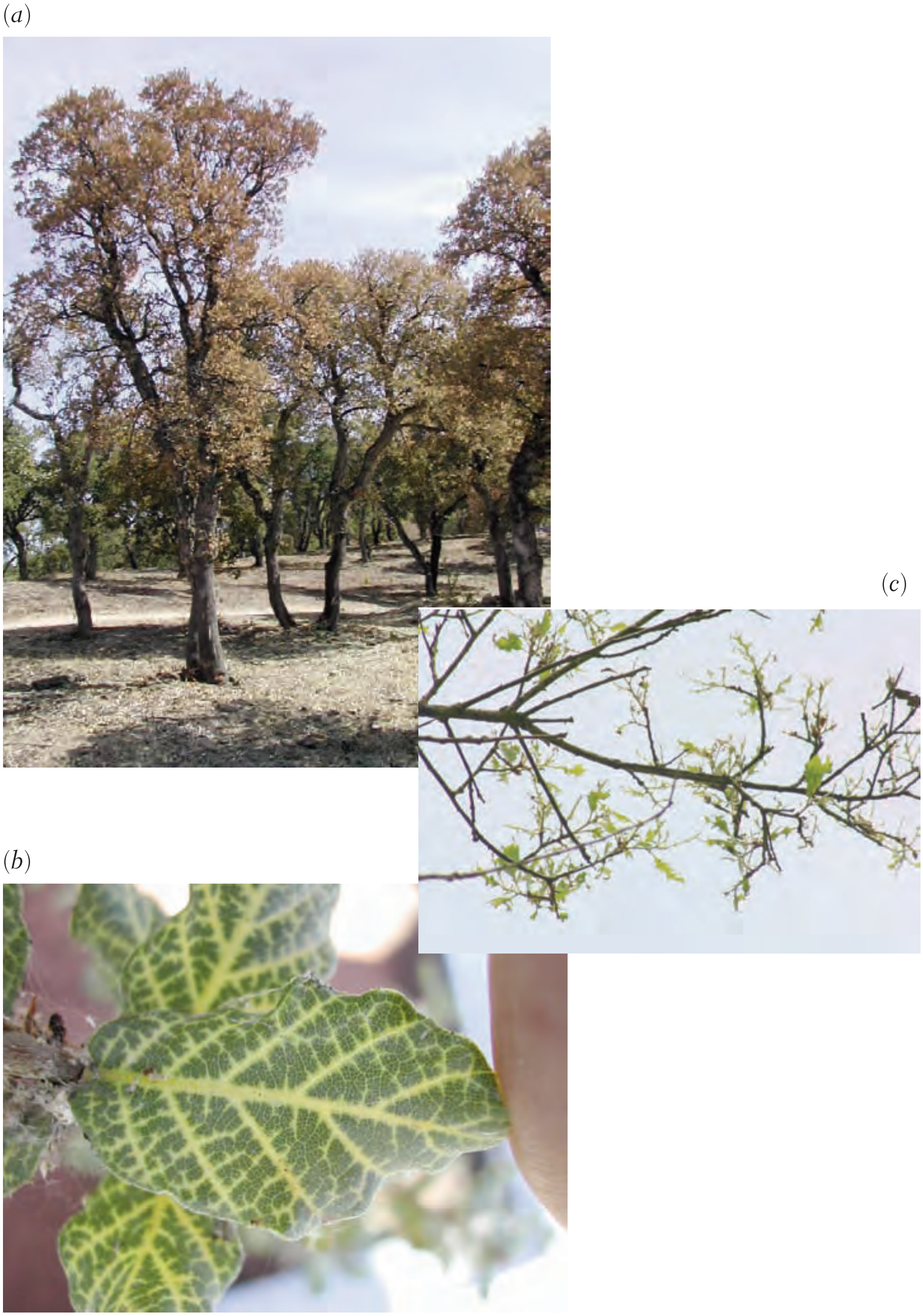
(*b*)

Color Plate 9. Faunal biodiversity: *(a)* Iberian lynx (*Lynx pardinus*) carrying one of her two newborn cubs in Spain and *(b)* Barbary deer (*Cervus elaphus barbarus*) in El Feija National Park, Tunisia. Photos: *(a)* © World Wildlife Fund/Michel Gunther and *(b)* © World Wildlife Fund/Ministerio de Medioambiente y Junta de Andalucia.

