

Research

Oak Persistence in Mediterranean Landscapes: The Combined Role of Management, Topography, and Wildfires

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ABSTRACT. Mediterranean ecosystems have been shaped by a history of human and ecological disturbances. Understanding the dynamics of these social-ecological systems requires an understanding of how human and ecological factors interact. In this study, we assess the combined role of management practices and biophysical variables, i.e., wildfire and topography, to explain patterns of tree persistence in a cork oak (*Quercus suber* L.) landscape of southern Portugal. We used face-to-face interviews with landowners to identify the management practices and the incentives that motivated them. We used aerial photographs and a Geographic Information System (GIS) to classify vegetation patch-type transitions over a period of 45 years (1958-2002) and logistic regression to explain such changes based on management and biophysical factors. The best model explaining vegetation transitions leading to cork oak persistence in the landscape included both biophysical and management variables. Tree persistence was more likely to occur on steeper slopes, in the absence of wildfires, and in the absence of understory management. We identified ecological, ideological, and economical barriers that preclude oak persistence and that are important to consider in implementing efficient environmental policies for adequate conservation and reforestation programs of Mediterranean cork oak landscapes.

Key Words: *agroforestry system; alternative ecosystem state; Cistus ladanifer; land degradation; Mediterranean; Portugal; shrub encroachment; succession; Quercus suber; vegetation transition*

INTRODUCTION

Mediterranean landscapes have long been shaped by a history of human management and natural disturbances (Aschmann 1973, Trabaud 1981, Conacher and Sala 1998). Understanding the dynamics of these ecosystems requires an understanding of how social and ecological factors interact, and how these interactions change over time (Lambin 2005, Perz 2007, Plieninger and Schaar 2008).

Since the 1960s, major socioeconomic changes in Mediterranean Europe have led to a gradual abandonment of traditional agriculture and stimulated rural exodus (Joffre et al. 1991, Pinto-Correia 2000). Abandoned farmland was colonized by shrub and tree species, and a natural succession process from fallow to forest was observed in many locations (Mazzoleni et al. 2004). In the drier southernmost regions, however, succession appears

arrested in early pioneer stages (Acácio et al. 2007, 2009, Costa et al. 2009).

The southwestern Iberian Peninsula has been shaped by a traditional agroforestry land use system where cork oak (*Quercus suber* L.), Holm oak (*Quercus ilex* L.), or a mixture of both, coexist with pastures and crops. The rural exodus of 50 years ago eliminated land ploughing and reduced herbivory in the understory of the oak savannas and forests (Pinto-Correia and Mascarenhas 1999, Alves et al. 2003, Pinto-Correia and Vos 2004). In the absence of human management, the usual pathway of natural succession in these agroforestry oak systems involves the gradual colonization of the understory by shrub species, i.e., pioneer *Cistus* shrubs, followed by other shrub communities like *Arbutus* and *Erica*, mixed with oak natural regeneration, which eventually can lead to forest recovery (Natividade 1950, Gonçalves 1991). However, several studies have reported decreasing oak density

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(Ferreira 2000, Vicente and Alés 2006, Vallejo et al. 2009), high oak seedling mortality (Direcção Geral das Florestas 1990, Montero et al. 1994), and lack of tree regeneration both in oak-dominated patches (Campos et al. 1998, Montero et al. 2000, Pulido and Díaz 2005), as well as in shrubland patches (Pons and Pausas 2006, Pausas et al. 2006).

Previous work in southern Portugal found that shrublands have expanded during the last 45 years at the expense of other vegetation patch-types, such as oak savannas and forests, particularly on southern slopes (Acácio et al. 2009). Although oak recruitment was observed in the years following the abandonment of agriculture and pastures, shrub encroachment progressed fast. In fact, since 1985 cork oak savannas and forests have been turning into shrublands at an increasing rate (Acácio et al. 2009). Initial cork oak recruitment in old fields after abandonment, followed by shrub encroachment, has also been observed in eastern Spain (Pons and Pausas 2006). Shrub encroachment can limit tree recruitment through multiple ecological mechanisms affecting tree seed dispersal, germination, and seedling survival (Acácio et al. 2007), and it is particularly severe under drier conditions or with frequent fires (Acácio et al. 2009).

Persistence of early successional stages may be intrinsically related to management decisions affecting the ecological processes involved in succession. Clearing of large areas for agriculture and pastures may eliminate nurse shrubs that facilitate tree seedling recruitment; it may also eliminate suitable seed dispersal sites and affect the habitats of the animal species responsible for seed dispersal. Also, livestock grazing, the second most common land use, contributes directly to seed and seedling predation (Herrera 1995, Pulido and Díaz 2002, Gómez et al. 2003, Leiva and Fernández-Alés 2003), preventing forest recovery. Management actions may interact with ecological processes and amplify limitations for seedling establishment, slowing down or preventing the natural process of succession even after management actions have been reversed. Although there is some understanding of the ecological mechanisms responsible for patch persistence in Mediterranean ecosystems (Fuentes et al. 1984, Gonçalves 1991, Montero et al. 1994, Puigdefábregas and Mendizabal 1998, Segura et al. 1998, Holmgren et al. 2000, Holmgren 2002, Holmgren and Scheffer

2001, Acácio et al. 2007), and the social factors involved (Pinto-Correia and Jorge 1996, Mazzoleni et al. 2004), the ways in which ecological and social mechanisms interact remains poorly studied and practically unknown (Rindfuss et al. 2004, Lambin 2005, Perz 2007). We hypothesize that management variables can play an important role in explaining persistence of cork oak trees and that they interact with topography and wildfire occurrence to explain the condition of arrested succession documented in cork oak landscapes of the Iberian Peninsula.

