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Mestrado em Biologia da Conservação

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Dissertação orientada pelo Professor Doutor Jorge Palmeirim (CBA/DBA-FCUL) e pelo
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A nidificação arborícola é uma estratégia reprodutora pouco comum nas populações europeias de águia de Bonelli (*Aquila fasciata*). A selecção do habitat de nidificação desta espécie em meio florestal é pouco conhecida, tendo sido apenas divulgado um estudo sobre a nidificação da espécie em pinheiro da Calabria (*Pinus brutia*) no Chipre. Desta forma, o presente estudo pretendeu identificar as características das árvores mais relevantes na escolha do local de nidificação pela águia de Bonelli e determinar a influência das variáveis do micro habitat na ocupação dos ninhos e no sucesso reprodutor. Os resultados permitem melhorar o conhecimento sobre os requisitos de habitat desta espécie e construir uma ferramenta de conservação, que serve de base à definição de medidas de conservação específicas.

O estudo foi efectuado em 32 casais arborícolas residentes na região montanhosa do Sudoeste de Portugal, que se distribuem desde a Serra do Cercal (Baixo Alentejo) até à Serra do Caldeirão (Algarve). Apesar da espécie apresentar estatuto de conservação Em perigo em Portugal, a população do Sudoeste apresenta características genéticas, ecológicas e comportamentais singulares, que a tornam na única população arborícola de crescimento rápido na Europa e, particularmente, na região do Mediterrâneo.

A recolha das variáveis relacionadas com as características das árvores de nidificação, dos ninhos e dos locais de nidificação foi efectuada em 52 árvores-ninho (1 a 2 por cada território) e 78 árvores-aleatórias (1 a 4 por território) entre Setembro de 2007 e Outubro de 2008, mas as medições foram interrompidas durante o período de reprodução das águias para evitar a perturbação. Posteriormente, utilizaram-se Modelos Lineares Mistos Generalizados (MLMG) para analisar os factores determinantes da selecção da árvore de nidificação e Modelos Lineares Generalizados (MLG) para aferir a influência das variáveis de micro habitat na ocupação dos ninhos e no sucesso reprodutor.

A maioria dos ninhos em estudo encontrava-se em eucalipto-comum (*Eucalyptus globulus*), mas também foram considerados ninhos em pinheiro-bravo (*Pinus pinaster*), pinheiro de Monterey (*Pinus radiata*), sobreiro (*Quercus suber*) e eucalipto-negro (*Eucalyptus camaldulensis*). Destaca-se a ocorrência excepcional de um ninho em

eucalipto de produção. Estas espécies de árvores representam o total de espécies com nidificação conhecida de águia de Bonelli no Sudoeste serrano.

Os ninhos considerados encontram-se preferencialmente em árvores dominantes e saudáveis e, em média, a 14,9 ± 5,7 m (5,5 – 31,0 m) de altura. As árvores dos ninhos apresentam perímetro médio à altura do peito (PAP) de 2,2 ± 0,8 m (0,94 – 4,10 m) e altura média de 23,9 ± 7,6 m (12 – 44 m). Todos estes valores médios são particularmente mais elevados para os eucaliptos-comuns que suportam ninhos (PAP 2,7 ± 0,7 m, altura árvore 30,0 ± 6,8 m e altura do ninho 18,9 ± 5,5 m). Na sua maioria, as árvores de nidificação localizam-se em encostas de elevado declive, com exposição N/NE, mas os ninhos em eucalipto localizam-se maioritariamente em bosquetes ao longo das linhas de água no fundo dos barrancos. As áreas de nidificação estão incluídas ou têm como vizinhança florestas de sobreiro ou montados abandonados, pinhais-bravos, pinhais de Monterey ou eucaliptais de produção, contudo, por vezes a nidificação ocorre em árvores isoladas rodeadas por matos. No que se refere ao habitat circundante ao ninho num raio de 25 m, a densidade arbórea é muito variável mas a cobertura vegetal é elevada. Os matos são maioritariamente mistos, mas os matos dominados por estevas (*Cistus* spp.) e os matagais altos de medronheiro (*Arbutus unedo*) e urze-branca (*Erica arborea*) também ocorrem em redor dos ninhos. A distância média aos factores de perturbação considerados (casas habitadas, estradas, linhas de transporte de energia, etc.) é de 2,3 km.

Através da comparação das características das árvores-ninho com as características das árvores-aleatórias, concluiu-se que o PAP é uma característica importante na escolha da árvore de nidificação pelas águias, para todos os grupos de espécies arbóreas considerados na análise (sobreiros, pinheiros – *P. pinaster/P. radiata*, e eucaliptos – *E. globulus/E. camaldulensis*). A altura apenas é relevante na escolha dos sobreiros como árvore de nidificação. Os ninhos de águia de Bonelli são estruturas grandes e pesadas, pelo que é necessária uma plataforma sólida e estável, formada por ramos robustos e pouco flexíveis, que só as árvores de PAP mais elevado poderão fornecer.

Os resultados obtidos revelam ainda que a ocupação dos ninhos é influenciada positivamente por algumas características do microhabitat: a presença de matos mistos e matos dominados por estevas (*Cistus* spp.), o declive da encosta, a percentagem de cobertura da vegetação entre os 4 e os 8 m de altura, o PAP e a presença de eucaliptos (*Eucalyptus globulus/Eucalyptus camaldulensis*). No entanto, a maior presença de matos altos de medronheiro (*Arbutus unedo*) e urze-branca (*Erica arborea*) e a menor cobertura da vegetação entre 1 e 4 m de altura, bem como a menor distancia ao caminho mais próximo, são as únicas variáveis que influenciam significativamente o sucesso reprodutor. A maioria das variáveis que influencia positivamente os parâmetros parece reflectir o reduzido nível de perturbação das áreas de nidificação, pois a maior cobertura por vegetação aumenta a protecção do ninho, o maior declive aumenta a inacessibilidade do local e a presença de matos altos de medronheiro e urze-branca está relacionada com as duas questões. Alguns dos resultados obtidos não eram esperados e podem estar relacionados com artefactos estatísticos e com a forma de aplicação do método de definição da variável.

Conclui-se que a águia de Bonelli selecciona árvores com um PAP elevado para construir o ninho e que ocupa preferencialmente árvores de grande porte localizadas em zonas de declive acentuado e com elevada cobertura por vegetação. Contudo, apenas uma das variáveis com influência na ocupação dos ninhos parece ter influência também na reprodução (presença de matos mistos). Este resultado evidencia uma provável influência de outros factores não considerados no presente estudo na produtividade da espécie, quer sejam de origem natural (e.g. pluviosidade elevada e constante durante o período reprodutor) ou humana (e.g. perturbação provocada por desmatações que resultam em alterações significativas do habitat). Destaca-se ainda a crescente importância de espécies exóticas (eucaliptos) em detrimento de uma espécie nativa (sobreiros) na nidificação desta ave de rapina.

A utilização de análises estatísticas mais robustas, que melhoram os poderes explicativo e preditivo dos modelos multivariados (<50%), poderão ajudar a clarificar a influência dos factores de micro habitat na selecção da árvore de nidificação, ocupação dos ninhos e sucesso reprodutor.

Apesar da população do Sudoeste apresentar actualmente uma tendência populacional positiva, a contínua degradação das árvores de grande porte com potencial para nidificação é uma ameaça importante para a população arborícola de águia de Bonelli em Portugal, particularmente relevante na região serrana do Sudoeste. Esta degradação pode ter efeitos severos na redução do potencial reprodutor da população a médio ou longo prazo. Desta forma, as conclusões obtidas neste estudo, mas também as medidas específicas de PAP que uma árvore deverá cumprir para poder ser utilizada como suporte de nidificação desta espécie, foram utilizadas para definir algumas regras de

gestão florestal incluídas no "Manual de Boas Práticas Florestais e Cinegéticas" e do "Plano de Acção para a conservação da população arborícola de águia de Bonelli em Portugal". Entre elas, destaca-se a preservação dos actuais locais de cria e suportes de nidificação mas também a protecção de árvores de grande porte, localizadas a meia encosta ou no fundo de barrancos com matos desenvolvidos, com PAP mínimo de 1,48 m para sobreiros, 1,01 m para pinheiros e 1,42 m para eucaliptos.

Palavras-chave: *Aquila fasciata*, arborícola, selecção de habitat, sucesso reprodutor, floresta, Portugal.