(*a*)

(*b*)

Color Plate 10. Degraded woodlands: *(a)* Serra Caldeiro, Portugal, and *(b)* northern Tunisia. Photos: *(a)* R. Vallejo and *(b)* J. Cortina.



Color Plate 11. Trees affected by *(a)* drought and *(b)* nutrient deficiency; *(c)* defoliation by *Periclista andrei* (*Hym: Diprionidae*). Photos: *(a, b)* J. Cortina and *(c)* I. Ferreira.

(*a*)

(*b*)

(*c*)

(*d*)

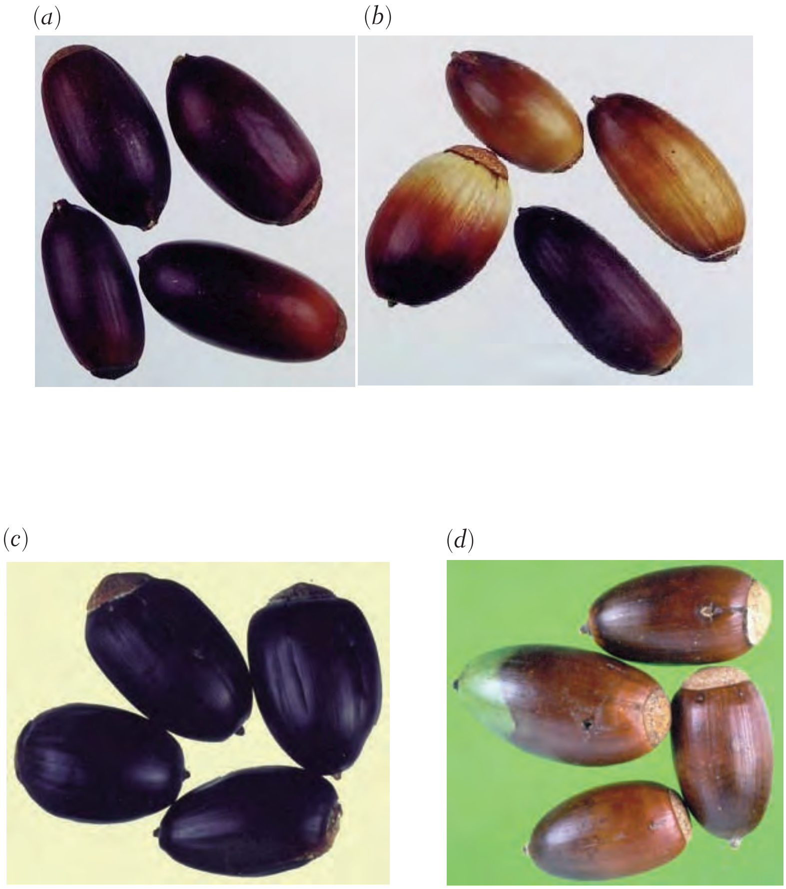
Color Plate 12. Postfire resprouting from stem buds in *(a, c)* Espadà (eastern Spain) and *(b, d)* Mafra (Portugal). Photos: *(a)* J. Cortina, *(b, d)* F. Catry, and *(c)* J. G. Pausas.

(*a*)

(*c*)

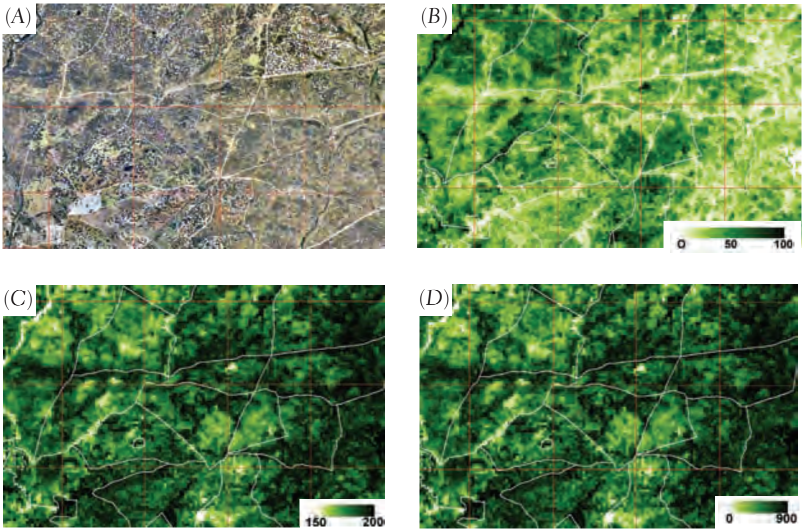
(*b*)

Color Plate 13. Plantations in *(a)* Extremadura, Spain, and *(b)* Montargil, Alentejo, Portugal; *(c)* seedlings in nursery, Spain. Photos: *(a, c)* J. Cortina and *(b)* R. Piazzeta.