In this study, we assess the combined role of management practices and biophysical variables in explaining cork oak persistence in a 45-year period (1958-2002) and relate management decisions with landowner's perceptions. This long time frame allows evaluating tree persistence in a patchy landscape of forests, savannas, shrublands, and grasslands, where cork oak is the dominant tree species. We used a combination of aerial image analysis, databases with biophysical variables, and interviews with landowners to evaluate the role of ecological and management factors and the motivations behind local land management decisions.

METHODS

Study area

The study area covers 11,000 ha of the Serra do Caldeirão (37° 14' N, 7° 56' W), a mountain ridge in the northeastern part of the Algarve province in southern Portugal. The climate is Mediterranean, with average annual temperature of 16.6°C (São Brás de Alportel meteorological station, INMG for the period 1958-1976, and SNIRHa for the period 1980-2002), and average annual precipitation of approximately 900 mm (Barranco do Velho udometric station, INMG for the period 1958-1988, and SNIRHb for the period 1989-2002). Altitudes range from 146 to 588 meters above sea level. Predominant soil type is schist lithosols (SROA 1970). Soils are shallow, with a topsoil of approximately 15 cm, low fertility, and prone to erosion. Cork oak is the dominant tree species. This study area is one of the most continuous remnants of the southern Mediterranean cork oak landscapes of the Iberian Peninsula.

Historical background

Before the 15th century, southern Portugal was covered with cork oak forests, which were mainly used by kings and nobility to hunt large game, for firewood, and for extensive grazing. Between the 15th and the 17th centuries, the cork oak area in Portugal diminished substantially because of an increasing demand for wood for shipbuilding, agricultural land, and pastures. Cork began to be used for bottling wine after the 17th century, acquiring an increasing commercial value. From the 18th century onward, cork oak forests were gradually transformed into an agroforestry system exploited for cork, crops, and pastures (Mendes 2007). It is likely that the management of such agroforestry systems throughout the centuries also included protection of oak natural regeneration and artificial seeding or planting, to maintain cork production (Capelo and Catry 2007).

In the first half of the 20th century, traditional management of cork oak systems in the Iberian Peninsula included cork extraction, extensive grazing by pigs and sheep, and crop production. Shrub clearing and other land operations were done by manual labor and trees were exploited in uneven-aged stands for natural regeneration (Soares et al. 1998). From 1929 until the beginning of the 1960s, most of the land in southern Portugal was cultivated for wheat, following a government policy known as The Wheat Campaign that strongly subsidized wheat production (Baptista 1993). During the 1950s, wheat cultivation expanded to less suitable lands with poor and shallow soils, such as oak forest lands, which tend to be more vulnerable to the detrimental effects of intensive cereal cultivation (Baptista 1993). At that time, most of the cork oak area in southern Portugal was exploited as an agroforestry system for cork, grazing, and cropping. The age-structure of stands included older trees from the 19th century and younger trees that had been planted at the onset of the 20th century, when large reforestation projects with cork oak took place in the south (Costa and Pereira 2007). Decades of The Wheat Campaign led to soil exhaustion (Pinto-Correia and Vos 2004), elimination of cork oak natural regeneration, and the felling of many adult trees for cereal cultivation (Mendes 2007). Only forest areas located on steep slopes were not utilized as an agroforestry system because steepness made understory management for crop cultivation difficult or impossible.

Between the 1960s and 1970s, the country's agricultural working population decreased by about one third (Baptista 1993) because of important national and international socioeconomic changes, i.e., industrialization, immigration to cities, and emigration. After 1975, understory use had already been abandoned in the least productive lands and smaller properties in southern Portugal, including our study area, and cork was maintained as the single production component (Pinto-Correia and Mascarenhas 1999). At present, agriculture in our study area is only practiced for local family subsistence around the few scattered settlements and livestock has been reduced to only a few flocks of goats and sheep, approximately 500 animals, feeding mainly on fallow lands and shrublands (Pires 2000). Land holdings within the area are very fragmented and all under private tenure. Cork extraction is currently the main economic activity of the region, because it is the major economic asset of cork oak lands (Pereira 2007).