Summary

Tree-nesting is an uncommon breeding behaviour in Bonelli's eagle (*Aquila fasciata*) European populations. As little is known about the nest site selection of this species in forest habitats, 52 nest trees located in Southwest Portugal were studied. Generalized Linear Mixed Models (GLMMs) were used to analyse the determinants of the nest tree selection and General Linear Models (GLMs) to assess the influence of microhabitat variables on nest occupancy and breeding success. By comparing actual nest trees with available randomly selected trees, perimeter at breast height (PBH) was found to be an important feature in the choice of the nest tree by the eagles, independently of the tree species. Regarding microhabitat features, presence of mixed shrubs and shrubs dominated by rockrose, hill slope, vegetation cover at 4 to 8 m height, PBH and eucalyptus trees (*E.globulus/E.camaldulensis*) influences positively nest occupancy. However, higher presence of taller thicket of strawberry tree (*Arbutus unedo*) and heath (*Erica arborea*) and lower vegetation cover at 1 to 4 m height and distance to the nearest unpaved road were the only variables significantly associated with breeding success. Therefore, Bonelli's eagle occupy preferentially large trees, particularly eucalyptus trees, located at higher slope and surrounded by tall vegetation cover, which reflects the lower disturbance level of the nesting areas. However, productivity is improved when nesting occurs at sites composed by complex and stratified native shrubby understory. Since the current decline of the quality and availability of large potential nest trees is a serious threat to the tree-nesting population of Bonelli's eagle in the country, PBH measurements obtained in this study were used to define forest management rules, as well as the protection of suitable trees for nesting and breeding sites, that land managers must respect to maintain, create or enhance nesting habitat for this endangered species.

Keywords: *Aquila fasciata,* tree-nesting, nest site selection, breeding success, microhabitat, forest, Portugal.

Bonelli's eagle (*Aquila fasciata* Vieillot, 1822) is a large resident raptor, with a distribution ranging from the Mediterranean region to Southeast Asia. Main areas of occurrence are Iberian Peninsula, Morocco, India and Southern China (Cramp and Simmons, 1980).

The European population is estimated to include from 860 to 1100 breeding pairs, 80% of which in the Iberian Peninsula (López-López *et al.*, 2006).

Worldwide, this species is classified as Least Concern (LC) by the IUCN Red List (IUCN, 2011) but has an Endangered conservation status in Portugal (Cabral *et al.*, 2006). Apparently, the population of Southern Asia has a favourable conservation status (Bildstein *et al.*, 1998), while the European population seems to be recovering from a serious decline during the 1980s (Real *et al.*, 1996; Del Moral, 2006; Cadahía *et al.*, 2008). The main causes for this decline were apparently direct persecution and electrocution and collision with power lines (Real *et al.*, 2001; Carrete *et al.*, 2002).

In Portugal, the population of the species was recently estimated at 116-123 breeding pairs (CEAI, 2011a). In the North and Centre of the country, the distribution of the species is heterogeneous and mainly restricted to areas near the Spanish border (Douro and Tejo International basins), but it is widespread in the South (CEAI, 2011a). The Northeast population has been declining since 1980s, while the southern population currently shows a marked increase (Palma, 2009).

The nesting behaviour of the Bonelli's eagle population varies across the country. In the North of Portugal, breeding pairs are cliff-nesters, whereas in the South they are almost all tree-nesters (Palma, 1994), a very unusual behaviour in the rest of Europe. In Spain, only 4% of the breeding pairs nest in trees (Del Moral, 2006) and this behaviour is poorly documented (Arroyo *et al.*, 1995; Cabot *et al.*, 1978; Gil-Sánchez, 1999a). In the Mediterranean region, only Cyprus and a few North-African populations have a significant number of tree-nesting pairs (Iezekiel *et al.*, 2004; Bergier & Naurois, 1985), while in Asia this is a frequent behaviour (e.g. Zheng 1987).

The Portuguese tree-nesting population comprises 81 to 88 breeding couples, distributed over 6 major breeding nuclei: International Tejo river basin, West (Estremadura region), Lower Tejo and Sado basin, Medium and Lower Guadiana basin and Southwest uplands (from Grândola to Caldeirão mountain ranges) (CEAI, 2011a).

Historical records and genetic analysis suggested that this Portuguese tree-nesting population has risen from a few founding pairs in the southwestern mountains and in the southeastern steppes in the first half of the 20th century (Mira, 2006). Its growth followed an extensive rural abandonment (Mira, 2006).

Mira (2006) has found that the southwestern population, the focus of this study, has a low level of genetic diversity and a high level of genetic differentiation from other populations (in the International Douro river basin in Portugal and Extremadura and Cadiz provinces in Spain), indicating an absent or rare immigration and suggesting a certain degree of reproductive isolation from its Portuguese and Spanish neighbouring populations. Imprinted tree-nesting behaviour causes a strong preference for these types of habitats over cliffless habitats, which may be the reason for the genetic divergence of this population (Mira, 2006). Consequently, according to its unique ecological, genetic and behavioural features, the Southwest tree-nesting population should be considered as an Evolutionary Significant Unit (ESU) of high importance, deserving an independent management approach in the context of the species conservation in the Iberian Peninsula (Mira, 2006).

One of the priorities of the European Union Species Action Plan (Arroyo & Ferreiro, 1999) for the conservation of Bonelli's eagle in Portugal is to increase the knowledge of the species habitat requirements and the factors influencing population trends. The availability of suitable sites for nesting is known to be, along with prey availability, a primary limiting factor for birds of prey populations (Newton, 1979). Since some of the anthropic impacts on the breeding pairs and their habitats are in continuous increase in the Southwest of Portugal (CEAI, 2011a), the study of the nesting habitat selection patterns and the identification of factors influencing the choice of nest trees are crucial for managing this population.

In the last decades, many papers concerning the breeding biology of Bonelli's eagle in the Iberian Peninsula have been published (e.g. Real & Mañosa, 1997; Fráguas, 1999; Balbontín *et al.*, 2003, 2005; Carrete *et al.*, 2006; Beja & Palma, 2008) but interest on the influence of habitat variables on distribution and breeding success is recent. The distribution patterns of the Bonelli's eagle population are well described for the cliff-nesting population in Spain. They are explained by topography, climate, vegetation, interspecific relationships and anthropic factors (e.g. Ontiveros, 1999; Gil-Sánchez *et al.*, 2004; Muñoz *et al.*, 2005; López-López *et al.*, 2006; Carrascal &

Seoane, 2008). The most suitable areas are located at low altitudes and in rough terrain, sparse vegetation cover and high levels of solar radiation (Muñoz *et al.*, 2005; López-López *et. al.*, 2006; Carrascal & Seoane, 2008). Cliff availability appears to be the most limiting factor for the breeding of the species in the Mediterranean region (Muñoz *et al.*, 2005). Some studies also revealed that there is a hierarchical process in habitat selection (López-López *et. al*., 2006) and that the local selection processes often translates into larger scale patterns (Carrascal & Seoane, 2008).

Inácio (1998) also confirmed the pattern for the Portuguese tree- and cliff-nesting breeding populations. Their distribution is mainly related to areas of high topographic irregularity (particularly in Northern Portugal; Palma, 2009), sparse road network, minimum precipitation in February and low cover by conifer stands.

The majority of the existing studies focus on habitat use and preferences at a large scale but studies about habitat and nest site selection at the local scale are also important. Habitat selection refers to a hierarchical process of behavioural responses, ranging from the selection of a geographical range to the selection of a particular tree, which may result in the disproportionate use of habitats influencing survival and fitness of individuals (Jones 2001). Thus, habitat selection studies lie in the understanding of the mechanisms by which individuals chose habitat and of the consequences of that decision, which determine demographic parameters, such as reproductive success, survival probability and distribution of a population across space (Cruz-Angón *et al.*, 2008). These studies are particularly useful in the case of endangered species (e. g. Bisson *et al.*, 2002; Muñoz *et al.*, 2005; Lima, 2006; Morán-López *et al.*, 2006; Sergio *et al.*, 2006; Poirazidis *et al.*, 2007; Monteiro, 2008; Magaña *et al.*, 2010).

Nest site selection has been quite well studied for cliff-nesting populations of Bonelli's eagle in Spain (e.g. Gil-Sánchez, 1996, 1999b; Ontiveros, 1999; Ontiveros & Pleguezuelos, 2003a,b). However, from the published data examined, only one study has addressed this subject for tree-nesting populations in forest habitats.

In the Cyprus population, Iezekiel (2001) showed that Bonelli's eagle nests in Calabrian pine (*Pinus brutia*) forests and prefers taller trees (mean height of 15.2 ± 0.9 m) with a larger diameter at breast height, located in stands on steep slopes with east-northeast orientation. Nest sites had a significantly higher total stem basal area and density of large trees compared to random sites, yet the total tree density of the nest sites was similar.

Nevertheless, Palma (1995) and Pais (1996) mentioned that breeding sites of tree-nesting population of Southern Portugal tend to be located in rough terrain and dominant hills, with reduced human presence and relative inaccessibility, and exhibiting high vegetation cover and large trees at valley bottoms. These studies represent the preliminary approach to a description of the nesting habitat characteristics at local scale of the tree-nesting populations in Portugal.

As explained above, the Southwest tree-nesting population of Bonelli's eagle shows special features in an European and Mediterranean context related to its breeding strategy, so the study of the requirements of this species to nest in trees is an element of great importance to define management actions. One such action could be the implementation of forest management measures to promote the availability of suitable nest sites and the protection of the actual breeding sites, allowing the preservation of the behavioural diversity and breeding plasticity of the species. Those actions would promote the ongoing positive demographic trend of the tree-nesting population and, ultimately, the conservation of the species at national level.