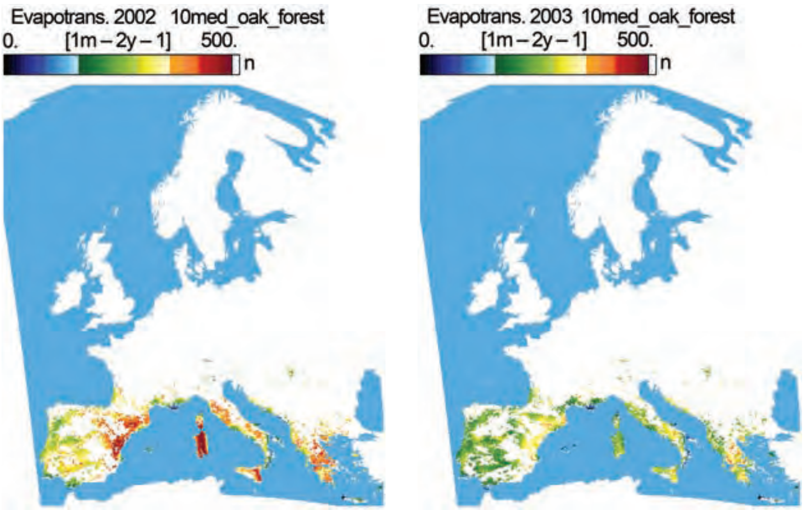


Color Plate 14. Cork oak acorns in different conditions: *(a)* Healthy, *(b)* dehydrated, *(c)* infested by fungi, and *(d)* attacked by chestnut weevil. Photos: *(a–c)* H. Mérouani and *(d)* A. Duarte Mil-Homens.

(*a*)

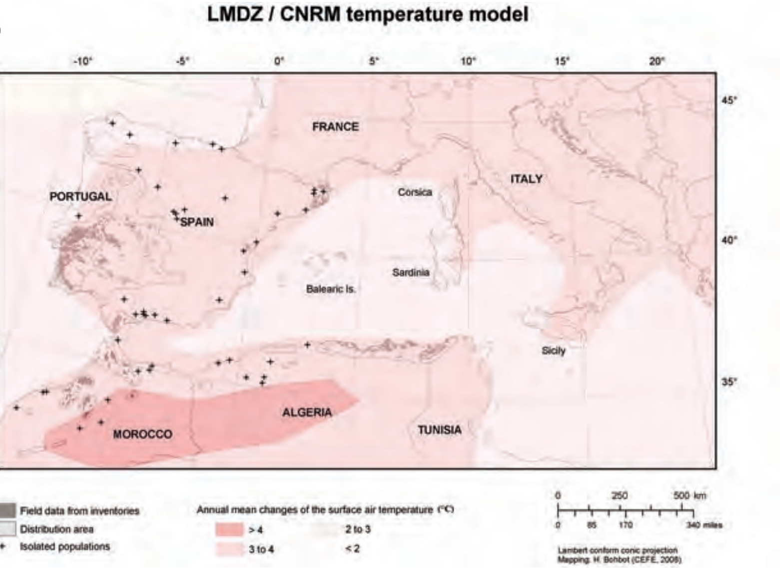


(*b*)

