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The dehesa system of southern Spain and Portugal as a natural ecosystem mimic

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Abstract. The dehesas of the southwestern Iberian Peninsula are 'man-made' ecosystems characterised by a savannah-like physiognomy. The trees are viewed as an integrated part of the system, and as a result are planted, managed, and regularly pruned. Palynological and historical evidence of the manipulation of initial ecosystems by man to obtain a savannah-like ecosystem is presented. The ecological functions of the tree are detailed using results obtained at two complementary scales. At the local scale, strong soil structural differences and functional differences in water budget and patterns of water use are observed under and outside the tree canopy. Using the concept of ecosystem mimicry, the two coexistent components of dehesas can be compared to two distant stages of a secondary succession characterised by very different behaviours. At the regional scale, evidence of relationships between tree density and mean annual precipitation over more than 5000 km^2 suggests that the structure of these man-made agroecosystems have adjusted over the long-term and correspond to an optimal functional equilibrium based on the hydrological equilibrium hypothesis. Finally, the future of dehesas in the face of contemporary exogenous threats of economic and global environmental origin is discussed.

1. Introduction

Agroforestry systems occupy an important place in the Mediterranean Basin where they have influenced the landscape for many centuries. Despite the diversity of the ecological, economic and social conditions existing in these areas, it is possible to distinguish some of their features that are common to all such systems. Firstly, this involves the profound influence of rural history in shaping the landscape and vegetation in the Mediterranean region. The variety of land tenure and land management systems in these areas has led to the extreme diversity of agrosylvopastoral systems at the present day (Joffre et al., 1991). The second fundamental characteristic of these systems is that they have to cope with the high variability of the Mediterranean climate, in other words they reflect a capacity to adapt to natural conditions and to overcome unpredictability. In ecological terms, which are what interests us here, this is reflected in the adoption of different strategies of using the plant resources corresponding to the main growth-forms. For example, in many livestock systems, forage resources are not just composed of herbs, but include trees that are used not only as a resource in their own right but also as a regulator of hydrological stress for the underlying herbaceous stratum.

A very peculiar agroforestry system, named dehesa in Spain and montado in Portugal, dominates the landscape of the southwestern Iberian Peninsula (Joffre et al., 1988b; San Miguel, 1994; Gómez Guttierez and Pérez Fernández, 1996). Characterised by the presence of a savannah-like open tree layer, mainly dominated by Mediterranean evergreen oaks – holm oak (*Quercus ilex*) and cork oak (*Q. suber*) – and to a lesser extent by the deciduous *Q. pyrenaica* and *Q. faginea*, they occupy more than 5,800,000 ha in the western and south-western provinces of Spain, representing 52% of total utilised agrarian area within these province (Campos Palacin, 1992) and more than 500,000 ha in southern Portugal.

In this paper we present some complementary points of view dealing with the origin, the history, and the present functioning of these dehesa systems. It seems unquestionable that the dehesa is a man-made ecosystem and that its two layered structure, tree and grass, is dependent on human practices and management. Nevertheless, some characteristics, particularly tree density, seem partly controlled by edaphic and climatic resources. Many empirical studies conducted on tropical savannahs have emphasised the importance of water resources in regulating the balance between woody plants and herbaceous vegetation (see Joffre and Rambal, 1993; Scholes and Archer, 1997). From a theoretical point of view, Eagleson (1982) developed hypotheses on patterns of plant water use at various time-scales (see Hatton et al., 1997 for a comprehensive account) and demonstrated that where a marked seasonality in water availability occurs, a mixed formation of grasses and woody plants is the only stable equilibrium state. These ecological optimality hypotheses lead to the prediction of an optimum tree density that is stable with respect to perturbations and metastable with respect to climatic variability. The structure of dehesas mimics those of tropical savannahs. We hypothesise that this structure, particularly present tree density managed from a long-term perspective by the farmers, follows an ecohydrological equilibrium *sensu* Eagleson (Eagleson, 1982; Eagleson and Tellers, 1982) and could be interpreted as the result of an ecological optimality, the distribution of tree density being indicative of its control by water availability.

2. Some definitions and key-characteristics

The Spanish term dehesa, the equivalent of the Portuguese montado, depicts both a landscape and a type of land use in the Iberian Peninsula. A brief history of the word dehesa in relation to changes in land utilisation will be given in section 4. Today, the dehesa can be defined as a multi-purpose agroforestry system with scattered oak trees planted by man (Joffre et al., 1988b).

The traditional system was highly diversified in terms of livestock types (sheep, goats, Iberian pigs, and cattle). Recent changes, since 1965, have led to an increase of cattle and decrease in sheep production (Joffre et al., 1988b). Pigs graze the seasonal acorn production, between October and February,

gaining about 60 kg live weight during 75 days. Ruperez (1957) reported that 9 kg of *Q. ilex* acorns corresponds to the production of 1 kg of pork meat. Today, the grazing of the high value Iberian pig is the most profitable component of the dehesa system.

The herbaceous layer is comprised of either cultivated cereals (oats, barley, wheat) or, more commonly, native vegetation dominated by annual species, which are used as grazing resources. Control of invasion of the dehesa by shrub species, matorral (mainly *Cistus ladaniferus*, *C. salviaefolius* and *C. monspeliensis*), has been traditionally composed of two complementary aspects: 1) manual uprooting in the central areas and 2) the clearing and ploughing of peripheral areas by landless peasants possessing a plough horse. In exchange for their labour, the owner would give these peasants permission to cultivate cereal crops on the newly reclaimed land and to have a share in the charcoal produced from the cleared vegetation. This was made economic, despite the low productivity, by the extremely low salaries paid to the workforce. At the end of the 1950's, the manner in which the dehesas were commercially exploited was thus broadly similar to that which occurred a century earlier. Today, this control is entirely performed through mechanical work.

The trees are viewed as an integrated part of the system, and as a result are planted, managed, and regularly pruned. Several prunings are done during the life of the oaks (Ruperez, 1957; Montoya, 1988). Cork oak is pruned quite differently to holm oak. In the first case, the main product of the tree is the cork whilst in the second, the aim is to maximise acorn production. Ruperez (1957) describes the successive pruning of holm oak: during the early stages, a form pruning is conducted in order to obtain a crown with three main vertical branches. This favours the horizontal spread of the fruiting branches. Maintenance pruning every seven to nine years allows opening of the crown and sustainability of acorn production. Production pruning provides firewood and browse during severe droughts, reducing leaf area.