*Microhabitat factors affecting nest site selection and breeding success of tree-nesting Bonelli's Eagles (*Aquila fasciata*)*

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ABSTRACT

Tree-nesting is an uncommon breeding behaviour in Bonelli's eagle (*Aquila fasciata*) European populations. As few is known about the nest site selection of this species in forest habitats, 52 nest trees located in Southwest Portugal were studied. Generalized Linear Mixed Models (GLMMs) were used to analyse the determinants of the nest tree selection and General Linear Models (GLMs) to assess the influence of microhabitat variables on nest occupancy and breeding success. By comparing actual nest trees with available randomly selected trees, perimeter at breast height (PBH) was found to be an important feature in the choice of the nest tree by the eagles, independently of the tree species. Regarding microhabitat features, presence of mixed shrubs and shrubs dominated by rockrose, hill slope, vegetation cover at 4 to 8 m height, PBH and eucalyptus trees (*E.globulus/E.camaldulensis*) influences positively nest occupancy. However, higher presence of taller thicket of strawberry tree (*Arbutus unedo*) and heath (*Erica arborea*) and lower vegetation cover at 1 to 4 m height and distance to the nearest unpaved road were the only variables significantly associated with breeding success. Therefore, Bonelli's eagle occupy preferentially large trees, particularly eucalyptus trees, located at higher slope and surrounded by tall vegetation cover, which reflects the lower disturbance level of the nesting areas. However, productivity is improved when nesting occurs at sites composed by complex and stratified native shrubby understory. Since the current decline of the quality and availability of large potential nest trees is a serious threat to the tree-nesting population of Bonelli's eagle in the country, PBH measurements obtained in this study were used to define forest management rules, as well as the protection of suitable trees for nesting and breeding sites, that land managers must respect to maintain, create or enhance nesting habitat for this endangered species.

Keywords: Aquila fasciata, *tree-nesting, nest site selection, breeding success, microhabitat, forest, Portugal.*

INTRODUCTION

In the last decades, many papers describing the breeding biology of Bonelli's eagle (*Aquila fasciata* Vieillot, 1822) in the Iberian Peninsula have been published (e.g. Real and Mañosa 1997, Fráguas 1999, Balbontín et al. 2003, 2005, Carrete et al. 2006, Beja and Palma 2008, Palma 2009) but studies about the influence of habitat variables on the distribution and breeding success are mainly available for the Spanish cliff-nesting populations (e.g. Ontiveros 1999, Gil-Sánchez et al. 2004, Muñoz et al. 2005, López-López et al. 2006, Carrascal and Seoane 2008). The most suitable areas for this species in Spain are located at low altitudes and rough terrain, sparse vegetation cover and high levels of solar radiation (Muñoz et al. 2005, López-López et al. 2006, Carrascal and Seoane 2008).

In Portugal, the Bonelli's eagle population includes an important number of tree-nesting pairs, mainly distributed in the South of the country (Palma 1994) and accounting for about 89% of the country's breeding population (CEAI 2011a). This breeding behaviour is very unusual in the rest of Europe but it is common in Asia (e.g. Zheng 1987). In the Mediterranean region, only Cyprus and a few North-African populations have a significant number of tree-nesting pairs (Bergier and Naurois 1985, Iezekiel et al. 2004).

Little is known about habitat and nest site selection of these tree-nesting populations in forested habitats. For Portugal, Inácio (1998) confirmed the influence of high topographic irregularity on the eagle distribution and Pais (1996) revealed their preference to breed in the bottom of valleys. However, from the published data examined, only one study has addressed the nest site selection of tree-nesting Bonelli's eagles at a microhabitat scale (Iezekiel 2001), which showed the importance of tall trees with large diameter at breast height for Cyprus populations.

Bonelli's eagle has an Endangered conservation status in Portugal (Cabral et al. 2006), but is classified as Least Concern (LC) at global scale by the IUCN Red List (IUCN 2011). Despite the species unfavourable status in Portugal, the tree-nesting Southwest population shows peculiar ecological, genetic and behavioural features (Mira 2006) that makes it a unique fast growing tree-nesting population in Europe and, particularly, in the Mediterranean region (Palma 2009). Comprehensive data about this population have been obtained on ecology, reproduction, genetics, demography, population dynamics and key threats (Palma 1995, Cardia 2000, Höfle 2000, Fonseca et al. 2001, Palma et al. 2001, 2005, 2006, Figueira 2009, Palma 2009) but few studies have attempted to describe nest site features (Palma 1995, Pais 1996) or nest site selection.

A detailed analysis of Bonelli's eagle nest trees in Southwest Portugal was carried out. The aims of this study were to (a) describe nests, nest trees and nest sites, (b) identify the most important tree characteristics that influence the choice of the nesting site by comparing actual nest trees with available randomly selected trees, and (c) investigate the microhabitat variables that influence occupancy of nests and breeding success. The knowledge about the requirements of Bonelli's eagle to nest in trees becomes a conservation tool that can help in the definition of specific conservation measurements for this population.

METHODS

Study area

This work focused on 32 breeding territories from the upland tree-nesting Bonelli's eagle population (Fig. 1) located in the Baixo Alentejo and Algarve regions (Beja, Setúbal and Faro districts) of Southwest Portugal. Breeding territories are mainly spread along Cercal, Vigia, Monchique, Silves and Caldeirão mountains and hills of the Mira river basin. This vast mountainous area of c. 4800 km^2, spanning between 37º 59' N - 8º 42' W and 37º 18' N - 7º 43' W, is a relatively homogeneous geographic unit included in the biogeographic Mediterranean Region, and coincident with the Serrano-Monchiquense District in vegetation terms (Costa et al. 1998). Bioclimatically, it is integrated in the dry to wet thermomediterranean floor, except in the highest areas where it reaches the wet mesomediterranean floor (Costa et al. 1998). The maximum altitude is reached at Foia, with 902 m, in the Monchique mountain range. Mean annual precipitation varies between less than 400 mm and 1400 mm, with 50 to 100 days of precipitation per year, and mean annual temperature varies between 12ºC and over 17,5ºC (Agência Portuguesa do Ambiente 2009). 42% of the studied area is classified by the Sistema Nacional de Áreas Classificadas (SNAC), which comprises 62% of the studied nests. The studied area also overlaps 5 Important Bird Areas (IBAs) (Fig. 1).

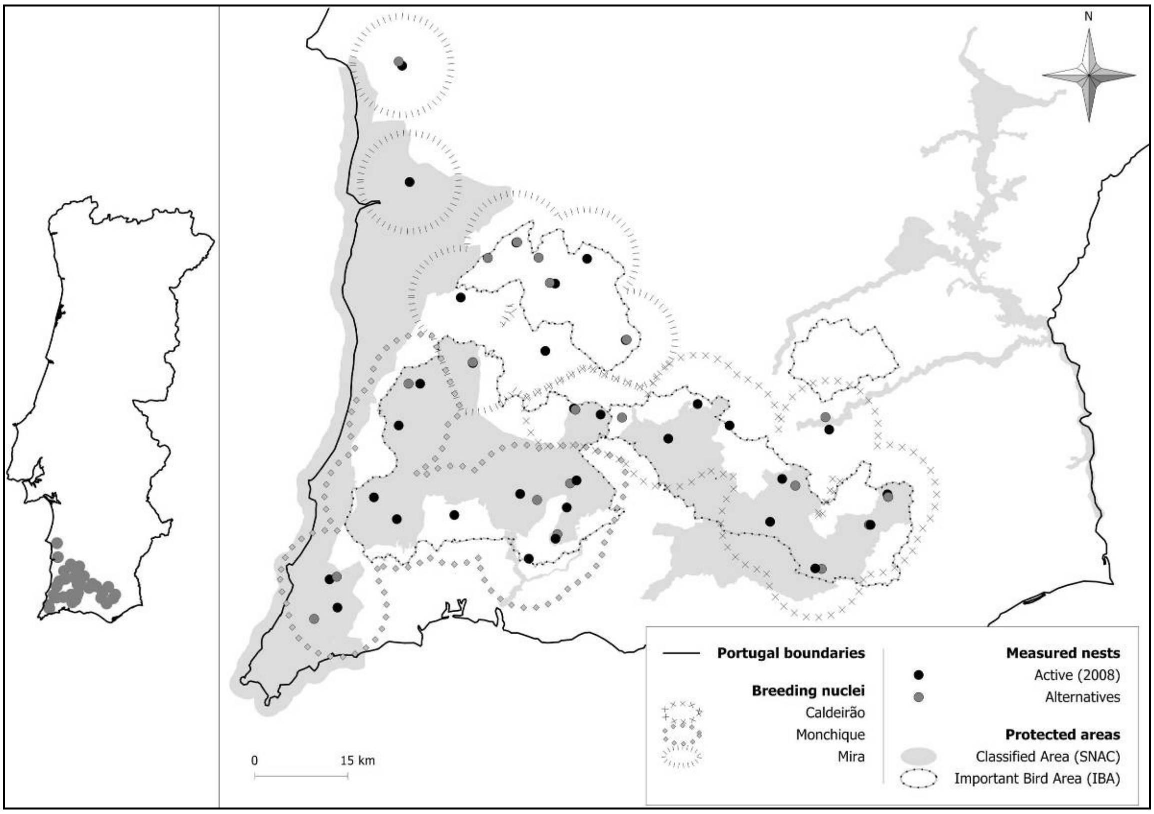

Figure 1. Bonelli's eagle breeding territories, tree nests studied and classified areas by the Sistema Nacional de Áreas Classificadas (SNAC) and IBAs in Southern Portugal.