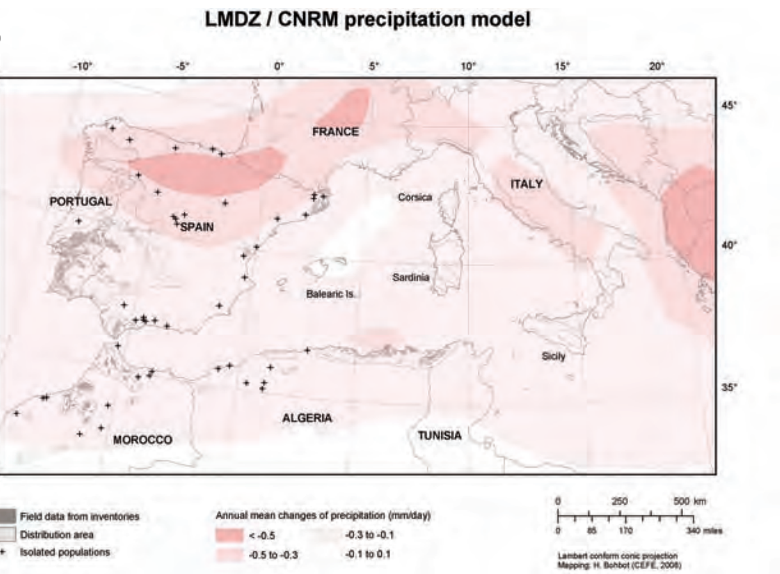


Color Plate 15. *(a)* Simulation results with the Pixel-Oriented Growth (PIXGRO) model for the Herdade de Mitra landscape in 2002: *(A)* Aerial photograph showing the vegetation mosaic, the road network, the facilities of Évora University *(lower left)*, and the eddy covariance tower site *(yellow circle)*; *(B)* tree canopy cover (%);*(C)* total annual ecosystem evapotranspiration (mm); and *(D)* annual aboveground herbaceous biomass production (g/m^2/year). *(b)* Estimations with the PIXGRO model of evapotranspiration and total ecosystem gross primary productivity (GPP) for woodlands across the Mediterranean basin. Pixel resolution is 10 × 10 km, where leaf area index and percentage cover for the woodland vegetation are averaged from all 1-km pixels evaluated in the Moderate Resolution Imaging Spectroradiometer (MODIS) method (Myneni et al. 2002).

(a)



(b)



Color Plate 16. *(a)* Predicted changes in temperature (°C) in the western Mediterranean over the coming century according to the coupled Centre National de Recherches Météorologiques (CNRM) climate model used. *(b)* Predicted precipitation (mm/day) in the western Mediterranean over the coming century according to the coupled CNRM climate model used. Figures modified from Ulbrich et al. (2006), with permission of Elsevier.

GLOSSARY

The following definitions pertain to the usage of terms of this book. Some terms may have broader or additional meanings that are not listed.

acidification. Process whereby soil becomes acid ($pH < 6.5$). It is a natural process that, in natural ecosystems, operates over many years, and it is produced by acid parent material or in regions with high rainfall, where soil leaching occurs. Some plants may also acidify their soil environment (see Chapter 8). Acidification can be accelerated by human activities (use of acid fertilizers, deposition of pollutants). The rate of soil acidification depends on the rate of acid addition and on the soil buffering capacity.

active restoration. The process assisting the recovery of a degrades ecosystem by artificial means, such as planting, seeding, or any other related techniques. Specifically we refer here to effects to reconstitute woodlands and cultural agroforests (including dehesas) mainly by seeding and planting.

afforestation. Planting or seeding of trees in an area that previously contained forest.

allozymes. Enzymes coded by the alleles of a specific gene.

amplified fragment length polymorphism (AFLP). A highly sensitive method for detecting polymorphisms in DNA. After restriction enzyme digestion of DNA, a subset of DNA fragments is selected for polymerase chain reaction amplification and visualization.

antiquitine. Chemical product that kills insects by inhibiting the production of chitin during molting.

arbuscular mycorrhiza (AM). A type of mycorrhiza of which the hyphae penetrate the root cell walls to form arbuscules into the periplasm (intermediate zone between the cell wall and the plasmalemma). In addition to arbuscules, arbuscular fungi often produce vesicles, which are storage organs.

autecology. The branch of ecology that deals with the biological relationship between an individual organism or an individual species and its environment.

azhagar. Berber term for a silvopastoral system in parts of Morocco.

base saturation. The ratio of the quantity of exchangeable bases (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) to the cation exchange capacity, often expressed as a percentage. High base saturation indicates soil alkalinity; low base saturation indicates acidity.

buffering capacity. The soil's ability to resist any change in pH. Soils with a high clay and organic matter content have higher buffering capacity and can tolerate the addition of acidifying compounds over an extended period or, at a higher rate of addition, without becoming too acid. There may be different buffer systems in a soil, including carbonate, silicate, exchanger, and aluminum buffers, in a sequence of decreasing pH and base saturation.

calcareous soil. Soil containing sufficient free $CaCO_3$ and other carbonates to effervesce visibly or audibly when treated with cold 0.1-M HCl. This soil usually contains 10 to almost 1,000 g/kg $CaCO_3$ equivalent.

cambium. A series of formative cells lying outside the wood proper and inside the inner bark. The growth of new wood takes place in the cambium, which is very soft.

canopy. The largely continuous cover of leaves and branches.