Management and social variables

Management and social data were derived from face-to-face interviews carried out by a single interviewer with local landowners. Landowners were defined as proprietors of the land although they may not necessarily live in the study area. Because there is no available landowner data for this region of Portugal, we selected landowners to be interviewed from the registration system of the Association of Forest Producers of Serra do Caldeirão (AFPSC). We were able to contact 20 landowners owning 31 parcels. This landowner sample is representative for the study region, because it includes about 20% of all members of AFPSC, who own about 10% of the land throughout the whole study area, according to data from AFPSC. The interviews included a combination of open-ended, qualitative questions along with closed, structured questions. Interviews were grouped in three main categories, each with questions covering several variables:

1. Land management between 1958 and 2002, using the following variables: 1) understory management, i.e., crops cultivation and/or livestock; 2) total livestock units; 3) livestock composition; 4) cutting adult cork oak trees; 5) shrub clearing; and 6) investments in land, including cork oak planting.

2. Landowner profile, using the following variables: 1) age; 2) level of education; 3) type of management decisions, i.e., decisions made by owner or others; and 4) profession.
3. Individual perceptions: 1) factors related with forest cover change, using closed questions on cork oak natural regeneration and shrub encroachment, and open-ended questions on erosion, cork oak mortality, and wildfires; 2) open-ended questions on the main problems faced in local forest management; and 3) open-ended questions on what is missing for local forest management.

It is well known that when questions refer to an event that occurred long in the past, interviewees may not accurately recall their motivations and decisions and may even be confused as to which management strategy was implemented in each parcel (Rindfuss et al. 2004). To account for this, national historical events, such as elections of certain governments, etc., were used as dates to help the landowner remember the past management practices and circumstances around it. Therefore, the years 1975 and 1985 were used as key years to detect management changes because 1975 was the first year following the revolution that ended the dictatorship period in the country and also marked the end of the land abandonment period. Also, 1985 was an important political year followed by the adhesion of Portugal to the European Economic Community, today's European Union (EU), in 1986, with important land management changes. Management variables were derived from subquestions relating to the respective time periods and answers showed that management changes coincided within these specific periods for most of the farmers.

From the initial six land management variables (category 1), we derived a set of three variables summarizing the more relevant information for assessing vegetation patch-type transitions:

1) understory management before 1975; 2) tree cutting after 1975; 3) tree planting after 1985. Understory management existed only for the period before 1975. For all parcels except one, owners stopped understory use for livestock or crops after 1975. Understory management before 1975 was positively associated with the presence of livestock ($\chi^2 = 10.2$, $P = 0.0014$), and this latter variable

resulted from a combination of the variables total livestock units and livestock composition, which were therefore excluded from further analysis. Understory management before 1975 was also positively associated with the variable shrub clearing ($\chi^2 = 21.6$, $P < 0.001$), so the latter variable was excluded from further analysis.

For all types of investments in land, such as acquiring machinery and equipment, pruning trees, improving forest road networks, and building water points, tree planting and cutting were the ones that had a higher visible impact in forest cover changes. Tree planting only took place after 1985 following EU subsidies. Adult cork oak trees were only cut after 1975 because of mortality.

Collection of data on vegetation patch-type transitions

Vegetation patch-type transitions were characterized using aerial photographs from 1958 and orthophotos, i.e., a rectified copy of an original aerial photograph, from 2002, thus covering a 45-year period. Aerial photographs were previously scanned and then orthorectified and georeferenced with ENVI 3.4 (Research Systems 2001) to produce geometrically correct images and project them onto the same coordinate references as the digital orthophotos (Transverse Mercator projection, datum WGS84). Digital elevation models with a spatial resolution of eight meters were used for altitude coordinates (orthorectification process), and between 10 and 15 ground control points per photo were taken from the 2002-orthophoto for map coordinates (georeferentiation process). We obtained a RMS Error of about 10 meters. We overlaid a regular 0.5 x 0.5 km grid of points over the entire study area, and selected all the points that were contained inside the parcels of the landowners who were interviewed. We selected 35 points from the 31 parcels (larger properties had more than one point) and photo interpreted on screen a 50 m-radius circle (sampling unit) around each photographic point. Photo interpretation was performed on a photo-by-photo basis. The grid was created with ArcView GIS 3.2 (Environmental Systems Research Institute 1999) and laid over the aerial photographs and orthophotos (imported into the GIS as scanned images). For 1958 and 2002, each of the 35 sampling units was classified into one of four vegetation patch-types (Table 1).

When more than one vegetation patch-type occurred in a sampling unit, it was classified based on the predominant type. Sampling units with only one kind of patch-type were predominant (>50% of the total units) and when not, we could usually clearly assign one dominant class to each unit. We used tree cover percentage rather than tree density because in many cases it was not possible to count the number of trees on the photographs. Boundaries for forest cover (10% and 30% of ground cover) follow the National Forest Inventory norms (Direcção Geral das Florestas 2001).

Before photo classification (2003) we visited the study area several times to familiarize ourselves with the different vegetation types and compare them with the patterns on the aerial photos of 2002. We estimated transitions between vegetation patch-types by counting the number of sampling units of any vegetation patch-type that changed into any other between 1958 and 2002. Vegetation changes where there was maintenance or increase in tree cover were registered as presence of cork oak persistence; whereas patch-type transitions toward absence or decrease in tree cover were registered as absence of cork oak persistence (Table 2).