The holm oak trees were selected for the production of sweet acorns as a high quality stock feed. Holm oaks have a high direct value as fodder crop, providing acorns and leafy branches. Cork is the main resource of *Q. suber*. Several other secondary resources such as firewood, charcoal and tannin are nevertheless still important in the dehesa economy.

3. A palaeoecological and archaeological point of view

The intriguing problem of the origin of this very peculiar landscape of south-western Iberian Peninsula has not been investigated over the entire area concerned. In the southern part of the dehesa distribution (province of Huelva), palynological work by Stevenson (1985a,b, 1988) and Stevenson and Moore (1988) allow reconstruction of the vegetation changes over the period 4500 BC to 1900 AD. The first anthropic action was the clearing of initial oak and

pine forests around 4500 BP, coinciding with high occurrences of *Vitis* pollen. This event could represent a period of early viticulture and agricultural intensification. Using pollen diagrams, charcoal fragment analysis, radiocarbon dating of the cores and modern pollen rain to establish analogy between fossil data and dominant vegetation-types, Stevenson and Harrison (1992) were able to define and describe six major phases of land-use for this region (Figure 1): 'the simple prehistoric dehesa established in Phase I, and developed in Phase II, is followed by a millenium of deforestation (Phase III), after which a more developed dehesa succeeds in the early Iberian period, to last throughout the Roman, Visigoth, Arab and Medieval periods (Phase IV). In the early modern period, pine and oak/ash forests characterise Phase V and VI'. In phase II, the peak of oak pollen is accompanied by high occurrences in the ruderals *Rumex* and *Plantago* indicating a strong modification of the understorey with shrub clearing and invasion by herbaceous species: 'it looks like the beginning of a true oak dehesa but with more limited management than in the sophisticated classical and Medieval dehesa of Phase IV'. Phase IV (500 BC–1200 AD) sees a dehesa system, now matured into a permanent feature of the landscape maintained for about 1700 years, coinciding with the establishment of urban civilisation. The increase of pine trees during the Phase V could be the result of plantation for naval supplies. Pine plantations were established in the Marismillas region (80 km west of the Stevenson study

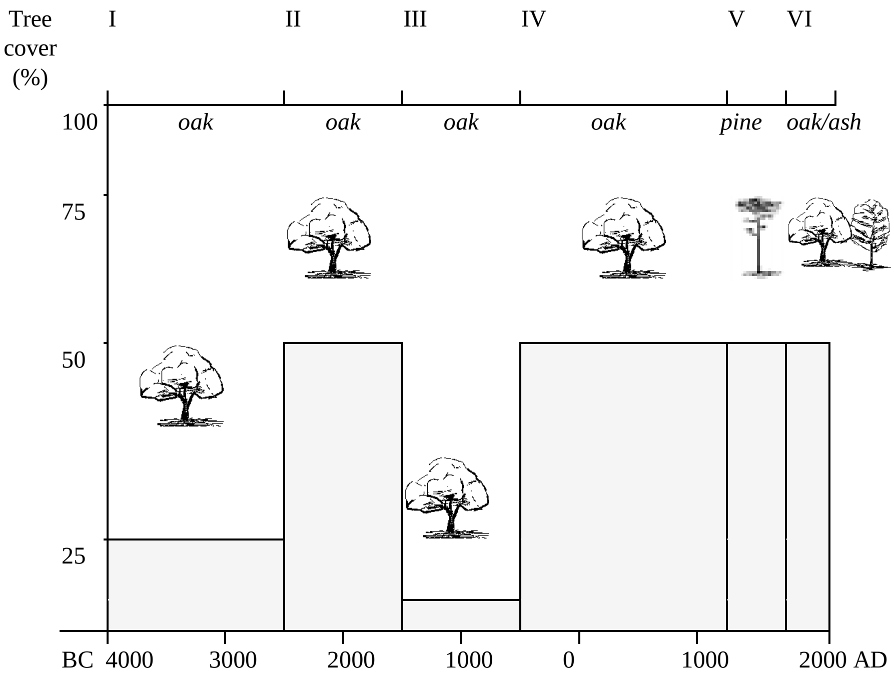


Figure 1. Palaeoecological history of some landscapes of the Huelva province, south-west Spain. Source: Stevenson and Harrison (1992).

site) from 1737, with a very rapid increase in the planted area (Granados Corona et al., 1984). Finally dehesas were re-established in the last Phase with plantations of ash (*Fraxinus* sp.) to provide browse for plough oxen.

4. An historical point of view

During the historical period, numerous written sources enable a precise meaning of the word dehesa and the formation of the corresponding landscapes. The majority of the following information on the semantic history of the word dehesa comes from Vacher (1984). According to various sources, such as the Diccionario Enciclopédico de la Agricultura, Ganaderia e Industrias Rurales (1895), the Codigos Antiguos de Espana (1885) and the Diccionario Etimologico (1977), the terms dehesa and dehesado appeared firstly in the oldest Spanish code, the Visigothic Fuero de Juzgo (VIIth century) in a law concerning the protection of fields against free ranging.

During the reconquest of southern Spain by the kings of Castile (VIIth to XVth centuries), the word dehesa specified rested grazing lands conceded by the King to military and religious orders and civil communities. This official protection was granted to avoid overgrazing by the numerous unauthorised herds of the transhumance (Mangas Navas, 1982). In the mid XIVth century, more than 3 million sheep moved each winter from Castile to southwestern Spain. The powerful breeders' organisation, *Mesta*, obliged the shepherds to keep the herds away from cereal fields, gardens, vineyards, stubble and dehesas (Klein, 1920).

The dehesas were of considerable importance for the economical autonomy of the Castile villages (Mangas Navas, 1982). These dehesas represented a generally large fraction of the territory of the villages. Royal protection was more easily conceded to civil communities than to military and religious orders (Cabo, 1978). Not only were these dehesas strictly defined, their use was restricted to specified types of livestock: the *dehesa boyal* was only grazed by plough oxen, the *dehesa yegual* by mares and foals, and the *dehesa carniceril* by animals assigned to slaughtering.