capital income. An owner's annual total benefit from the services of both human-made and natural capital invested (e.g., in a cork oak woodland).

carbonate. 1. A mineral composed mainly of calcium (Ca) and carbonate (CO_3) ions; may also include magnesium (Mg), iron (Fe), and others. 2. Rock or sediments derived from debris of materials, composed mainly of calcium and carbonate (e.g., shells, corals), or from the inorganic precipitation of calcium (and other ions) and carbonate from solution (seawater). Examples include **limestone** and **dolomite.**

cation exchange. Interchange between a cation in the soil solution and another cation in the boundary layer, between the solution and surface of negatively charged soil particles, such as clay and organic matter. It is usually expressed in centimols of charge per kilogram of exchanger ($cmol_c/kg$).

cavitation. Expansion of an air bubble in a xylem tracheary element, temporarily blocking the xylem tube.

chlorosis. Yellowing of normally green tissue, caused by chlorophyll destruction or failure of chlorophyll formation.

chlorotypes. Genetic characteristics of a chloroplast DNA molecule.

conservation value. A joint value estimated by contingent questionnaire asking individuals what will be their willingness to pay for maintaining, in a given natural area, its actual option and existence nonmarket goods and services. It also relates to the conservation status of species, that is, their level of threat in the ecosystem (e.g., endangered, vulnerable, critically endangered), as defined by organizations, such as the International Union for the Conservation of Nature.

contingent valuation survey. A technique for the valuation of nonmarket goods and services. Usually relies on questionnaires to estimate the willingness of respondents to pay for consuming nonmarket goods or services, or willingness to accept compensation in the case of a loss in consumption of nonmarket goods or services.

convergent evolution. The independent acquisition of similar (analogous) structures (e.g., corky bark) in unrelated phylogenetic groups (i.e., unrelated species in distinct evolutionary lines). Convergent evolution is thought to be the result of similar selection pressures acting on the different groups.

cost–benefit analysis. Economic tool applied to public or private investment decision making that attempts to quantify and compare, in monetary terms, the present discounted value of the future benefits and costs associated with a particular investment project. This usually entails the use of a discount rate.

cutting. A portion of stem, root, or leaf cut from the parent or stock plant and induced to form roots and shoots by chemical, mechanical, or environmental manipulation.

decalcification. Removal of calcium carbonate or calcium ions from the soil by leaching (e.g., by the rain).

dehesa. Spanish term for savanna-like open oak (including cork oak) **woodlands** maintained by humans (often grazed by livestock or cropped).

discounting. Method used to determine the current monetary value of an investment or a project's future costs and benefits by weighting monetary values that occur in the future by a value less than 1 (the **discount rate**). Generally, following human nature, progressively lower numerical values are assigned to both benefits and costs the further into the future they are expected to occur.

discount rate. The interest rate or rate of profitability that an owner or investor expects to obtain from a given investment in a given period, usually one year, and usually in the context of a long-term investment project cycle.

dolomite. A sedimentary rock rich in Mg, typically composed by more than 50% of the mineral calcium magnesium carbonate ($CaMg(CO_3)_2$). See **limestone** for comparison.

douar. An administrative entity in several North African countries that refers to a village compound with a certain number of households that share a territory.

ecosystem respiration. Corresponds to the sum of plant respiration with the respiration of ecosystem animals and microorganisms, especially those of the soil.

ectomycorrhiza (ECM). Mycorrhizal structure generated by ectomycorrhizal fungi, which build a hyphal sheath enclosing the rootlet and usually do not penetrate the cell wall. Hyphae or mycelial strands (or rhizomorphs) radiate outward from the sheath to the soil. Hyphae also penetrate inward between the cells of the roots to form an intercellular network, the so-called Hartig net. Involve essentially fungi belonging to the Basidiomycetes and Ascomycetes; hosts are woody, long-lived plants.

embolism. Blockage in the movement of materials in a tube or conduit. In the case of **xylem,** embolism results from permanent air bubbles (emboli) caused by **cavitation.** A tree dies when xylem embolism extends irreversibly to the main stem.

endophyte. An organism that lives within a plant for at least part of its life cycle without causing apparent disease.

entomopathogen. Agents causing disease in insects, such as fungi, viruses, and bacteria.

epicormic. Shoots developing on the trunk or branches of a tree from dormant or adventitious buds.

epicormic buds. Dormant vegetative buds embedded beneath the bark that have a regenerative function after crown destruction, for example by fire.