Despite having slightly different geological and climatic characteristics, the main habitat features are similar throughout the area and reflect the continuous favourable habitat between Grândola, Cercal, Monchique and Caldeirão mountain ranges.

Breeding territories are mainly established in extensive schist and granite mountains of low and medium altitude and rolling topography, interrupted by small rivers and streams in moderately deep valleys. Major water courses in the area are Mira, Arade, Seixe and Odelouca.

Some of the current vegetation cover of these mountainous areas results from the gradual abandonment of widespread cereal cultivation (established during the "Wheat Campaign" at the early XX century) since the 1960s, which permitted the reinstatement of native plants, resulting in areas at different stages of soil and vegetation recovery (Costa et al. 2003, ICN 2006a,b). This vast area is predominantly covered by open to dense cork oak (*Quercus suber*) woodland and extensive scrubland often dominated by the gum cistus (*Cistus ladanifer*) (Acácio et al. 2009). Climax-type vegetation is now limited to small areas located on the northern and shadowed, wetter slopes (ERENA et al. 2008, Palma 2009). This type of vegetation is indicated by the presence of cork oak forests (*sobreirais*) and a complex and stratified shrub layer, with heath (*Erica arborea*) and strawberry tree (*Arbutus unedo*) creating a dense and tall understory. On steeper slopes Portuguese oaks (*Quercus faginea*) of high conservation value also occur (Costa et al. 2003, ICN 2006a,b). On southern and sunny dry slopes, cork oak forests are sparse and the shrub layers is dominated by small to medium-size plants highly resistant to drought: *Cistus ladanifer*, *Ulex parviflorus*, *Genista hirsuta*, *Lavandula stoechas* and *Helichrysum* spp. (Acácio et al. 2009). In areas where human intervention is still present, cork oaks are managed as *montados* through the regular clearing of the shrub layer, and where the understory composition depends on the clearing frequency and shrub age (Porto et al. 2011, Santana et al. 2011).

The gradual abandonment of cereal cultivation led to a widespread rural exodus (Palma 2009) but human occupation is still present in areas of mild relief. The low population density implies low levels of disturbance on breeding sites, which is of extreme importance to the reproductive stability of Bonelli's eagle breeding pairs. After the abandonment of cereal cultivation, eucalyptus (*Eucalyptus globulus*) plantations rapidly expanded on the western mountains (Krohmer and Deil 2003) and several European Community funding programmes to promote reforestation resulted in thousands of hectares of various single-species plantations, particularly of native oaks (*montados* of cork oak *Quercus suber* and holm oak *Quercus rotundifolia*, etc.) and conifers (maritime pine *Pinus pinaster*, stone pine *Pinus pinea*, Monterey pine *Pinus radiata*, etc.) (Louro 1999, Costa et al. 2003). The latter species is mainly located in the Monchique mountain range and around the Mira basin. Thus, the most important forestry activities are related to cork production, strawberry tree liquor production, and eucalyptus and pine forests exploitation. Hunting is also an important activity, mainly in the Caldeirão mountain range (ERENA et al. 2008).

Data collection

The study was performed at 52 nest trees: 18 nest trees in Caldeirão (11 territories), 18 nest trees in Monchique (12 territories) and 16 nest trees in the Mira river basin (9 territories). Two nest trees were measured per territory: the active nest tree during the breeding season of 2007/2008 and an alternative nest tree. This did not apply to territories with only one nest known.

Data collection was carried out between September 2007 and October 2008, but the measurements at the active nests were interrupted during occupation, laying, incubation and nestling periods to avoid disturbance of the breeding pairs.

Studied nests, tree nests and surrounding habitat were characterised using basic forest inventory techniques (Lima 2006, P. Monteiro pers. comm.), a 30 m tape-measure for small distances and an altimeter Blume Leiss® BL6 to determine tree heights, except in trees shorter than 8 m, where a rod with marks spaced at 50 cm intervals was used.

The study variables (Table 1) were chosen based on the general knowledge of the breeding behaviour of Bonelli's eagle in the region and on the literature on birds of prey (e.g. Bakaloudis 2000, 2001, Sergio et al. 2003, Guinn 2004, Lõhmus 2006, Lima 2006, Morán-López et al. 2006), taking into account their measurability and potential relevance for the selection of the nest tree and microhabitat variables in the study area.

Besides the nest trees, two random trees located within a 50 m radius circle meeting the minimum requirements of use by the eagles, were selected at random distance and orientation. For both types of trees, tree variables considered in Table 1 were measured. The imposition of minimum requirements for random trees is a common procedure in other studies of nest tree selection (e.g. Bakaloudis 2000, 2001, Lõhmus 2006, Lõhmus and Sellis 2003). The minimum requirements considered were: *a)* the random tree is of the same species of the nest tree, and *b)* the random tree has more than 1,40 m of PBH (Perimeter at Breast Height) if it is a *Quercus suber,* 0,97 m PBH if it is an *Eucalyptus globulus/camaldulensis* and 0,94 m in the case of *Pinus pinaster/radiata*. These minimum PBHs were determined by preliminary analyses of 29 nest trees measured between 1992 and 1998 (L. Palma unpubl. data).

The characteristics of habitat surrounding nest trees were registered within a 25 m radius circle. All arboreal plants with more than 18 cm PBH were measured and its species, height and PBH registered. The record of the nest site variables described at Table 2 enabled the estimation of microhabitat characteristics.

L. Palma (unpubl. data) and the LIFE-Nature project "Conservation of tree-nesting Bonelli's eagle in Southern Portugal" LIFE06 NAT/P/000194 provided the information about the occupancy and breeding success at the studied nests between 2004 and 2010.

Geographic Information System analysis was performed on Manifold® System 8.0 (CDA International 2010) to draw maps and find distances to the nearest disturbance factor, with the assistance of Google Earth® satellite images.

Table 1. Explanatory variables used for data analysis (more details at S1 in Supplementary Material).

Variable	Description	Categories
Tree features		
SP_G	Groups of tree species	Cork oak, Pine trees (*P. pinaster* and *P. radiata*), Eucalyptus trees (*E. globulus*, *E. camaldulensis* and *E. globulus* plantation tree)
DOMIN	Tree dominance within the arboreal stratum	Dominant, Co-dominant, Intermediate, Dominated
HEALT	Tree Health Condition Index, measured as a defoliation index, adapted from Páscoa & Salazar (2006)	0-10%, 11-25%, 26-40%, 41-60%, 61-99%, 100%
PBH	Tree stem perimeter measured at breast height (1,3 m)	Continuous
hT	Tree height	Continuous
hB	Height of the first branch	Continuous
Nest features		
ACT	Nest activation (used for nesting) in the breeding season of 2008	Active, Alternative
hN	Nest height from tree base	Continuous
BRAN	Number of branches supporting the nest	Continuous
RAMIF	Type of the supporting branching of the nest, except for cork oak	Radial, Alternate
VERT	Vertical location of the nest at the tree crown, except for cork oak	Lower, Middle, Upper
HORI	Horizontal location of the nest at the tree crown, except for cork oak	Central, Lateral, Eccentric
QS_L	Nest location at the cork oak crown	Inner, Middle, Outside
Nest site features		
LOCAL	Tree location on the ground	Hillside on the valley, Stream margin on the valley, Floodplain on the valley, Plateau
POSIT	Tree position on the slope	Lower third, Medium third, Upper third
SLOPE	Average slope of the nest tree hill (m)	Continuous
ORI	Orientation of the nest tree hill	N, NE, NW, S, SE, SW, E, W
ALTI	Altitude of the dominant hill (with bench mark) closer to the nest (m)	Continuous
DIS_W	Distance to nearest waterline (m)	Continuous
DIS_HFT	Distance to nearest Bonelli's eagle nest of the same territory (m)	Continuous
DIS_HF	Distance to nearest Bonelli's eagle nest of other territory (m)	Continuous

Variable	Description	Categories
SHRUB	Type of shrub cover	None (< 25% shrub cover), Mixed scrub, *Cistus* spp. scrub (>50% *Cistus* spp. cover), Tall thicket of *Arbutus unedo* and/or *Erica arborea*
RICH	Species richness: Minimum number of arboreal species	Continuous
HEIG_C	Mean height of all trees in the studied plot (m)	Continuous
PBH_C	Mean perimeter at breast height of all trees in the studied plot (m)	Continuous
DENS_T	Tree density, measured as the coefficient of the number of trees in the studied plot and the plot area (r=25m, A= 0,19635 ha)	Continuous
DENS_Q	Quercus spp. density, measured as the coefficient of the number of oaks in the studied plot and the plot area (r=25m, A= 0,19635 ha)	Continuous
COV	Total vegetation cover of the studied plot, measured as the mean of the visual of estimates of percentage cover taken in 4 directions from the studied trees, by height vegetation classes	COV_I [0-1m], COV_II]1-4m], COV_III]4-8m], COV_IV]>8m]
PASS	Location of the human crossing routes	Hill bottom, Half slope, Hill top, At the same level (for trees located in plateaus), Mixed
DIS_H	Distance to nearest inhabited house (m)	Continuous
DIS_V	Distance to nearest inhabited village (m)	Continuous
DIS_UN	Distance to nearest uninhabited house or village (m)	Continuous
DIS_PR	Distance to nearest paved road (m)	Continuous
DIS_URF	Distance to nearest unpaved road with frequent traffic (m)	Continuous
DIS_URO	Distance to nearest unpaved road with occasional traffic (rural/forestry) (m)	Continuous
DIS_PL	Distance to nearest Medium Tension power line (m)	Continuous
DIS_PLH	Distance to nearest High or Very High Tension power line (m)	Continuous
HUMAN	Human activity index, measured as the mean value of all distances to nearest human disturbance factors (m)	Continuous

Data analysis

Nesting trees, nests and nest site features

The characteristics of the nest trees, nests and nest sites (at microhabitat level) of Bonelli's eagle in Southwest Portugal are described in this chapter. The main results are presented in percentage or mean values ± standard deviation (range).