In the course of centuries, the reference to grazing, initially absent in the first definitions of the word, become more and more important. This semantic evolution corresponds to a strong modification of agricultural equilibrium from the XVIIth century. The transhumance declined, and grazing lands became seriously threatened with cereal cropping (Caxa de Leruela, 1630). This short insight does not explain the absence in all the meanings of the word dehesa of any criteria connected to the trees. Nevertheless, there are numerous references since the Roman period to the importance of the oaks. Strabo and Pline (in Bauer, 1980) emphasised the role of sweet acorns both for human food consumption and to feed domestic animals during the Roman period (see also section 3 for previous periods). Later, the importance to the farmers of exploiting the fodder resources of the trees was recognised by law (Fuero Real

de Espana, 1273). The Catholic Kings ordinances, from the Xth century, favoured restoration and conservation of the trees for animal and human uses (Bauer, 1980). From the Xth to the XVIIIth centuries, various laws recommended the reforestation of dehesas with holm oak and cork oak. In 1716, the King Felipe V ordered local authorities to protect and replant the south western Iberian dehesas (Mangas Navas, 1982). It is of interest to point out that very often the ownership of the land and of the trees was distinct (Humbert, 1980). This juridical distinction between soil and tree was frequent in Mediterranean civilisations.

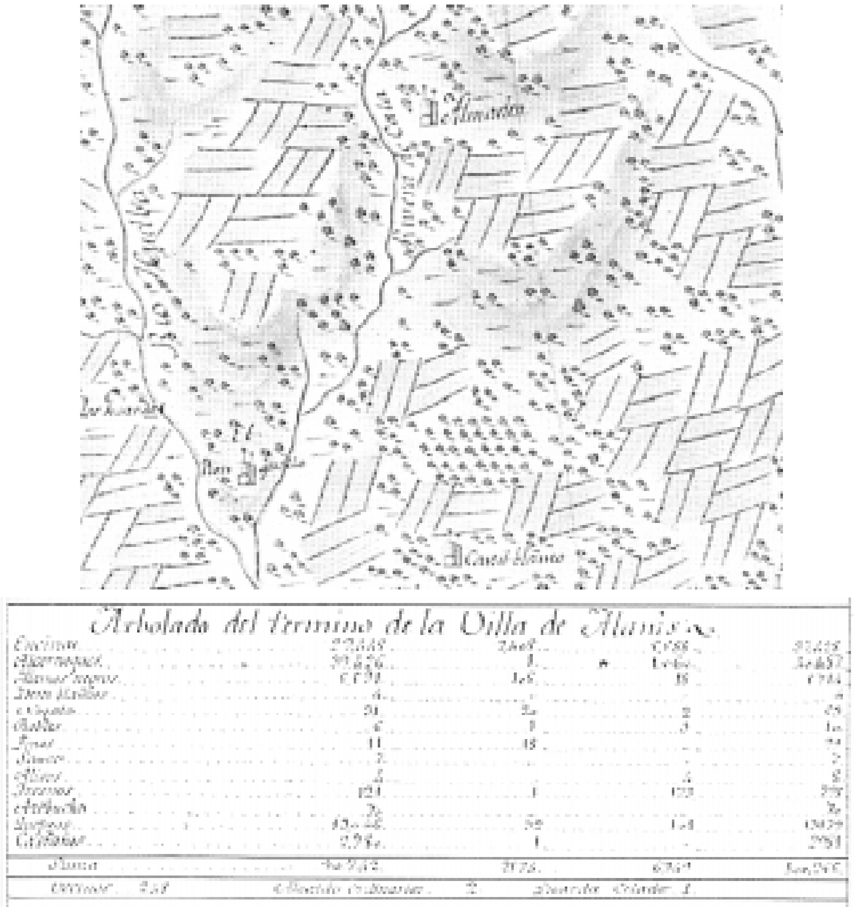
The presence of the trees is indicated in the first Spanish property register, the famous Catastro de la Ensenada, drawn up between 1750 and 1760. At the same time, maps of the Maritime Provinces of Spain were drawn giving an extraordinarily precise inventory of the trees and their location (Prat, 1754; Gomez Cruz, 1991) (Figure 2). This survey was primarily undertaken as an inventory of timber for naval supply at a time when naval construction was very active and important. A law was introduced in 1748 specifying that every tree growing at less than 25 leagues (i.e. 138 km) from the coast or from a navigable river was under the authority of the navy. As a consequence, cutting a tree was only permitted by licence. The abundance of the trees is next highlighted in Madoz' Diccionario Geográfico-Estadístico-Histórico covering all Spanish continental and overseas territories (Madoz, 1845; Sanchez Zurro, 1986). This dictionary pointed out the abundance of holm oak and cork oak for the Sierra Norte of Sevilla and more generally for the Sierra Morena.

5. An ecological point of view

The principal ecological constraints acting on the dehesa ecosystem can be grouped under three headings:

1. water resource;
2. nutrient availability; and
3. human management.

These constraints are highly modified by the unique vegetative structure of the dehesas, which is made up of two ecological components. The first, located outside the tree canopy, is composed of herbaceous plants, while the second, is composed of the oak tree and its associated herbaceous stratum. This difference in structure leads to predictable variation in the relative importance of the above three constraints. For the tree-grass component, the climatic constraint is generally considered to be of primary importance. This discussion focuses on what is currently known about the functional ecology of the tree grass component principally using research conducted in the dehesas of the Sierra Morena (Andalusia) as a model (Joffre and Rambal, 1988a, 1993; Joffre, 1996; Infante et al., 1997).



Species		Young	Mature	Old	Total
Encinas	*Quercus ilex*	29 445	2405	568	37
Alcornoques	*Quercus suber*	39 426	1	106	40
Alamos negros	*Populus nigra*	5 596	105	18	5 714
Alamos blancos	*Populus alba*	4			4
Nogales	*Juglans regia*	31	20	2	53
Robles	*Quercus robur*	6	1	3	10
Pinos	*Pinus sp*	11	18		29
Sauces	*Salix fragilis*	7			7
Alisos	*Alnus glutinosa*	4		4	8
Fresnos	*Fraxinus angustifolia*	121	1	173	295
Acebuches	*Olea europea ssp. silvestris*	70			70
Quejigos	*Quercus faginea*	13 046	32	101	13
Castaños	*Castanea sativa*	2 980	1		2981

Figure 2. Excerpt from ‘Carta Geográfica o Mapa General de los pueblos, montes y sus principales arboledas de la provincia de marina de Sevilla’, Antonio Prat 1754 (General Map of the villages and tree layer for the province of Sevilla) and the corresponding tree survey from the shire of Alanis, Sevilla, Spain.