Biophysical variables

Three environmental variables were registered: slope, exposure, and wildfire occurrence. Slope determines soil depth and erosion risk, which in turn affect tree growth and survival. The exposure of a slope determines the amount of incident irradiance and therefore is strongly correlated with plant water stress, e.g., southern exposures are drier, and often plant survival. Wildfire directly affects tree and seedling mortality and indirectly influences several ecological processes involved in tree seedling recruitment and vegetation succession.

The topographical variables, slope and exposure, were derived from digital elevation models (Portuguese Military Geographic Institute, IGeoE) and stored as two ArcView GIS layers. We assigned one class of slope and exposure to each sampling unit based on the most common type. The slope categories were: low to medium (0-20%); steep (20-30%); very steep (>30 %). The exposure categories were: north facing slopes (including NW, N, and NE), south facing slopes (including SW, S, and SE) and others (E and W). Wildfire occurrence was available as spatially referenced and digitized

data for every year between 1984 and 2002 (provided by the Tropical Research Institute for 1984-1989 *unpublished data*, and by the General Directorate of Forests for 1990-2002, <http://www.afn.min-agricultura.pt/portal/dudf/cartografia/cartografareas-ardidas-1990-2009>). The limits of the burned area per year were stored as an ArcView GIS layer and overlaid with the sampling units to identify the sampling units that were affected by fire between 1984 and 2002. The maximum number of times a unit was affected by fire in this period was two.

Statistical analyses

Logistic regression (Hosmer and Lemeshow 2000) was used to model the influence of biophysical and management variables on oak tree persistence (coded as 1=presence/0=absence) during the period 1958-2002. Because of the small sample size in the lower slope class, only 2 slope categories were considered, $\leq 30\%$ and $>30\%$. Exposure and wildfire were also considered as categorical variables.

To assess the relative importance of biophysical and management variables on the probability of cork oak persistence, we used an Information Theoretical Approach (ITA; Burnham and Anderson 2002). The ITA looks for simplicity and parsimony of several working hypotheses and is based on finding the strength of evidence of each model, for a set of candidate predictive models. The AIC adjusted for small samples (AIC_c) was used as a measure of information loss of each candidate model, with the best fitting model having the lowest AIC_c and the highest Akaike weight (w_i). The latter measures the relative likelihood that a given model is the best one, given the data and the set of competing candidate models. AIC_c differences (Δ_i) between each model and the model with the smaller AIC (AIC_{min}) can be used to assess the relative support for the different alternative models (Burnham and Anderson 2002, Rushton et al. 2004).

To avoid overfitting and finding spurious effects when working with small sample sizes, the number of candidate models should be small (Anderson 2008). Thus, we used stepwise regression as a way of keeping the number of candidate models low, relative to our sample size, prior to the ITA evaluation. In this sense, we did not use null hypothesis testing to compare models, but we used it to restrict the number of candidate models in our set to be evaluated by the IT approach. Overall, we

Table. 1 Classification of vegetation patch-types.

Vegetation patch-type	Description
Cork oak forests	High cork oak (<i>Quercus suber</i> L.) density (more than 100-150 trees/ha) and a diverse shrubby layer, e.g., <i>Arbutus unedo</i> , <i>Viburnum tinus</i> , <i>Erica arborea</i> , <i>Pistacia lentiscus</i> , <i>Rhamnus alaternus</i> , <i>Phillyrea latifolia</i> ; this class corresponds to a tree cover higher than 30%
Cork oak savannas	Low cork oak density (less than 100 trees/ha) with sparse shrubs in the understory; this class corresponds to a tree cover between 10% and 30%
Shrublands	Dominated by <i>Cistus ladanifer</i> shrubs, pure or mixed with <i>Ulex argenteus</i> , <i>Genista hirsuta</i> , and <i>Lavandula stoechas</i> shrubs; this class corresponds to a tree cover lower than 10%
Grasslands	Dominated by cultivated croplands, semi-natural pastures, or fallow land; this class corresponds to a tree cover lower than 10%

built 12 models: a) separate models for each of the predictor variables (6 models); b) models for each set, i.e., biophysical and management, of variables (2 models); c) stepwise models, forward and backward stepwise selection yielded similar models, for each set (2 models); and d) stepwise models, forward and backward selection, pooling all 6 variables from both sets (2 models). The relative importance of each variable was estimated by summing the Akaike weights across all models that contained that variable (Burnham and Anderson 2002). Model fit and predictive performance of each model were evaluated through the likelihood ratio statistic (full model χ^2) and by calculating the area under the receiver operating characteristics (AUC) curve (Pearce and Ferrier 2000).