Determinants of nest tree selection

In order to determine the characteristics of the trees that predict the presence of Bonelli's eagle nests, the characteristics of nest trees were compared to those of random trees (non-nest) (Table 1) by using Generalized Linear Mixed Models (GLMMs). These models are extensions from General Linear Models (GLMs) by adding random effects to the predictor (Zuur et al. 2007). Considering the way the data was obtained, plot identity (group of nest tree and 1 or 2 random trees) was included in the models as a random effect. In this analysis, 44 nest trees (8 nest trees were excluded because of lacking of available random trees) and 78 random trees were analysed.

The presence of nest was considered the response variable, therefore a binomial error distribution and a logit link function were used. The influence of the independent variables on the dependent variable was specified by several different models, one for each group of tree species: cork oak, pine trees (*P. pinaster* and *P. radiata)* and eucalyptus trees *(E. globulus, E. camaldulensis* and *E. globulus* at plantation stands). Model selection was performed using likelihood ratio tests by a backward stepwise method.

Nest occupancy and breeding success in relation to microhabitat factors

The influence of microhabitat factors (nests, nest trees and nesting sites) (Table 1) on occupancy and breeding success of Bonelli's eagle pairs was tested in a random sample of 32 nest trees, one for each territory, according to 2 different analyses. For the influence on occupancy, the number of years of nest occupation in relation to total years of nest monitoring between 2004 and 2010 (OCUP) was specified as the dependent variable. For the influence on breeding success, the dependent variable was specified as the number of years of successful breeding (more than one fledgling) in total years of nest occupancy between 2004 and 2010 (SUC). Orientation of the nest tree hills has a circular distribution that should not be analyzed using statistical methods like the ones used before (Zar 1999), so this variable was not considered in these analyses. Generalized Linear Models (GLM) with a binomial error distribution and a logit link function were used. Firstly, univariate analyses selected the significant variables for the multivariate models. Model selection was then performed using AIC by a backward stepwise method.

For all the analyses, spearman correlations were estimated since collinearity increases the standard errors of the estimates of the model coefficients and can produce unreliable results. None of the numeric variables used in the final models of tree nest selection were significantly correlated with each other. However, several correlations were obtained when studying the influence of microhabitat variables in occupancy and breeding success, therefore variables with lower significance were not included in the multivariate analysis.

Overall model fit was assessed through evaluation of two distinct aspects: the explanatory power and the predictive power of the model. The explanatory power of the model, i.e. the proportion of variation in nest occurrence explained by the model, was accessed by the calculation of the R^2, through the likelihood ratio R^2: $R_L^2 = -2[\ln(L_0) - \ln(L_M)] / -2[\ln(L_0)]$, where L_0 is the likelihood function for the model containing only an intercept and L_M is the likelihood function for the model in question. This test was found to be the superior measure in a comparison of coefficients of determination for multiple logistic regressions (Menard 2000). For the predictive power, we calculated the sensitivity (i.e. proportion of true positives or model capacity to classify a tree with nest when the tree has a nest), specificity (i.e. proportion of true negatives or model capacity to classify a tree without a nest when the tree doesn't have a nest), positive predicted values (i.e. proportion of true positives in relation to all the positive predictions or the tree has a nest when model classified it as having a nest) and negative predictive values (i.e. proportion of true negatives in relation to total negative predictions or the tree doesn't have a nest when the model classified it as don't having a nest), considering the cut-off point as the percentage of non-cases.

In addition to the coefficient estimates of the models we present the odds-ratio (arising from the adopted link function: logit), as well as confidence intervals at 95% given by: CI (95%) = $\exp(\beta_i \pm Z_{1-0.95/2} \times SE(\beta_i))$, where β_i is the model coefficient, Z is the standard normal distribution and SE is the standard error.

All statistical analyses were performed with R 2.13.1 (R Development Core Team 2011) software, using the lmer function from Lme4 library and the glm function from STATS library. Significance level was set at $P \leq 0.05$.

RESULTS

Nest tree, nest and nest site features

The 52 studied nest trees concern 5 arboreal species: 44.2% nests were on blue gum (*Eucalyptus globulus*), 23.8% on maritime pine (*Pinus pinaster*), 21.2% on cork oak *Quercus suber*, 9.6% on Monterey pine (*Pinus radiata*) and 1.9% on river red gum (*Eucalyptus camaldulensis*). Regarding nest occupancy in 2008 breeding season, 44% of the 32 studied breeding pairs nested on *Eucalyptus globulus*, 22.0% on *Pinus pinaster*, 19.0% on *Quercus suber,* 13.0% on *Pinus radiata* and 3.0% on *Eucalyptus camaldulensis* (only one nest). Nest tree photos are in S2 of Supplementary Material.

Bonelli's eagles mostly build nests on dominant trees (73.1%), as they are larger and taller, whose tops rise above the average level of arboreal stratum. In general, nesting trees show a good health condition, as defoliation index ranges from 0 to 10% (59.6%). However, the studied pairs also have nests on dead or nearly dead trees (1 on *Quercus suber* and 1 on *Eucalyptus globulus*).

The 52 studied nest trees have 2.2 ± 0.8 m (0.94 – 4.10 m) of mean perimeter at breast height (PBH) and 23.9 ± 7.6 m (12 – 44 m) of mean height. Excluding the nest on a plantation stand, *Eucalyptus globulus* trees holding nests have a higher mean PBH (2.7 ± 0.7 m) and height (30.0 ± 6.8 m) than other species. However, *Quercus suber* (2.2 ± 0.6 m) mean PBH and *Pinus radiata* (23.6 ± 3.4 m) height are also noteworthy. The unique nest tree within a plantation stand displays much lower values of PBH (0.97 m) and height (23 m) than other eucalyptus trees used to build nests, since the structure of both are very different. The trees first branch is at an average height of 4.0 ± 2.4 m from soil, revealing a presumed relative inaccessibility to climbing carnivores.

Average distance between nests of the same breeding pair is 1795.0 ± 2169.7 m (39.07– 7878.1 m) but in relation to nests of neighbouring territories the distance rises to 7049.3 ± 3334.1 m (3435.2 – 18910.7 m). Assuming a buffer of 7 km radius around the active nest of a breeding pair, the size of virtual home-ranges can be as large as 15000 ha.

Nests are located 14.9 ± 5.7 m (5.5 – 31.0 m) mean height in the trees: 18.9 ± 5.5 m for *Eucalyptus globulus* (excluding the nest on a plantation stand), 14.7 ± 2.1 for *Pinus radiata,* 13.5 ± 3.2 m for *Pinus pinaster*, 8.5 ± 2.3 m for *Quercus suber*, 14 m for the only nest on *Eucalyptus camaldulensis* and 15 m for the only nest on a eucalyptus plantation stand.

On average, 3.9 ± 1.3 (2 – 8) branches supports the nest. Supporting branching of the nest is mainly alternate (88.2%) in pine trees but alternate and radial branching of the tree stem are equally (50.0%) represented in eucalyptus trees. In both species, nests are also frequently located laterally in relation to the tree stem (63.4%), leaning against it, and at the middle (44.2%) or in upper sectors of the tree crown (42.3%). In cork oaks, nests are regularly placed in the outside area of the tree crown (45.5%).

The 52 studied nest trees were mostly located at the hill slopes (67.3%), at the medium third of the hill (65.7%), with N or NE orientation (51.4%) and had an average slope of 36.6 ± 10.2 degrees (13.8 – 67.2 degrees). However, nests at the bottom of the valleys are also common (26.9%) because eucalyptus tree nests are mainly located at galleries along waterlines (50.0%). The mean altitude of the hills where the studied nests are located is 312.3 ± 119.8 m (112 – 580 m).

In what concerns nest site in a 25 m radius circle, the studied breeding areas are mainly embedded on cork oak or holm oak woodlands or abandoned *montados* (44% of the studied sites), but, as said before, nest sites located at eucalyptus galleries along waterlines (21%) are also common. Nevertheless, maritime pine forests (13%), Monterey pine forests (10%), eucalyptus stands (where the tree nest is usually a tree that belongs to the stand but was left uncut for a period of time longer than usual) (6%) and single pine trees surrounded by scrublands (6%) also constitute alternate nest sites.