5.1. *Climate variability, climatic drought and actual drought*

The high variability of precipitation and the length of the summer drought are among the most important climatic factors affecting vegetation function. Mean annual precipitation at Sevilla is 572 ± 176 mm but varies from less than 400 mm to more than 1000 mm (Figure 3). Several occurrences of three or four consecutive dry years can be observed over the period 1865–1993. The summer drought, defined as the interval between the last day of spring and the first day of autumn with rainfall events higher than 5 mm or 10 mm, has a mean value of about 120 days (Figure 4), while a summer drought of 150 days has a return period of 4.25 years (Joffre and Rambal, 1993).

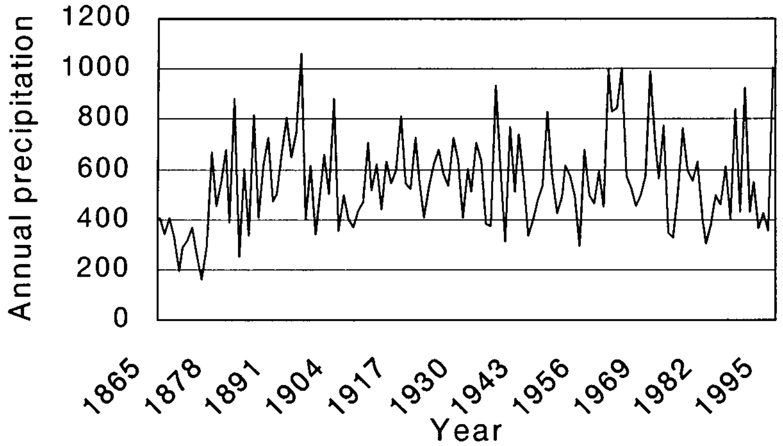


Figure 3. Precipitation records for Sevilla, Spain from 1865 to 1990.

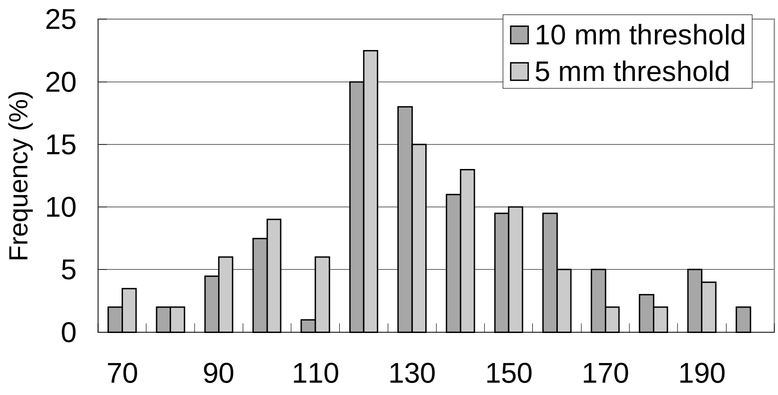


Figure 4. Duration of summer drought period (expressed in days) at Sevilla, Spain for the period 1922–1984.

Moreover, the absence of statistical relationship between annual rainfall and summer drought highlights the unpredictability of rainfall.

The water stress experienced by a plant is not only dependent on climatic conditions but depends also on edaphic conditions. Rambal (1984a) proposed a numerical approach to actual drought using both Penman potential evaporation (E_p) and maximal soil water reserve R_{max}:

$$R_{(i+1)} = \mathrm{Min}[(1 - E_p/R_{max})\, R_{(i)} + P,\, R_{max})$$

where R is the soil water reserve (expressed in mm), E_p Penman potential evaporation (mm) and P precipitation (mm). We calculated the seasonal time-course of actual soil water on a 10 day basis over the 1975–1995 period based on a maximal soil reserve of 250 mm (Joffre and Rambal, 1993).

The soil water reserve reached this maximal value in less than half the years, and during two periods of four consecutive years there was a strong soil water limitation (Figure 5). The same result was obtained over several meteorological stations of southwestern Spain indicating the spatial homogeneity of the precipitation regime (Font Tullot, 1983). This means that the persistent woody elements of the dehesa (the trees) must be able to overcome recurrent multi-year drought periods without mortality. What are the mechanisms involved? Results obtained at two complementary scales will give us some pertinent information on: 1) how tree cover influences soil properties and water balance at the local scale and 2) whether variation in tree density reflects changes in water resources at the regional scale.

5.2. *Local scale*

Considering the dehesa as a juxtaposition of two ecological components, it is possible to compare soil characteristics and patterns of soil water storage and

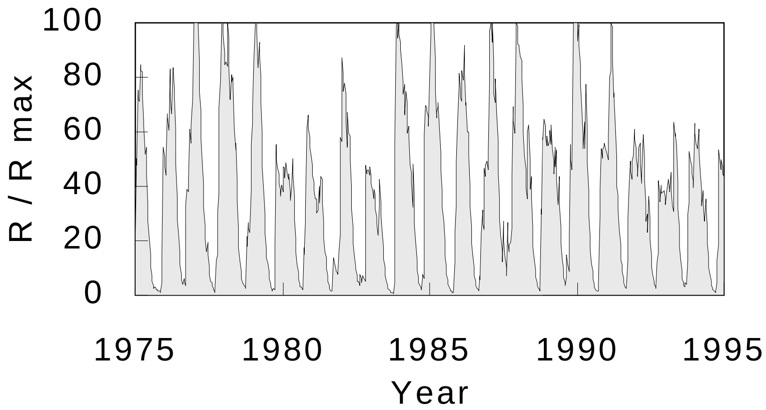


Figure 5. Time-course of simulated soil water reserve R expressed as percent of the maximum soil water reserve R_{max} for the period 1975–1995, Sevilla, Spain.