RESULTS

Land management and landowner's profile

Before 1975, most landowners used their lands as an agroforestry system for cork, pastures, and crops (70% of respondents at 26 sampling units). Herd sizes of mostly sheep and pigs varied between 50 and 100 animals per herd, which grazed on each landowner parcel, with an average parcel of 10 ha, but also throughout the study area. After 1975, adult dead trees were cut at 29 sampling units (about 80%

of total sampling units) and after 1985, cork oak tree planting was carried out at 14 sampling units (40% of all sampling units). All interviewees are responsible for the decisions and implementation of their own land management practices, however, only 10% work directly on the land, 50% are retired, and 40% have a different profession than land management. Most landowners were older than 60 years (60% of interviewees), and only one (5% of interviewees) was younger than 45 years old. Half of the interviewees had only a primary school education and 20% were college-educated.

Landowner's perceptions

Table 3 shows the frequency, i.e., number and percentage, of landowner responses regarding the main causes of soil erosion, tree mortality, and fire, changes in natural regeneration, and changes in shrubland cover since 1960. Table 4 shows direct quotations from landowners regarding difficulties and needs on local forest management.

For landowners, soil erosion was mostly caused by the use of disk harrowing, rippers, and heavy machinery (21.2%), followed by heavy rains. However, opposite reasons such as cereal cultivation in the past and lack of cereal cultivation were also pointed out as responsible for soil erosion

Table 2. Types of vegetation transitions (1958-2002) grouped into presence of cork oak (*Quercus suber* L.) persistence or absence of cork oak persistence (Fo: forest; Sa: savanna; Sr: shrubland; Gr: grassland)

Presence of cork oak persistence (maintenance or increase in tree cover)		Absence of cork oak persistence (absence or decrease in tree cover)	
Type of transition	% from the total sampling units classified as presence of oak persistence	Type of transition	% from the total sampling units classified as absence of oak persistence
Fo→Fo	48	Fo→Sr	33
Sa→Sa	13	Sa→Sr	17
Sa→Fo	13	Sa→Gr	8
Sr→Fo	9	Sr→Sr	17
Sr→Sa	4	Gr→Sr	17
Gr→Sa	13	Gr→Gr	8

(15.2% and 9.1% of total causes, respectively). We also found that 35% of interviewees perceived that soil erosion was not a problem at the study site. On the other hand, 7.7% of farmers perceived soil erosion as a cause of oak mortality (Table 3).

The landowners identified a long list of main causes to explain cork oak mortality but by far the most frequent one was disease (24.4% of all responses corresponding to 95% of all interviewees). The disease to which landowners are referring is the one caused by the fungi *Phytophthora cinnamomi*, which has been correlated with cork oak decline in several recent studies (Moreira and Martins 2005). Perhaps surprisingly, lack of traditional land use that combines wheat cultivation and livestock, was mentioned as the second most frequent cause of cork oak mortality (15.4% of all responses corresponding to 60% of interviewees). Landowners further explained that wheat cultivation and livestock provided fertilizers and manure to the soil, and the lack of such management is responsible for cork oak mortality today. Drought and management changes from traditional manual labor to the use of disk harrowing and heavy machinery are the two next most frequent responses for cork oak mortality (12.8% and 9%, respectively; Table 3).

Most interviewees (80%) considered that oak natural regeneration increased since 1960 after

understory cultivation ceased, whereas 20% of the interviewees stated that natural regeneration has decreased since that date (Table 3). Most landowners stated that they do not protect natural regeneration during silvicultural interventions such as shrub clearing, which can lead to the destruction of seedlings. Landowners also claimed that the use of inadequate techniques, such as bad terrain preparation and insufficient supervision during the first years, in planting were responsible for low seedling survival rates. Furthermore, during the course of the interviews, several landowners stated that direct oak seeding should be used instead of planting because it would allow higher seedling survival, but EU programs have only been subsidizing planting operations. Two of those landowners included seeding with selected acorns and subsidies for seeding when asked about “what is missing for local forest management” (see Table 4). Interestingly, most interviewees (80%) reported that *Cistus* shrublands have increased since 1960 and only one affirmed that shrubland area has decreased because of subsidized shrub clearing in the last decades. Three respondents stated that there were no changes in shrubland area (Table 3).

Cork oak mortality, including disease, and wildfires were pointed out as the two main difficulties for local forest management by 35% and 30% of all respondents, respectively (Table 4). Setting fire

Table 3. Landowner’s individual perceptions (frequency of responses). Total number of responses per question (in Q1, Q2, and Q3) is higher than number of interviewees (20) because each interviewee usually provided more than one response to each question.