As a result, tree density ranges from 0 to 1461.7 trees/ha (297.2 ± 282.7 trees/ha) but mean vegetation cover is high, especially in the lower strata (78.4 ± 19.4 % at 0 to 1 m and 47.7 ± 19.4 % at 1 to 4 m).

Regarding the arboreal stratum in the plot, mean height and PBH is 5.9 ± 3.0 m and 0.6 ± 0.3 m, respectively. The shrub stratum, in most cases, shows a mixed composition (*Cistus* spp., *Rubus* spp., gorses, ferns, *Lavandula stoechas, Arbutus unedo*, *Erica arborea* and other species typical of this region) (46.2%) rather than solely dominated by *Cistus* spp. (17%). Nest trees surrounded by complex shrublands of taller thicket made of strawberry tree (*Arbutus unedo*) and/or heath (*Erica arborea*) correspond to 19.2%. Sometimes, no scrubs are found around nest trees (17%).

On average, Bonelli's eagle build their nests at 1577.6 ± 538.2 m (684.4 – 2722.6 m) away from the disturbance factors related to the human activities evaluated in this analysis. Among those disturbance factors, the distance to the nearest inhabited village sands out (mean distance: 2288.1 ± 1278.7 m), since it is the factor that showed the highest minimum distance (521.5 m).

More details in S3 of Supplementary Material.

Determinants of nest tree selection

For cork oak, the model shows that the probability of tree use by Bonelli's eagles increases significantly with tree height, and marginally so with PBH (Table 2). The odds of nest occurrence in a cork oak rises 2 times ((exp(0.53)) (CI 95%=[1.04;2.81]) by each meter of height, maintaining PBH constant, and 31 times (exp(3.43)) (CI 95%=[0.81;1175.65]) by each meter of PBH, maintaining the height constant.

The models for pine trees and eucalyptus trees show that the probability of tree use by Bonelli's eagles increases significantly with PBH (Table 2). The odds of nest occurrence rises 23 times (CI 95%=[1.26;411.55]) for pine trees and 6 times (CI 95%=[1.83;16.78]) for eucalyptus trees, by each meter of PBH. If a variation of 10 cm in the PBH is considered, an increase of 44% and 70% in the odds of nest occurrence is expected in pine trees and eucalyptus trees, respectively.

Table 3 shows the fit of all the models and Fig. 2 presents the scatterplots with smoothed density lines of the fitted values and the variables included in the final models.

Table 2. Summary statistics of the logistic regression models relating the occurrence of Bonelli's eagles nests and tree characteristics ($P \leq 0.05$ in bold).

Model	Variable	Estimate	Standard error	z value	Pr(>|z|)
Cork oak	Intercept	-14.23	4.85	-2.93	**0.0034**
	PBH	3.43	1.86	1.84	0.0651
	hT	0.53	0.25	2.10	**0.0361**
Pine trees	Intercept	-4.77	2.00	-2.38	**0.0172**
	PBH	3.13	1.48	2.12	**0.0344**
Eucalyptus trees	Intercept	-4.26	1.29	-3.29	**0.0010**
	PBH	1.71	0.57	3.02	**0.0025**

Table 3. Explanatory (R^2) and predictive power (sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV)) for cork oaks, pine trees and eucalyptus trees models (percentages).

Model	R^2	Sensitivity	Specificity	PPV	NPV
Cork oak	47	72.7	94.7	88.9	85.7
Pine trees	10	20	100	100	70
Eucalyptus trees	19	38.9	93.6	77.8	72.5

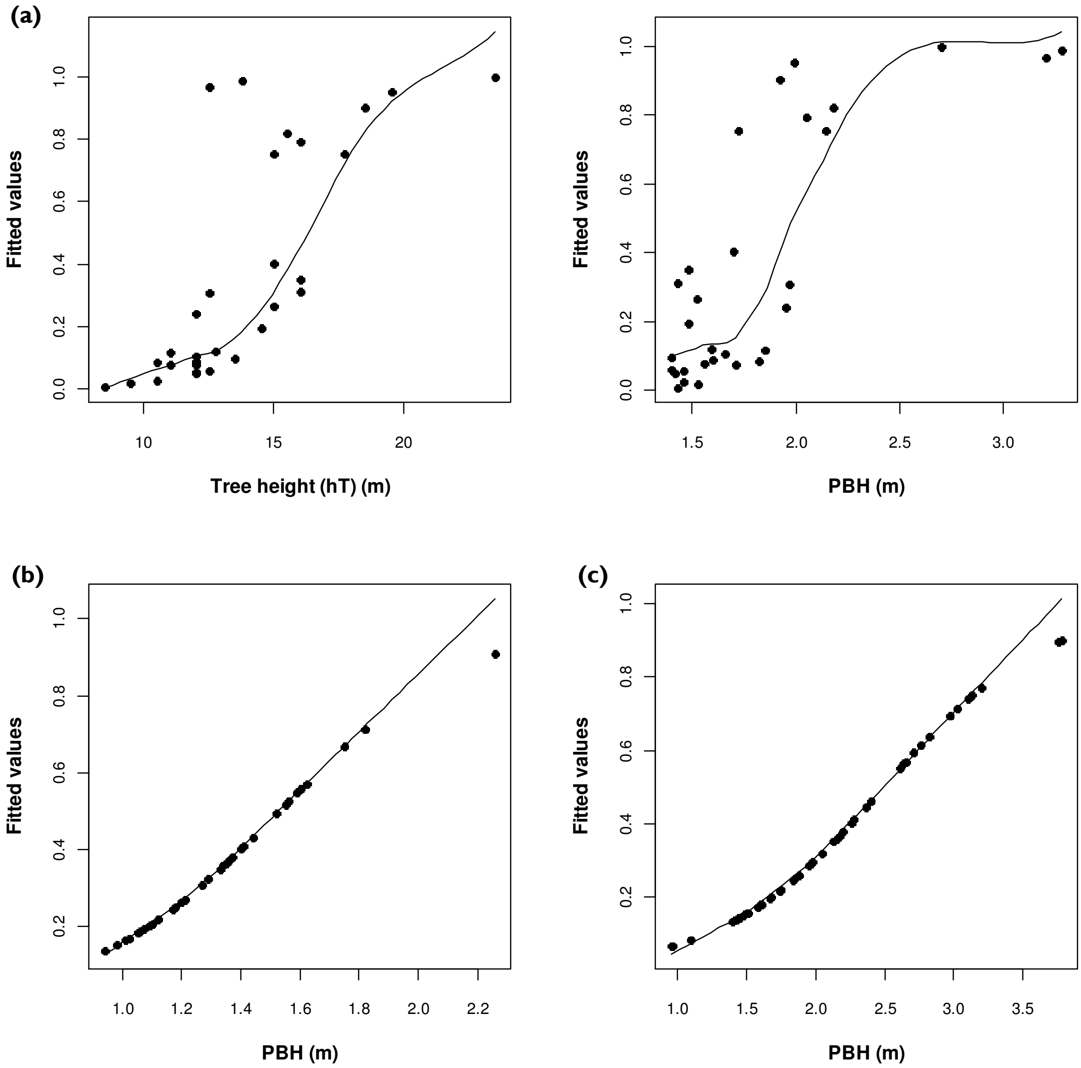

Figure 2. Scatterplots with smoothed density lines relating (a) tree height (left) and PBH (right) in cork oak, (b) PBH in pine trees and (c) PBH in eucalyptus trees, and fitted values of the final logistic models built to explain the selection of nest tree characteristics by the Bonelli's eagle.

Nest occupancy and breeding success in relation to microhabitat factors

The model for nest occupancy shows that the probability of nest use increase significantly with the group of tree species (SP_G), PBH, average slope of the nest tree hill (SLOPE), type of shrub cover (SHRUB) and percentage of vegetation cover at 4 to 8 m height (COV_III) (Table 4). The odds of occupancy rises 99 times when shrubs around the nest tree are dominated by *Cistus* spp. (CI 95%=[11.30;876.20]), 6 times when mixed scrubs are present (CI 95%=[1.21;30.18]), 4 times when the nest is on eucalyptus trees (CI 95%=[1.12;13.26]), 2 times by each meter of PBH of nest tree (CI 95%=[1.06;3.73]), 1 time for each degree in slope of the nesting hill (CI 95%=[1.01;1.14]) and for each percent unit of vegetation cover at 4 to 8 m height (CI 95%=[1.00;1.13]). Location of human intrusion pathways (PASS) is not statistically significant but seems to help in other variables explanation.

The model for breeding success shows that the probability of rearing one flying juvenile or more by Bonelli's eagles increases significantly with shrub cover type, particularly with shrubs dominated by *Cistus* spp. (SHRUB2) and shrubs composed by mixed shrubs (SHRUB1), percentage of vegetation cover at 1 to 4 m height (COV_II) and distance to the nearest unpaved road with occasional traffic (DIS_URO) (Table 4). The odds of successful breeding rises 21 times when tall thicket of strawberry tree and/or heath occurs in the microhabitat (CI 95%=[1.45;312.69]), 14 times when mixed scrubs are present (CI 95%=[1.75;111.90]), but decreases 1 time for each percent unit of vegetation cover at 1 to 4 m height (CI 95%=[0.92;0.10]) and for each meter to the nearest unpaved road with occasional traffic (CI 95%=[0.97;1.01]).