to quantify the water balance of these two components. The presence of isolated trees was shown to cause marked variations in physical properties such as dry bulk density (Joffre and Rambal, 1988a). Soils under the tree canopy were richer in nutrients and organic matter (Vacher, 1984; Escudero, 1985; Joffre, 1987). It should be noted that nutrient enrichment under the canopies was a feature of various mechanisms. Trees act as nutrient pumps, drawing nutrients from deep horizons and laterally from areas beyond the canopy, depositing them beneath the canopy through litter decomposition (Scholes and Archer, 1997). Another mechanism linked with animal behaviour seeking shade may be of importance. Transfer of nutrient under the canopies by livestock through dung deposition certainly plays a role in enhanced fertility. It has been found in three dehesas of the Sierra Morena region that the dry bulk density of the upper soil layer and moisture retention curves were significantly different and soil water content was always significantly higher under tree cover than in open areas (Joffre and Rambal, 1988a). The increase in maximum soil water storage of soils, calculated for the first 150 cm, estimated from the difference between field capacity and the driest profile observed, ranged from 40 to 110 mm under the trees. This allowed important time lags in late spring in the drying of the upper soil layers. The lowest soil water content for a given depth was reached more than one month later under tree canopies than outside. This buffering effect of the trees allows a longer growing season for understorey grasses.

Differences in water budget between the two components of the dehesas were highlighted by estimating monthly and annual time-scale water balance (Joffre and Rambal, 1993). Mean annual actual evaporation (*Ea*), estimated over three consecutive years, was 400 mm and 591 mm outside and under the trees respectively. This difference in water uptake between the two ecological components of the dehesas is in agreement with previous results on shrub and grass vegetation in the Mediterranean region. In the open areas, losses due to drainage and surface runoff were large (ranging from 65 to 100% of the *Ea*) whereas under the tree canopy losses represented only 20 to 40% of the *Ea*. Linear regression of *Ea* against annual rainfall (*P*) showed a significant correlation for the grass component but not for the tree-grass component. Under the tree canopy, when annual precipitation was less than 570 mm, water yield was negligible and all precipitation was lost by evaporation. In contrast, outside the tree canopy, water yield occurred as soon as annual precipitation was greater than 250 mm, i.e. each year. These results show that as a result of tree-induced modifications of soil properties, the availability and uptake of water for plant growth is greater for the tree-grass component.

The strong soil structural differences and the functional differences in water budgets and patterns of water use observed between the two components are coarsely similar to those found between early and late stages of succession. Using the concept of ecosystem mimicry, the two coexistent components of dehesas can, in fact, be compared to two distant stages of a secondary

succession characterised by very different behaviours. Due to the long human history of these savannah-like man-made ecosystems, it can be argued that the modifications of functional properties of the tree-grass component are a result of the improvement of ecosystem function due to tree establishment and maintenance over many centuries. The situation is quite distinct from that of clearing a forest to obtain a similar landscape, where the modification of soil properties occurs more in the cleared areas and normally leads to impoverishment of soils, a decrease of organic matter and degradation of physical and chemical properties such as acidification. The trees in the dehesas cannot be considered as remnant vegetation of an hypothetical initial forest but as a structural element acting as an ecological engineer over many centuries (see section 2) in a complex man-made agroforestry system. Several studies have shown that the nutrient enrichment in tree-dominated patches of savannahs was strongly related with tree age (Bernhard-Reversat, 1982; Barth, 1980).

5.3. *Regional scale*

Based on the hypothesis that under seasonally water-limited resources, vegetation systems will develop a canopy density that produces both minimum water stress and maximum biomass, the theoretical work of Eagleson (Eagleson, 1982; Eagleson and Tellers, 1982; Eagleson and Segarra, 1985) has emphasised that a mixed formation of grasses and woody plants, i.e. savannah, is the only stable equilibrium state. These functional models permit the prediction of tree density according to the level of water resources. This concept of water resources integrates evaporative demand, amount and temporal pattern of precipitation and hydrodynamic properties of the soil. Hence, the distribution of woody plants is indicative of control by moisture availability and is a key to the conceptualisation of an ecosystem-level model of oak savannahs. In Eagleson's theory, ecosystem stability, which is characterised by the persistence of the tree layer, seems to be more fragile when climatic changes are significant, particularly when they involve a decrease of precipitation. In order to verify this hypothesis, we selected a large region of southern Spain encompassing a gradient of annual precipitation and dominated by dehesa landscapes (Figures 6 and 7). This area was predominantly grazed with occasional cropping and the dehesas were subjected to the same management system over the entire region. Consequently, the researched relationships between structure (i.e. tree density) and ecological resources would not be obscured and/or counterbalanced by local modifications of land management. Comparison of tree density and climatic resources was achieved through GIS methodology. Over this zone, a map of precipitation was overlaid with tree density mapped by remote sensing. The methods we used are briefly described below.

Figure 6. Dehesa stand with a density of 45–50 trees ha^{-1} in a 750 mm annual rainfall area, Sevilla, Spain.

Figure 7. Typical landscape with density < 10 trees ha^{-1} in a 500 mm annual rainfall area, Sevilla, Spain.

5.3.1. *Study area and regional estimation of precipitation*

A study was conducted over a 250 km × 150 km part of Sierra Morena and Meseta of southern Spain (Figure 8). Monthly and annual precipitation from 173 weather stations located in this zone were averaged over the period 1951–1991. The spatial distribution of precipitation was investigated using a geostatistical analysis. In its simplest form, this procedure involved a three-step process:

1. defining the semi-variogram, i.e. the degree of spatial correlation among the data;
2. interpolating values between measured points based on the degree of spatial correlation encountered (see Webster and Oliver, 1990 for a comprehensive account);
3. mapping the estimates.