Question asked	Response	Frequency of response	
		Number	%
<i>Q1. What are the main causes of soil erosion at the study area?</i> (open-ended)	Lack of fertilizer and lack of cereal cultivation	3	9.1
	Drought	5	15.2
	Cereal cultivation in the past	5	15.2
	Disk harrowing, use of rippers and heavy machinery	7	21.2
	Heavy rains	6	18.2
	Complete shrub clearing in steep terrains	2	6.1
	Decreasing tree density	1	3.0
	Wildfires	4	12.1
Total		33	100
<i>Q2. What are the main causes of cork oak mortality at the study area?</i> (open-ended)	Disease	19	24.4
	Drought	10	12.8
	Wildfires	5	6.4
	Complete shrub clearing	3	3.8
	Lack of traditional land use with wheat cultivation and livestock (lack of fertilizer and manure)	12	15.4
	Pesticides	1	1.3
	Disk harrowing and ploughing, shrub clearing with heavy machinery	7	9.0
	Less soil water	1	1.3
	Old age of cork oak trees	1	1.3
	Soil erosion	6	7.7
	Pollution	5	6.4
	Clayey soils	2	2.6
	Inadequate human management	6	7.7
Total		78	100
<i>Q3. What are the main causes of wildfires at the study area?</i> (open-ended)	Arson	19	52.8
	Lack of shrub clearing and fuel management	5	13.9
	Drought	3	8.3
	Lack of firemen capacity: bad coordination among firemen during combat; firemen lack forest fire fighting techniques and have bad knowledge of the terrain	5	13.9
	Negligence	2	5.6
	Accidents	2	5.6
	Total		36
<i>Q4. How did cork oak natural regeneration change since 1960?</i> (closed)	Increased	16	80.0
	Decreased	4	20
	Total	20	100
<i>Q5. How did shrubland area change since 1960?</i> (closed)	Increased	16	80.0
	Decreased	1	5.0
	No changes	3	15.0
	Total	20	100

Table 4. Management difficulties and needs identified by landowners. Table shows direct quotations from landowners.

Interview Number	Main difficulties for local forest management	What is missing?
1	Properties are too small to invest	Government subsidies
2	Topography of the landscape	More shrub clearing to prevent wildfires
3	Wildfires, cork oak disease	(no answer)
4	Wildfires, lack of machines, high costs of shrub clearing	Roads, machines, seeding with selected acorns, prescribed burning in the winter
5	Wildfires and disease	Manpower
6	Cork oak mortality, lack of cadastre, small property	Landowner cooperatives and concerted management, scientific research; environmental instruments are too rigid concerning fuel management
7	Cork oak mortality, long time for subsidies payment; acorn production has been decreasing	More communication between landowners and researchers, livestock to feed on the grass and shrubs (fuel management)
8	Wildfires	(no answer)
9	(no answer)	(no answer)
10	Lack of land profitability, land abandonment	(no answer)
11	Lack of land profitability, decreasing cork production because of disease	Compensations for restrictions from environmental instruments such as Natura 2000, cadastre
12	Bureaucracy (e.g., long time to get an authorization to cut a dead cork oak)	There are no subsidies for seeding, (which is more successful than plantations), landowners cooperatives, more decision making power for Associations of Forest Producers
13	Cork oak mortality (still without a cure for the disease), market competition with plastic stoppers	(no answer)
14	Lack of forest fire fighting techniques; too much bureaucracy for investments with subsidies and long time waiting for money	Subsidies for livestock (which is good for fuel management and fertilizing the soil); improvement of inspection
15	Cork oak mortality, decreasing cork production, money has to be invested before receiving subsidies	Find a cure for the cork oak disease
16	Cork oak mortality	Manpower, people working the land and living there
17	Land abandonment, lack of profitability of small landowners	Forest management, faster payment of subsidies and less bureaucracy
18	Small property and land fragmentation	Livestock for fuel management, landowners cooperatives, multiple-use forest management
19	Wildfires	Less taxes for managers and businesses; incite production
20	Wildfires	Landowner cooperation

intentionally was pointed out as the main reason for wildfires (52.8% of total responses), followed by lack of firemen capacity to fight forest fires and lack of fuel management (both with 13.9% of total responses; see Table 3). Bureaucracy, i.e., the long wait for subsidies payment and for authorization to cut a dead cork oak tree (20%), small property size, and lack of land profitability (both with 15%) were the next most frequent answers. Many other issues were quoted as problems for local forest management, including decreasing acorn and cork production, land abandonment, lack of cadastre, and market competition with plastic stoppers (Table 4).

Landowner cooperatives, subsidies for seeding, livestock, and compensation for restrictions from environmental programs, livestock for fuel management, manpower, and communication between researchers and landowners were quoted as the most important needs for local forest management (Table 4). Five landowners did not respond when asked about what is missing.

Determinants of tree persistence: management or biophysical variables?

Vegetation patch-type transitions indicating presence of tree persistence were observed at 23 sampling units (65.7% of all units) mostly because of persistence of forest and savannas (48% and 13% from the total sampling units registered as presence of oak persistence, respectively) and transitions from savannas to forests (13% from the total sampling units registered as presence of oak persistence). Vegetation patch-type transitions indicating absence of tree persistence were observed at 12 sampling units (34.3% of all units) mostly because of changes from forests, savannas, and grasslands to shrublands (33%, 17%, and 17% from the total sampling units registered as absence of oak persistence, respectively), and shrublands persistence (17% from the total sampling units registered as absence of oak persistence; see Table 2).