Fig. 3 presents the scatterplots with smoothed density lines of the fitted values and the numeric variables included in the occupancy model.

Table 4. Summary statistics of the logistic regression models, including explanatory power (R^2), relating the occupancy and breeding success of Bonelli's eagles with the microhabitat features ($P \leq 0.05$ in bold).

Model	Variable	Estimate	Standard error	z value	Pr(>|z|)	R^2
Occupancy	Intercept	-8.46	2.24	-3.77	**0.0002**	41%
	SP_G2	1.17	0.81	1.44	0.1492	
	SP_G3	1.35	0.63	2.16	**0.0306**	
	PBH	0.69	0.32	2.15	**0.0313**	
	SLOPE	0.07	0.03	2.30	**0.0216**	
	SHRUB1	1.80	0.82	2.18	**0.0293**	
	SHRUB2	4.60	1.11	4.14	**0.0000**	
	SHRUB3	1.18	0.92	1.28	0.1992	
	COV_III	0.06	0.03	2.27	**0.0235**	
	PASS2	1.39	1.63	0.85	0.3931	
	PASS3	-0.62	0.67	-0.93	0.3510	
	PASS4	0.89	0.75	1.19	0.2339	
Breeding success	Intercept	1.27	1.23	1.04	0.3005	19%
	SHRUB1	2.64	1.06	2.49	**0.0127**	
	SHRUB2	1.68	1.01	1.67	0.0943	
	SHRUB3	3.06	1.37	2.24	**0.0250**	
	COV_II	-0.04	0.02	-2.02	**0.0430**	
	DIS_URO	-0.01	0.01	-2.04	**0.0409**	

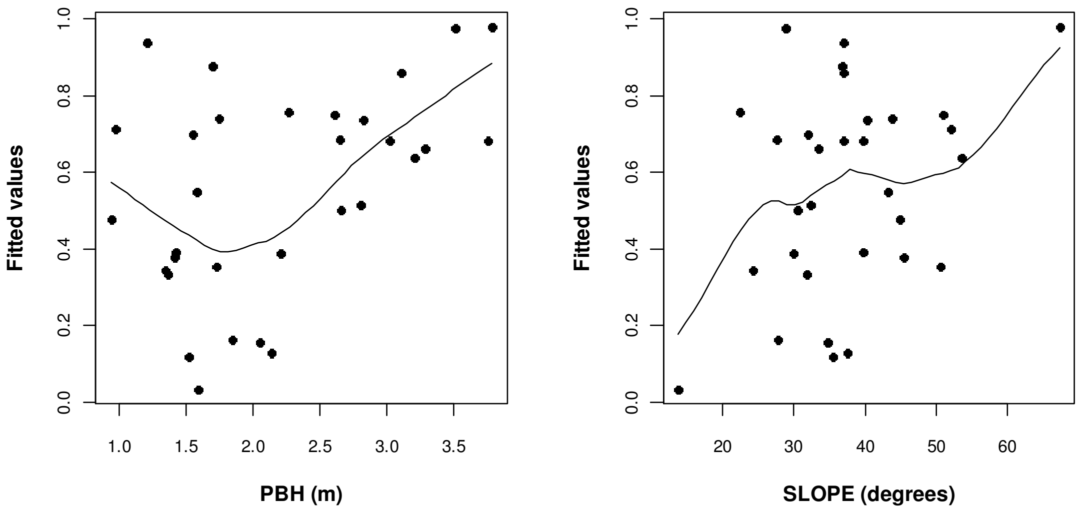

Figure 3. Scatterplots with smoothed density lines relating PBH (left) and SLOPE (right), and fitted values of the final logistic models built to explain the influence of microhabitat features in nest occupancy by Bonelli's eagle.

DISCUSSION

The main features of nest trees, nests and nest sites described in this study confirm the importance of the following structural and physiographic factors for the tree-nesting Bonelli's eagle population:

- Presence of emergent large and tall trees, capable of supporting wide and heavy nests;

- Rough terrain (steep slopes) and presence of dominant hills near the nest locations, as their commanding position act as vantage points for the eagles to overlook the territory. The mean altitude of the hills with nests (312 m) is above the mean altitude of the Algarve mountain ranges (Caldeirão, Monchique and Espinhaço de Cão) (216 m) (MAOT 1999);

- High vegetation cover (arboreal and shrubby), that provides protection to the nest and reflects a minor disturbance of the nesting site;

- Low degree of human presence.

These features reflect the requirement of quiet and inaccessible areas for the species to breed and are equivalent to those mentioned in Palma (1995).

The substantial variation of nest tree and nest features between groups of tree species (cork oak, eucalyptus trees – *E. globulus*/*E. camaldulensis* – and pine trees – *Pinus pinaster*/*Pinus radiata*) is related to their morphology and structure. However, for all the studied groups, PBH is an important feature for eagles in the choice of a tree to nest, but tree height was only significant for cork oak. Since Bonelli's eagle nests can be large and heavy structures, trees with a smaller PBH have too thin and flexible branches to withstand a solid and stable platform required for nesting, so they tend to nest in trees with a high PBH. These results support the idea that large trees are important for the breeding of Bonelli's eagle (Palma 1995, CEAI 2011a).

Iezekiel (2001) also found an identical importance of PBH for Bonelli's eagles nesting in Calabrian pine (*Pinus brutia*) forests in Cyprus. The average PBH (1.48 m) and height (15.2 m) of Calabrian pines used are similar to the average PBH (1.48 m) and height (14.7 m) of maritime pines used by the eagles in Southwest Portugal. The number of branches that supports the nest is of identical range: 2 to 6 branches.

PBH (or DBH, diameter at breast height) is known to be an important dendrometric parameter in the choice of the nesting tree by raptors and forest species (Rottenborn 2000; Malan and Robinson 2002; Poirazidis et al. 2004; Abe et al. 2007; Andersen 2008; Monteiro 2008).

However, eagles sometimes choose trees with a lower PBH. This choice can be explained by (a) the decreasing quality and availability of large trees (CEAI 2011a) and (b) the occurrence of a particular structure of the tree that promotes nest stability. One example is the high number of branches of Monterey pine (*Pinus radiata*) trees that may compensate for the lower PBH. However, nests built in this tree species are more vulnerable to collapse than a nest built in an eucalyptus tree or even in a maritime pine (L. Palma pers. comm.), because their branches are thin, brittle and cannot withstand an heavy weight. An equivalent situation is found when eucalyptus trees within forest stands are chosen for nesting, despite its higher flexibility and lower PBH.

In accordance with the preference for nesting in trees with a high PBH, the nest occupancy model (Table 4) also revealed the importance of PBH and particularly eucalyptus trees for the breeding of Bonelli's eagle.

The growing use of exotic tree species as eucalyptus and pines, and the decreasing use of the native cork oak by Bonelli's eagles in the region also stand out when studying the occupancy rates between 1994 and 2008 (Fig. 4). In 1994, most occupied nests (44%) of the 16 breeding pairs known were built on cork oaks (Palma 1995) but this result was reversed in 2008, since the majority of the occupied nests of the 32 studied breeding pairs were built on blue gum eucalyptus (*Eucalyptus globulus*) (44%). It is worth mentioning that 5 of the 7 breeding pairs known to breed on cork oaks in 1994 still nested in the same tree species in 2008. Furthermore, only 1 of the new 17 couples in 2008 chose to breed in cork oaks whereas 7 and 6 chose blue gum eucalyptus and maritime pine (*Pinus pinaster*), respectively. This work studied nesting trees of 89% of the current tree-nesting population (36 breeding pairs, CEAI 2011a) so this can be considered a robust overall tendency.

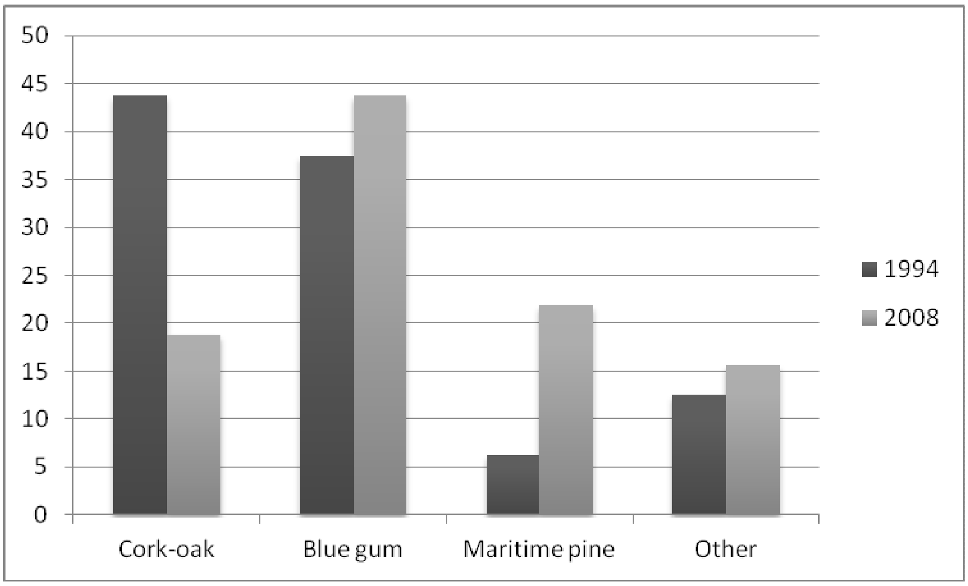

Figure 4. Percentage of occupancy of Bonelli's eagle nests by tree species in 1994 and 2008 in Southwest Portugal.