ericoid mycorrhiza (ERM). Endomycorrhiza quite similar to **arbuscular mycorrhiza,** except it is generated in plants of the Ericales, and it forms coils into the periplasm. Ericoid fungi belong to the Ascomycetes.

exchange price. The unitary value of a good or service that is observed in the market.

existence value. Sometimes called nonuse or **passive use value,** reflects individual users' willingness to pay to ensure the future existence of a good or service, independently of its current use.

forage unit (FU). Represents 2,723 kilocalories of metabolic energy, the amount of energy contained in a kilogram of barley with 14.1% humidity.

forest reproductive material (FRM). Seeds (cones, fruits, and seeds) and vegetative parts of trees intended for the production of plants, as well as plants raised by means of seeds or vegetative parts.

grazing rent. Landowner revenues derived from livestock grazing and consumption of the sum of **forage units** available on a given piece of land.

gross primary productivity (GPP). The amount of carbon (energy) assimilated by photosynthesis per unit of land area and unit of time.

heterozygosity. The occurrence of a minimum of two alleles at a locus (gene).

Hicksian income. Total or maximum sustainable income (e.g., of a cork oak woodland), that is, the monetary flow (real or simulated) generated in a given period (one year) that, even when totally spent, leaves the capital value intact and thus leaves the landowner and society with the same **total economic value** for the **woodland,** in real terms, in absence of new discoveries and net transfers from outside.

hydraulic conductance (and conductivity). A measure of the ease with which liquid water can be transported. Root hydraulic conductances, normalized on the basis of root length, have been called root hydraulic conductivities (Augé 2001).

hydraulic lift. Passive mechanism occurring during the night when plant stomata are closed, redistributing water through plant roots from deep soil horizons, with high soil water potential, to shallower soil horizons, with lower soil water potential.

income at factor costs. Incomes that are estimated considering operating subsidies and taxes on products.

income at market prices. Incomes that are estimated without considering operating subsidies and taxes on products.

introgression. The occurrence of DNA that belongs to a specific species and is observed in another species.

isohydric. Isohydric species control stomata so that daytime minimum leaf **water potential** never falls below a species-specific minimum value despite differences in soil water potential. Most temperate woody plants are isohydric or nearly so.

isoprenoid. Characterizes a family of chemical compounds produced naturally by specific plant species (trees) under high temperatures to protect photosynthesis activity.

isozymes. Enzymes that play the same metabolic role.

labor cost or labor income. Compensation paid to a hired worker (employee) or household worker (self-employed) for services rendered. Includes landowners' and workers' social services payments.

leaching. Movement of soluble materials to lower parts of the soil profile.

leaf area index (LAI). Area of leaves per unit area of ground surface of a plant community or stand.

leaf water potential (Ψ). Determination of water deficit in leaves, measured with a "pressure bomb" or by psychrometric methods. In the continuum or nexus of soil–plant–atmosphere, water moves from higher potentials to lower (more negative) potentials.

lenticel-associated tissue. The tissue that contours and gives rise to lenticel channels.

limestone. A **carbonate** sedimentary rock composed of more than 50% of the mineral calcium carbonate ($CaCO_3$).

lysimeter. A device for measuring, under controlled conditions, percolation and **leaching** losses from a column of soil and soil–root interactions in plants.

marginal cost. Increase in total cost that arises when the quantity produced of a good or service increases by one unit.

market accounting residual value. A good or service value that results from market output minus cost. Often used for valuing nonmarketed intermediate and final goods. In the Iteimia case study (Chapter 14), the grazing rent measures the marginal product of nonpriced productive grazed **forage units** by subtracting all other estimated livestock costs of production (including self-employed labor cost) from total value of livestock output.

masting. Strong interannual variability in seed production, including some high seed-producing years (the mast year) and other low seed-producing years.

mesic. Habitat with moderate or well-balanced availability of water.

mesophytic. Said of a land plant that grows in an environment having a moderate amount of moisture (i.e., a mesophyte).

microsatellites. DNA variation corresponding to multiple repetitions of the same short nucleotide sequence.

montado. Portuguese term for cork oak **woodlands,** also used for holm oak or mixed evergreen oak woodlands, typically maintained by humans (often grazed by livestock or cropped).

mulch. Materials, such as cereal straw, wood chips, and bark, that are loosely spread on the soil surface to modify soil microclimate and control weed growth.

mycorrhiza. From *mukès* (= "fungus") + *rhiza* (= "root"). This organ is formed by the connection of fungal hyphae and plant root.