The best model for tree persistence, i.e., persistence of forest and savannas, transitions from any patch-type to forests, and transitions from shrublands and grasslands to savannas, during the period 1958-2002, included both biophysical, i.e., slope and wildfire, and management variables, i.e., understory management and tree planting, and had an Akaike weight of 0.76 (model 1 in Table 5).

According to Anderson (2008), models within Δ_i up to four have substantial support, thus the second model ($\Delta_i = 2.304$) is also considered an alternatively good fit to the data. This second model (Akaike weight of 0.24) is similar to the first one but with the exclusion of slope. All remaining models have much higher Δ_i and residual Akaike weights. The evidence for the first two models is expressed by summing their Akaike weights, showing that they represent an approximate 99% confidence set, i.e., we have 99% confidence that these two statistical models represent the best fit among the set of models compared. In these two models, wildfire occurrence, understory management before 1975, and cork oak planting were the most important variables. These three variables were equally important, each with an Akaike weight of 0.99. Slope followed in importance (Akaike weight = 0.76) whereas the remaining variables were not relevant for the models (Akaike weights <0.01). The two best models showed that cork oak persistence was more likely in areas where understory management, using livestock or cultivation, and cork oak plantings were never carried out, in steeper slopes and in the absence of wildfires (Table 5).

DISCUSSION

Cork oak persistence best explained by both management and biophysical variables

The analysis of alternative statistical models shows that cork oak persistence is better explained by models including both biophysical and management variables than by those based only on one set of variables alone. Previous work at the study area had identified two ecological variables, wildfire and exposure, as the two most important biophysical variables explaining patch-type transitions (Acácio et al. 2009). Our results now clearly demonstrate that vegetation changes are better explained by also taking management variables into account. Cork oaks are most likely to persist in areas where understory management, using livestock or cultivation, and cork oak plantings were never carried out, especially on steeper slopes and in the absence of wildfires. This indicates that management is a significant driver of vegetation change and a significant variable to explain patch-type transitions and tree persistence patterns in this Mediterranean landscape.

Table 5. Statistical models for tree persistence. For each model, the table shows the predictor variables entering the model (remaining variables did not enter), respective direction of association (positive + or negative -) with the response variable (presence of cork oak persistence), the AICc value, AICc differences (Δ_i) and Akaike weights (w_i), and model fit (full model χ^2) and area under curve ($AUC \pm s.e.$). Models are ordered by increasing Δ_i , with the best model having $\Delta_i=0$ (model 1) and the worst model having $\Delta_i=29.0$ (model 12). The type of model is also coded according to the method used: (a) separate models for each variable, (b) models for each set of biophysical and management variables, (c) stepwise models for each set of biophysical and management variables, (d) stepwise models with the whole set of variables. Codes for management variables: underst= understory management pre 1975; cuttree= tree cutting post 1975; afforest= tree planting post 1985.

Model	Variables						AIC _c	Δ_i	w_i	χ^2	AUC
	aspect	slope	fire	underst	cuttree	afforest					
1 d		+	-	-		-	22.618	0.000	0.759	34.45	0.98±0.019
2 d			-	-		-	24.922	2.304	0.240	29.41	0.95±0.035
3 c				-		-	37.062	14.444	0.001	14.71	0.83±0.069
4 b				-	-	-	38.583	15.965	0.000	15.75	0.85±0.066
5 c		+	-				39.933	17.315	0.000	11.84	0.80±0.084
6 a				-			40.265	17.647	0.000	9.11	0.69±0.087
7 a			-				41.612	18.994	0.000	7.76	0.73±0.097
8 a						-	43.947	21.329	0.000	5.43	0.70±0.096
9 b	-(S) [†]	+	-				44.481	21.863	0.000	12.59	0.81±0.080
10 a		+					45.902	23.284	0.000	3.47	0.66±0.100
11 a					-		48.278	25.660	0.000	1.01	0.56±0.100
12 a	-(S) [†]						51.661	29.043	0.000	0.12	0.52±0.103

[†] less probability of tree persistence in southern exposures

The role of management

The fact that tree persistence was found to be more likely in areas where understory management had not occurred in the past can be explained in several ways. In southern Portugal, decades of intensive wheat cultivation and grazing pressure under oak savannas and forests led to severe soil fertility loss, still evident today (Natividade 1950, Oliveira 1955, Gonçalves 1991, Pinto-Correia and Vos 2004). Agroforestry practices in southern Spain had similar

consequences (Montero et al. 1994). Intensive understory cultivation and grazing reduce perennial vegetation cover, increasing water and soil nutrients losses by water run-off and soil erosion that lead to soil degradation (Lima et al. 2000). Additionally, trampling by grazing herds causes soil compaction, which reduces water infiltration and further contributes to soil degradation (Pulido and Díaz 2002). Poor, degraded soils and higher insolation in nonvegetated sites make conditions for seedling establishment very difficult and thus halt tree

persistence and recruitment. These positive feedbacks can maintain semiarid ecosystems in persistent states of low biomass (Westoby et al. 1989, Rietkerk and van de Koppel 1997, Holmgren and Scheffer 2001).