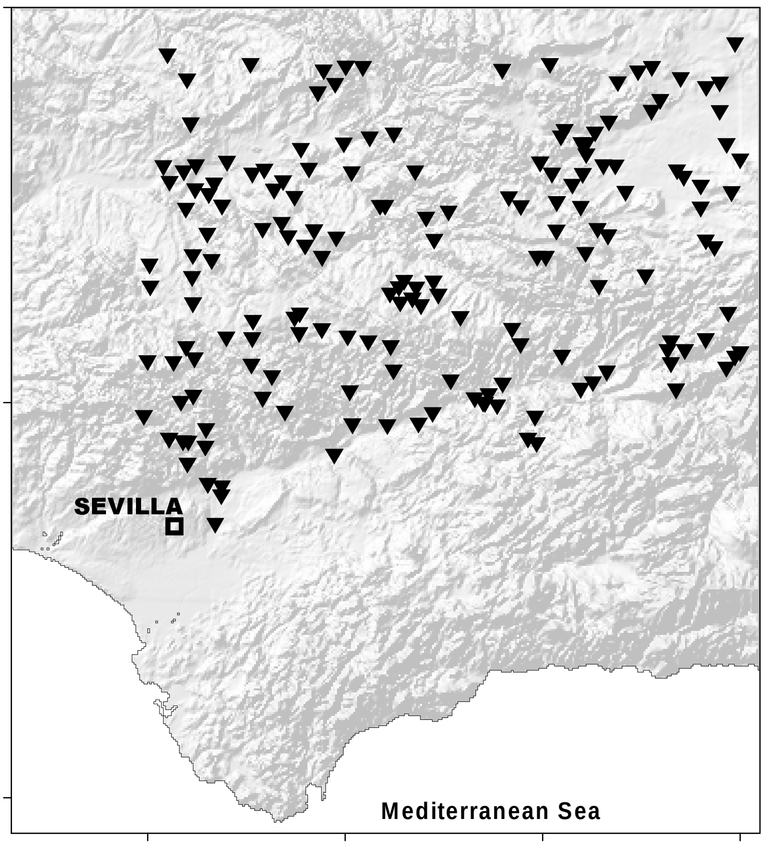


Figure 8. Locations of the 173 weather stations in the Sierra Morena and Meseta, southern Spain.

The experimental semi-variogram obtained for our set of data have been fitted to bounded spherical models. The second step uses semi-variogram parameters to interpolate values for points not measured using kriging algorithms (Trangmar et al., 1985). Maps were based on these kriged data provided by Geopack and drawn using the software program Surfer.

5.3.2. *Tree density estimation*

The estimation of tree density using the highest spatial resolution data (SPOT panchromatic = 10 m resolution) is based on the assumption that for sparse trees on a contrasting herbaceous background, spatial filters could provide a direct mapping of tree cover. Four scenes of SPOT-HRV data (scenes 31-274, 31-272, 33-273 and 35-272) were used. These scenes were selected in order to cover the range of annual precipitation in this region (Figure 9). Aerial photographs at the scale of 1/40,000 are available for part of the study area (data acquisition in October 1984). In addition to these data, several ground observations were made from 1983 to 1995. In each scene, two test areas of approximately 10 × 10 km, corresponding to 1024 × 1024 SPOT panchromatic pixels were selected. Using a supervised approach, homogeneous test sites representative of most common tree densities have been defined on the basis of visual inspection of aerial photographs and the trees directly counted on aerial photographs. The SPOT data was processed to enhance local contrast between one pixel and its nearest neighbours. According to the size of tree crowns (less than 10 m) and the distance between trees, three by three pixel windows were selected. A numerical filtering approach involving two edge-enhancement filters and a level-slicing procedure was adopted for discriminating the trees from the background (Joffre and Lacaze, 1993). The result was a binary image where the value of 0 corresponded to background pixels,

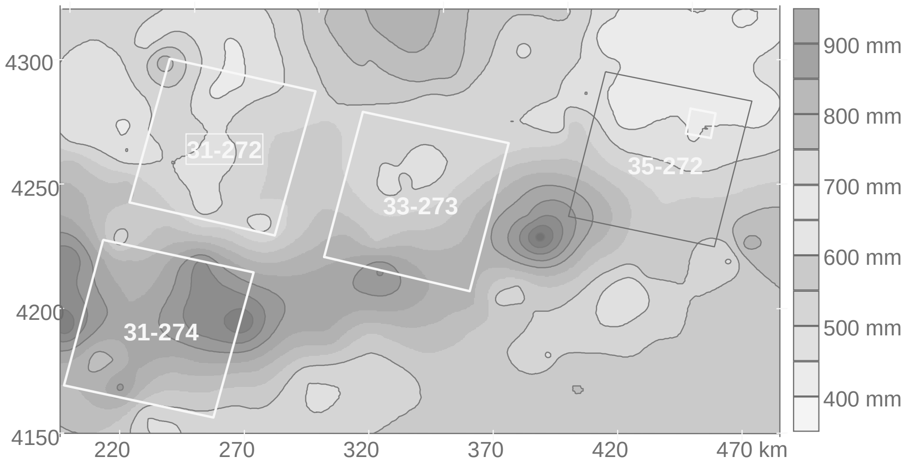


Figure 9. Locations of the SPOT scenes on a map of mean annual rainfall for part of Sevilla province, Spain.

and one for pixels belonging to class tree. So, for each test site, it was then possible to compare directly the mean value of remote estimation of trees and the number of trees counted from aerial photographs. This calibration procedure was then validated on other distinct sites and finally applied to the entire scene. Resulting maps of tree density were obtained by averaging pixels over three by three pixel windows.

5.3.3. *Looking for a functional equilibrium*

Over the studied zones, mean annual precipitation ranged from 500 mm to more than 800 mm, covering semi-arid to subhumid conditions according to the Emberger's classification of Mediterranean climate (Daget, 1977) (Figure 9). Geo-referenced climatic and tree density maps were overlaid over 10,800 km^2. Our hypothesis relating the structure of dehesas to water resources is only relevant for landscapes where slopes would not affect water balance. Consequently, a digital elevation model was used to select zones with slopes of less than 5% and 10%. These masks were applied over the density maps to obtain a coincidence tabulation report. In the same way, a mask was built from Corine Land Cover data (CEC, 1993) to exclude cultivation, plantation forest, water, bare soils and urban areas. Soils over the study zones are derived from acidic bedrocks (mainly granites and schist). These do not exhibit significant differences in physical properties, so we did not consider the soil type in our sampling strategy and excluded this layer from our co-variant analysis. The resulting database used for the coincidence tabulation analysis covered 5421 km^2 when excluding slopes higher than 5% and 5942 km^2 when excluding slopes higher than 10%.