mycorrhizal symbiosis. Mutualistic association between a soil fungus and a plant root in which plant photosynthates are exchanged for mineral resources acquired by the fungus from the soil. In other words, the fungi facilitate the absorption of nutrients from soil by plant roots, while the fungal symbiont obtains organic C as a recent photosynthate from the plant (Smith and Read 1997).

net ecosystem CO_2 production (NEP). Net ecosystem productivity (in mass of carbon stored per unit of land area and unit of time) is the difference between the assimilation of CO_2 (photosynthesis) and the losses of carbon associated with the total **ecosystem respiration.**

option value. Individual's willingness to pay for the future provision of an economic good or service (or a single natural site) in hopes that the individual will use it later. In some cases, individuals make no clear distinction between option and **existence values,** and for these situations they estimate a joint **conservation value.** The latter includes the sum of option and existence values.

organellar. Refers to the nuclear genome present in cell cytoplasm.

osmotic adjustment. Active accumulation of solutes in plant cells, resulting in a decrease in osmotic potential and increased ability for water uptake.

pascolo arbolato. "Wooded grasslands," in Italian.

passive restoration. The process of assisting the recovery of a degraded ecosystem through influencing or piloting natural processes like enhancing seed dispersal or seedling survival, or reducing predation.

passive use value. See **existence value.**

phelloderm. A layer of green parenchymatous cells formed on the inner side of the **phellogen.**

phellogen or **cork cambium.** The growth tissue (meristem) that produces cork to the outside (centrifugal manner) and phelloderm to the inside (centripetal manner).

phenology. The periodic phenomena of life cycle events, often related to climate, especially seasonal changes.

photoinhibition. Inhibition of photosynthesis caused by excessive radiance.

photoprotection. Biochemical mechanisms developed by plants to avoid the hazardous effects of excessive radiance.

photosynthetic capacity. Measure of plant's capacity to fix carbon.

phylogeography. Geographic distribution of variants that are ordered according to evolutionary time.

planting stock. Collection of seedlings with the same seed origin and the same nursery management techniques. Plants raised from seed or from vegetative tissues.

polymerase chain reaction (PCR). A DNA amplification process using a polymerase.

polyphosphate. Polymer of orthophosphate ($H_2PO_4^-$, HPO_4^{2-}, PO_4^{3-}), including energetically rich acid anhydride bonds between P and O atoms.

population. Usually a collection of individuals of a given species from a limited area that have a certain degree of adaptedness to that area.

private amenity. Includes unpriced recreation and **conservation values** that landowners are willing to pay for. In the case of an Iberian Peninsula private cork oak **woodland,** the private amenity value is internalized as a market value component.

public amenity. Benefit received from a public good. Includes unpriced recreation and **conservation values** that the public is willing to pay for. In the case of Iberian Peninsula cork oak woodlands, the public amenity usually is supplied free to citizens and is financed by government expenditures.

regeneration. Regrowth of lost or destroyed parts or organs. Usually applied to the regrowth of plants or communities after disturbance by natural means.

region of provenance. For a species or subspecies, the area or group of areas showing uniform ecological conditions, such that stands or seed sources show—or can be expected to show—similar phenotypic or genetic characteristics.

relative growth rate (RGR). The increment of seedling biomass per unit of biomass and time. Commonly estimated as $RGR = [\ln(Wt) - \ln(W0)]/t$, where Wt and $W0$ are morphometric measures at time 0 and time t, and t is the elapsed time.

Reserva Agrícola Nacional (RAN). Agricultural National Reserve. According to the Portugese law, the use of the land included in this category cannot be changed.

Reserva Ecológica Nacional (REN). Ecological National Reserve. According to the Portugese law, the land included in this category is subject to specific rules about its use in order to provide certain ecosystem services.

restriction fragment length polymorphisms (RFLPs). RFLP is obtained by cutting DNA at specific sites using endonucleases (restriction enzymes) into fragments. Fragment size varies according to DNA variation.

rhizosphere. Narrow zone of soil influenced by living roots, as manifested by the leakage and exudation of substances that affect microbial activity.

root growth potential (RGP). The capacity of seedlings to develop new roots in a given period of time; it is usually tested during a short period of time (one to four weeks) under controlled environmental conditions and non-limiting water and nutrient availability. It is often related to seedling vitality and performance.

saprobic fungi. Fungi that gain nutrients, especially carbon, from dead or decaying organic matter.