We also found that absence of tree persistence and transitions toward shrublands were more likely where cork oak planting had taken place, which seems a contradictory result at a first glance. However, cork oak plantations in the Algarve province have registered very low survival rates, especially on drier southern exposures (Lima et al. 2000). Inadequate planting techniques have been pointed out as a major reason for poor seedling and sapling recruitment, such as inadequate terrain preparation and shrub management and poor monitoring during the first years (Lima et al. 2000). Also, the low genetic quality of the reproductive material used in many cork oak reforestation projects in Portugal has been identified as a contributing cause of low reforestation success (Almeida et al. 2006). In Spain, oak plantings also suffer from high mortality rates because of summer drought (Alloza and Vallejo 1999, Castro et al. 2002).

Furthermore, initial vegetation clearings for reforestation projects not only destroy existing seedlings but eliminate nurse plants that can facilitate seedling recruitment (Castro et al. 2002). As a result, unvegetated sites are quickly invaded by *Cistus* shrubs that compete with the remaining seedlings for soil water and nutrients, increasing oak mortality and subsequently decreasing tree persistence.

The role of biophysical variables

Cork oak persistence was most likely to occur in the absence of wildfires. Frequent fires or intense ones can kill adult cork oak trees especially when burning occurs immediately after cork extraction (Cabezudo et al. 1995, Pausas 1997, Moreira et al. 2007), which takes place in the summer months, coincident with the start of the wildfire season in Mediterranean Europe. Because the abandonment of traditional agroforestry led to shrub colonization and the accumulation of dead wood, former cork oak systems experienced an increase in wildfire hazard (Pausas and Vallejo 1999, Piussi and Farrell 2000, Pardini et al. 2004). Higher fire frequency increases the loss of soil fertility by accelerating erosion

(Pardini et al. 2004). Moreover, because colonizing *Cistus* shrubs are well adapted to very poor soils (Gonçalves 1991) and rely on fire to spread their seeds, this triggers the conditions for a positive feedback where cork oak recruitment is difficult and the system remains in an arrested early successional stage dominated by pyrophytic *Cistus* shrubs.

The best statistical model also shows that cork oak persistence was more likely to occur on steeper slopes, although slope presents a lower Akaike weight than understory management and wildfire. This is probably because on these slopes, forests were less vulnerable to human interventions, especially ploughing, which is practically impossible on very steep slopes.

Landowner's perceptions behind management decisions

From an ecological perspective, the landowners' perceptions on the ecological conditions of these systems and the mechanisms that explain them appear perhaps surprising: 15% of the landowners believe that the absence of traditional land use combining wheat cultivation and livestock is one of the main causes of oak mortality; 9% believe that the lack of wheat cultivation is in fact responsible for soil erosion; and 35% of them believe that soil erosion is not a problem.

Landowners are likely to have a landscape preference for agroforestry systems because this is the type of traditional landscape they perceive as appropriate and they may find it difficult to accept its transformation (Gómez-Limón and de Lucío Fernández 1999). Therefore, they deny the existence of a problem, such as soil erosion. This ideological barrier (Scheffer et al. 2000) can prevent landowners from choosing adequate management practices, such as adequate techniques for shrub clearing or protection of natural regeneration, which could certainly contribute to increase cork oak persistence in the study area.

Landowner behavior within the region is also conditioned by the perception that their holding is too small and that further improvement through investment would not pay dividends. On the other hand, some types of land operations are subsidized by the EU, which facilitates management actions that may not be appropriate. For instance, although landowners believe that seeding is the best method

for cork oak artificial reforestation, they chose to use planting operations instead because these are economically subsidized. In fact, subsidies are included on the list of needs for local forest management. Subsidies play an important role in management decisions and can contribute to further degradation of tree cover in some cases (Pinto-Correia and Vos 2004). In our statistical analysis, planting was a significant variable contributing to absence of tree persistence and was also identified by many landowners as a problem.

CONCLUSION

Our results show that the dynamics of Mediterranean landscapes are better understood as coupled social-ecological systems requiring an integrated approach that combines interdisciplinary tools from ecological and social sciences. We found that land management, i.e., intensive understory use and inadequate planting operations, in combination with biophysical factors, i.e., wildfire and slope, facilitated shrub encroachment and prevented tree persistence or recovery between 1958 and 2002. It is likely that oak savannas and forests lost resilience, as a result of past land uses damaging soil and vegetation, and are currently additionally threatened by more frequent wildfires. As a result, natural succession appears halted into a pioneer state dominated by *Cistus* shrublands where cork oak forest recovery can become very difficult even through assisted reforestation. Our study highlights a series of ecological, ideological, and economical barriers that contribute to this process. If the cork oak systems are to be maintained, forest regeneration should be stimulated by addressing those barriers in a concerted way.

Responses to this article can be read online at:
<http://www.ecologyandsociety.org/vol15/iss4/art40/responses/>

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