The two thresholds of 5% and 10% of slopes for the pixels eliminated for the analysis gave very close results. The distribution frequency of tree density along classes of annual rainfall (Figure 10) showed a very clear trend. As rainfall increased, mean tree density increased up to 40 trees per hectare. The distributions, asymmetric for the lower values of rainfall, tend to greater regularity as the rainfall reached 650–700 mm. For the areas where mean annual rainfall was higher than 650 mm, the highest classes of tree density (> 50 trees ha^{-1}) represented more than 10% of the dehesas.

We have seen (section 5.2) that under the tree canopy, when annual precipitation was less than 570 mm, water yield was negligible and all precipitation was lost by evapotranspiration. These results are in accordance with studies conducted in other Mediterranean climate zones (chaparral of California, Ng and Miller, 1980; garrigue in southern France, Rambal, 1984b). It seems that under 600 mm of mean annual rainfall, the tree density corresponding to a metastable equilibrium was low (< 20 tree ha^{-1}). One can interpret this result with the previous values of around 600 mm of annual evapotranspiration for the tree-grass component. Under a mean annual precipitation of 600 mm, it is possible that competition between the two components of the dehesa, the grass outside the tree canopy and tree-grass

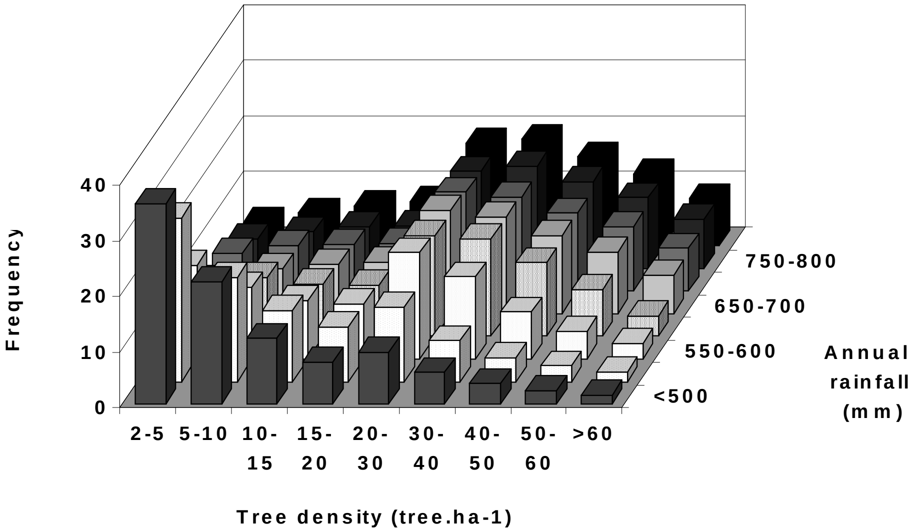


Figure 10. Frequency distribution of tree density against mean annual rainfall, Sevilla, Spain.

component, sets the boundary for the optimal equilibrium density. In these climatic conditions, the survival of the trees in the event of severe drought (three consecutive years, return frequency 20–30 years at Sevilla) is only possible if the root system of the tree can extend beyond the influence of the tree canopy (Eastham et al., 1988). An extension of the root system 0.5 m outside the projected limits of an average crown diameter of 7 m would increase the volume of soil exploited and hence the availability of water by ca. 30%.

In this zone, it appears that tree density is suboptimal as neither severe tree water stress (predawn leaf water potential lower than –2.5 Mpa) nor tree mortality was observed over a period of 15 years. That means that no tree-tree negative interaction for water use occurs. By contrast, in a closed dense woodlands of *Q. ilex* in Catalonia, a high degree of mortality was observed following a severe drought in 1994 during this period (J. Piñol and coll., pers. comm.). Better knowledge of the extension of the root system is needed to support this hypothesis about the adjustment of tree density facing severe climatic drought. Nevertheless, empirical evidence of relationships between tree density and mean annual precipitation over more than 5000 km^2 suggests that the structure of these man-made agroecosystems are adjusted over the long-term and correspond to the hydrological equilibrium hypothesis of Eagleson's theory.

6. A prospective point of view

Two issues present uncertainty for the future of the dehesas. The first is their development as an agriculturally productive system within the local socio-economic conditions and the general agricultural politics of the European Union. The second concerns the stability of this complex ecological system in the face of long-term climatic change caused by increasing atmospheric CO_2.

6.1. *Land use modifications*

Considering the evolution of the main land use types in the Sierra Norte of Sevilla, Vacher et al. (1985) showed that there was very little change in the dehesas of this region between 1750 and 1956. Between 1956 and 1977, however, dramatic changes have occurred. These have been the result of three predominant human activities:

a) a decrease in agro-pastoral management practice;
b) an increase in deforestation and clearing processes in order to extend cropping lands; and
c) reforestation.

When grazing pressure is removed, dehesas are invaded by Mediterranean matorral species (Lacaze and Joffre, 1987; Vacher, 1984), which in turn increase the fire risk. Spain and Portugal have been members of the European Union (EU) since 1986 and as a consequence subjected to the Common Agricultural Policy (CAP). Within the marginal agricultural areas, the two main regulations affecting land use changes are Regulation 2078/92 (Agricultural production methods compatible with protection of the environment and maintenance of the countryside) and Regulation 2080/92 (Community aid scheme for forestry measures in agriculture). The incentives offered to take cropping land out of production and to re-aforest marginal agricultural land could promote a strong and rapid land use change (Anon., 1992; Lawson, 1996; Ridley, 1997). An ambitious re-aforestation program concerning the region with large dehesa areas was implemented in 1995. Regulation recognises that premiums are necessary to compensate landowners for the loss of income during the non-productive period of aforested agricultural land. In some parts of the dehesa areas, abandonment of grazing activity for re-aforestation program could be interpreted as a strong decline of sustainability of the system as the promoted forest schemes do not take into account the difficulty of establishment and maintenance of the trees planted at higher density in this very variable and harsh environment.