sclerophylly. Plants that have small, hard, thickened leaves, with a short distance along the stem between the leaves (short internodes). Sclerophyllous plants are often from dry areas. The word *scherophyll* means "hard leaf" in Greek.

self-employed labor income. An income estimated as a **market accounting residual value** from different household and woodland uses and the costs afforded by household workers for these specific uses.

society-tolerable cost. Highest government expenditures to avoid an irreversible loss in a given natural area that current generations will accept in order to maintain known and unknown natural life support services for future generations.

stomate (plural: stomata). An opening defined by a pair of guard cells that controls gas exchange and water loss. They are located mostly on the leaf surface.

suberized. Deposition of a specific cell wall component, suberin, as in cork (phellem) or in endodermal and exodermal cells of roots. Suberin is characterized by the deposition of both polyphenolic and polyaliphatic domains and, like cutin and associated waxes, forms a barrier between the plant and its environment.

synthetic cork deflator. International price index of cork products, with a base set at 100 in 2000. It was calculated (Zapata 2006) as the average of Laspeyres, Paasche, and Fisher's indexes of unitary values of production and exports from Portugal and Spain and of the United Kingdom's imports of three representative products: raw cork, cork planks, and natural cork stoppers.

thermotherapy. The use of high temperature to control seedborne diseases. Preventive treatment against fungi (e.g., *Ciboria batschiana*) and insects (e.g., *Curculio elephas*) by submerging acorns in warm water (41–44°C) for two hours.

total economic value. Valuation criteria that show why people might attach a value to scarce things when they are consumed actively (direct, indirect, and **option values**) or passively (**existence value**). It measures the sum of active use plus **passive use values.**

transshumance. Transfer of livestock from one grazing ground to another, as from lowlands to highlands, with the changing of seasons.

water use efficiency (WUE). At a growing season time scale, it is generally calculated as the ratio of the aboveground (or aboveground plus belowground) dry biomass gain observed during this period and the corresponding amount of transpirated water. At an instantaneous time scale, it is calculated as the net photosynthesis/transpiration rate ratio. Intrinsic WUE is the ratio of net assimilation and **stomatal** conductance.

woodland. A plant community dominated by broad-leaved trees but with a lower tree density (or **canopy** projection) than forests. Typically, the open areas between trees bear grasses, forbs, and shrubs unless they are removed by plowing, burning, or overgrazing. *Dehesas*, in Spanish, also called *montados* in Portuguese, are a type of anthropogenic woodland or savanna whose origin is tied to human use rather than to natural processes.

xylem. The water-conducting tissue of plants composed of tracheids, vessels, fibers, and parenchymal cells. Xylem constitutes the stem wood, transports water and minerals up the stem, and provides structural support.

xylem vulnerability. The likelihood of xylem being severely affected by environmental stress, namely drought, in its ability to conduct water. Because water deficits may cause **embolism** in the xylem conduits, it may be measured in terms of the plant tissue water potential at which 50% of the wood **hydraulic conductance** is lost, as compared with an unimpaired condition.

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SCIENCE I ECOLOGY

THE SCIENCE AND PRACTICE OF ECOLOGICAL RESTORATION

Advance praise for *Cork Oak Woodlands on the Edge*

"This book brings together the best of the ecological and social sciences to assess the condition of an iconic ecosystem of the western Mediterranean world, with results as useful and beautiful as the cork oak itself."

—J. R. McNeill, Georgetown University, author of *Something New Under the Sun*

"Cork oak forests have coevolved with human societies for thousands of years; they support the livelihoods of millions of people and are a key component of treasured Mediterranean landscapes, but the pressures on these forests have never been greater. This scholarly work offers a wealth of knowledge on the management and restoration of a critical forest system and contains much of significance to those concerned with our relationship to all forests worldwide."

—Jeff Sayer, science advisor, IUCN

"*Cork Oak Woodlands on the Edge* provides a broad introduction to a vanishing cultural landscape. Cork oak woodlands are rich in species and also in traditional knowledge and lessons for understanding and coping with global change."

—Fernando Valladares, Instituto de Recursos Naturales, CSIC, and Rey Juan Carlos University, Madrid

"This comprehensive account of Mediterranean cork oak trees and the cultural landscapes they have dominated for millennia reveals much about ecology, management, history, and culture. The contributors represent an international group of researchers and managers engaged in exploring and restoring these emblematic ecosystems."

—Francis E. Putz, Department of Biology, University of Florida

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