6.2. *Stability of vegetation functional equilibrium facing changing climate*

For southern Europe, a general consensus of simulation models (Global Circulation Models) is that a doubling of atmospheric carbon dioxide could lead to a decrease of precipitation and, more importantly, an increase in the probability of extreme events such as severe drought. In Europe, Gregory and Mitchell (1995) showed that in middle latitudes (35–40° N), the average decrease in total annual rainfall is associated with a decrease in the number of rainy days. Moreover, this decrease is associated with a decrease in the frequency of low rainfall days. This means that there will be an increased frequency of dry spells despite an increase in the number of heavy rain events. Rambal and Hoff (1998) showed in a simulation exercise based on contemporary data at Puéchabon (10 km west of Montpellier) that a change in daily rainfall distribution, based on a strong increase in the frequency of occurrence of the largest rainfall class and a decrease in the amount and frequency of low rainfall, results in a slight decrease of annual rainfall (–3%) and evapotranspiration (–5.5%). More interestingly, they showed that the critical period defined for *Q. ilex* by a leaf water potential threshold fixed here at –4.2 MPa, corresponding to the water potential at which the loss of xylem conductivity is approximately 90% (Lo Gullo and Salleo, 1993), increased by 16%. In addition, results of the GCM of the Hadley Center for Climate Prediction (UK Meteorological Office) based on a 1% annual gradual increase, resulting in a doubling atmospheric CO_2 after 70 years (Murphy, 1995; Murphy and Michell, 1995), showed a decrease of about 80 mm for the annual rainfall of Sevilla in 75 years (Figure 11). This decrease would have dramatic consequences in

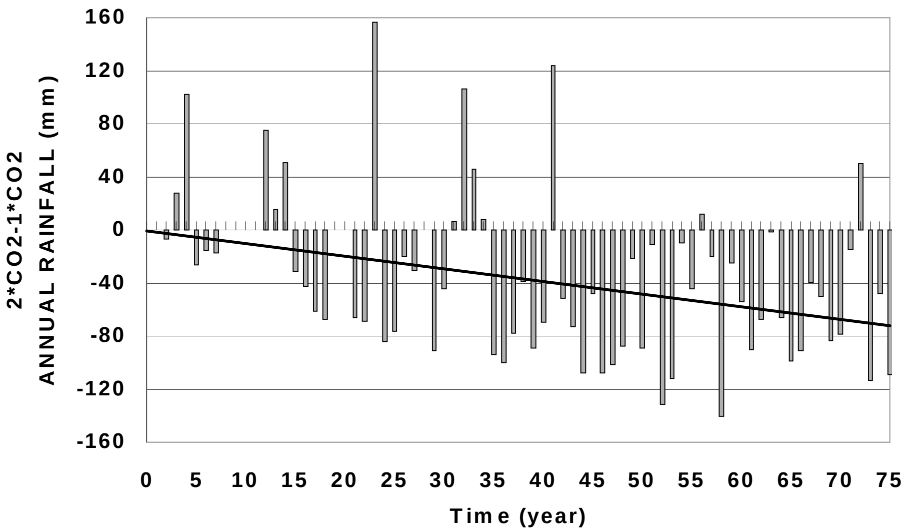


Figure 11. Changes in annual rainfall amounts for Sevilla, Spain, using the transient simulation model. The changes are with respect to the full 75-year control means.

the optimal distribution frequency of the trees for all the regions of dehesas where present annual rainfall is lower than 700 mm, as shown by Figure 10. The foreseeable changes in both the total amount and distribution of precipitation would therefore affect the structure of 88% of the studied region. A regulation mechanism could nevertheless be proposed. Elimination of individual trees which experience the most severe climatic stress would contribute to both a redistribution of water resources in favour of the remaining trees and a new functional equilibrium for the long-term persistence of the community.

7. Conclusion

The historical perspective clearly shows the influence of farmers' long-term decisions in shaping the dehesa landscapes. To quote Ridley's (1997) investigation of the sustainability of Iberian agroforestry systems, 'the concept of time scales is very marked in European agroforestry systems, illustrated by the Portuguese traditional saying "you plant vines (or crops) for yourself, olives for your children and cork oak for your grandchildren"'. It should be noted equivalent sayings also exist in Spain and Languedoc. The most intriguing and interesting characteristic of the present dehesas is the existence of a spaced tree component with an important productive function. We have not considered the composition of the grass layer as it is more directly related to particular practices (year-long continuous grazing, periodic ploughing) and could be modified without greatly altering the functioning of these system (Joffre et al., 1988, 1991). It should be noted that the present productivity of this layer seems low compared to similar systems in Mediterranean-type climate, either in Europe or in Australia. Nevertheless, various native species of high agronomic interest, legumes and perennial grasses, are remarkably adapted to this harsh environment and grow naturally in the dehesas. The potential of the local native flora is so interesting that for many years Australian scientists have collected and improved numerous pasture species from the Mediterranean Basin. A sustainable increase in total productivity would need to be based on optimisation of the multiple plant (forage, acorns, firewood, charcoal) and animal (sheep, cattle, pigs) components. Where short-term maximisation of the herbaceous layer has been the major goal, as in the case in Australian crop and pasture systems, large land degradation problems have resulted. Soil acidification and salinisation have been attributed to the high intensity of production and low water use of agricultural species compared with the native vegetation they replaced. The profitability of the dehesas has been based on the diversity of products and permitted the long-term ecological sustainability by a sub-optimisation of the resources for many centuries. This is still more evident when considering all the ecosystem services provided by the dehesas to the human population (Lefroy et al., 1993; Chapin et al., 1997), in addition to the farmers.

To gain an ecological perspective, we applied a simple monofactorial analysis to the present tree structure and function of the dehesa, based principally on water resources. Two distinct areas within the dehesa zone were defined, apparently determined by different factors. The first corresponds roughly to the areas receiving less than 650–700 mm annual rainfall, the second to areas receiving more than 650–700 mm. For the drier areas, results showed that tree density is related to rainfall amount and seems to conform to ecohydrological optimality theories. In the higher rainfall zone, tree density does not increase with rainfall. This pattern suggested that the dehesa structure is under the control of additional factors likely to be related to historic, socio-economic, and agronomic origins. Two possible candidates are:

1. limited labour for tree management (establishment, pruning); and
2. the choice by the farmers to maintain a more open structure to optimise grass production.

Diversity of production is characteristic of the dehesa in both components (forage, acorn, wood, cork, charcoal). The connection between suboptimal tree density and whole ecosystem production, i.e. the trade off between ecological and economic characteristics of these peculiar agroforestry systems, is the result of a long-term landscape management by local populations. Given the current exogenous threats of economic and global environmental origin, this diversity of production does not guarantee the persistence of the dehesas in the near future.

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