The increased use of eucalyptus trees and pine trees may be related to the relative availability of suitable trees in face of the extensive morbidity and mortality occurring in cork oaks coupled with the degradation of cork oak woods by forestry-linked perturbation, as discussed later. On the other hand, the increase in the number of eucalyptus trees used may be also due to the large limb structure and tall growth pattern of this species, compared to pine trees and native cork oaks. Mature eucalyptus trees growing near waterlines, of no economic interest, have their size and strength enhanced, developing large spreading branches (Palma 1995). This species is preferably chosen by the eagles because those features provide better support to the large and heavy nests that they build, and maximize nest height, reducing accessibility by predators.

Additionally, size and quality of nest tree structure also have a direct influence on the probability of nest collapse, particularly due to tree sway. The supporting structure of the nest depends on tree robustness (related with tree age) but also on the number of supporting branches and branching type (related to tree morphology) (CEAI 2011a), which increase stability. Nests are frequently built in eucalyptus trees of over 70 years, with lower flexibility (CEAI 2011a). In eucalyptus trees, nests are built near the stem or on a radial branching of the stem, which allows the adjustment of nest weight to the gravity centre of the tree (Palma 1995, CEAI 2011a). Partial collapse of nests outside the gravity centre of the tree is a common event (L. Palma pers. comm.).

In California, hawks nesting in eucalyptus and other exotic trees were found to have an higher breeding success, due to better stability and cover provided by those trees compared to native species (Rottenborn 2000).

The preference for nest sites with high occurrence of *Cistus* spp. in the shrub layer (Table 4) might represent a statistical artifact due to several nests with higher occupancy rates and *Cistus* spp. in the understory being the only nests available for nesting in the territory. Moreover, when only a nest existed in the territory in the monitored period, that nest was always occupied, maximizing the occupancy rate.

On the other hand, probably because they are the most common type of understory cover around nest trees (46.2%), nest trees surrounded by mixed shrubs also presented a higher occupancy.

As explained before, developed, taller vegetation in less accessible areas, provides protection to the nest during breeding, hence it contributes to a lower degree of disturbance. These features may explain the significant and positive influence of higher vegetation cover at 4 to 8 m height and steeper slopes in nest occupancy.

The influence on breeding success of complex and stratified native shrublands dominated by strawberry tree (*Arbutus unedo*) and heath (*Erica arborea*), of lower penetrability, around the nests reveals the importance of habitat renaturalisation and stability for a higher productivity, since the presence of this kind of vegetation means that little habitat perturbation occurred during the last decades (Santana et al. 2011). The relationship between the increase of breeding success and the decrease in the vegetation cover at lower strata (1 to 4 m height) might be explained by the presence of taller shrubs at nesting sites. Although they have a higher branch and foliage density at canopy height, they show a lower density under the canopy, matching lower strata (pers. observ.).

Despite the lower significance level, the increasing breeding success with distance to the nearest unpaved road was not expected because these eagles tend no nest on sites with little disturbance, as demonstrated before. The way the variable was constructed does not allow the differentiation between permanent forestry pathways with relatively frequent traffic and temporary pathways created across the shrub layer to allow cork extraction (which takes place at most only each 9 years). This hinders a correct evaluation of the differential impact of both kinds of paths near the nests, which may help to explain why a shorter distance to unpaved roads seems to favour breeding success. In fact, a large number of pathways are only sporadically used.

In addition to its importance in the choice of the nest tree, PBH also influences nest occupancy by the Bonelli's eagle. The occurrence of mixed scrub in the microhabitat seems to influence both nest occupancy and breeding success but none of the nest tree features seem to have influence in the breeding success. Of all the studied variables, only 3 entered the breeding success model. The explanatory power of this model is low (only 19%), suggesting that factors unrelated to the microhabitat structure may be acting upon the productivity of Bonelli's eagle. Other factors known to influence breeding success can have human origin, such as (a) disturbance events related to understory clearing taking place during breeding season that frequently cause breeding failure (CEAI 2011a), or be related to natural causes, such as (b) strong and persistent rainfall during winter and spring that affects nest occupation, posture and incubation (CEAI 2011a) and (c) fertility decline, probably related to density-dependent regulation mechanisms (Beja and Palma 2008).

Several authors have also examined whether preferred nest sites are also the most successful. Some studies found an association between habitat variables related to nest site selection and successful breeding (Chase 2002, Krüger 2002, Greenwood and Dawson 2011) but other studies found no relationship (Braden 1999, Misenhelter and Rotenberry 2000). Non-adaptive habitat preferences may occur due to temporal or spatial variation in selective pressures (Misenhelter and Rotenberry 2000), so if rapid changes in habitat have occurred and a species had no time enough to adapt to the new selective pressures, the expected association between nest site preferences and nest success may not be evident (Gates and Gysel 1978).

The models explanatory power (R^2) is less than 50% (Table 3 and Table 4). Therefore, they only explain part of the existing variability, revealing the importance of integrating other factors in the analysis, since the choice of a nesting tree may depend on other variables, besides PBH. As explained before, tree structure might have a relevant weight in the choice of a nesting tree, so the suitability of a random tree to support a nest should be investigated and tested as a new predicting variable.

For the nest tree selection models, the predictive power is higher in the classification of trees with no nests (Table 3). The cork oak model has the better explanatory power (47%) as well as the better predictive power. It correctly classifies 73% of the trees with nests (sensitivity) and 95% of the trees without nest (specificity), but it is essential to notice that (a) taking into account all the predictions of trees with nest, 11% are misclassified (absence of nest) (positive predictive value), and (b) taking into account all the predictions of trees without nest, 14% are misclassified (presence of nest) (negative predictive value). The model for pine trees is weaker when explaining the existing variability (10%) but the predictive power is acceptable.

Therefore, further research is required to clarify the relative importance of factors associated with microhabitat that affect nest tree selection, nest occupancy and the observed differences in reproductive success of Bonelli's eagle tree-nesting population.

The extrapolation of these models to other tree-nesting Bonelli's eagle clusters in the country or other populations should be done with precaution. In different habitat conditions, other factors may be involved in tree selection or may influence occupancy and breeding success.

The requirement of breeding sites with little disturbance, high level of renaturalisation and vegetation stability, that promotes breeding success, is illustrated by the results, but the increasing adaptation to the declining in the quality of native trees for nesting is also noteworthy.

Despite the positive trend of the population, the current decline in the quality and availability of large potential nest trees (i.e. high PBH) is a serious threat for the tree-nesting population of Bonelli's eagle in Southwest Portugal (Palma 1995, CEAI 2011a). This decrease may contribute to reduce the reproductive potential of the population in a medium or long term.

In addition to frequent wildfires and high mortality rates observed in all the tree species used for nesting due to pathogen driven morbility and other causes, forestry activities also play a role on this decline (CEAI 2011a). Although the commoner impact is upon the understory composition and development and through disturbance, forestry could even imply the loss of breeding sites (Palma et al. 1996) by logging of large trees, especially when holding nests. In fact, forest management is known to have a potential major impact on wildlife populations, especially by influencing habitat structure (e.g. Hunter 1999).

Microhabitat measurements obtained in this study were used to define sustainable measures for compatibility of forestry activities with conservation and improvement of breeding conditions of the species in the National Action Plan for the tree-nesting Bonelli's Eagle population (CEAI 2011a) and in the Forestry and Hunting Best Practice Guide (CEAI 2011b).

In general, such measures include:

- The preservation of current breeding sites and nest trees;
- The protection of large trees (isolated or in galleries along waterlines) which meet the minimum requirements for nesting, according to perimeter of breast height (PBH): cork oaks 1.48 m, pine trees 1.01 m and eucalyptus trees 1.42 m;

  and according to occupancy preferences: located in the middle or lower third of the hills, surrounded by high vegetation cover and developed shrublands, and relatively far from inhabited houses and frequently used pathways.
- The protection of large trees should be accompanied by maintenance of the tree gallery or a set of 50 to 10 mature trees within immediate surroundings. These trees should be dominant in the case of extensive stands;
- Understory clearings should be selective and avoid deep changes in the nests surrounding habitat.

These measures favour the protection of current breeding sites and nest trees but also the coexistence of alternative nesting supports for tree-nesting Bonelli's eagles.

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This study shows the great importance of trees with a large PBH, especially eucalyptus trees, located in valleys with higher slope and vegetation cover, mainly composed of mixed shrublands and/or dominated by *Cistus* spp. scrubs, for tree-nesting pairs of Bonelli's eagle. The presence of complex and stratified native shrublands of strawberry tree (*Arbutus unedo*) and heath (*Erica arborea*) around the nests are also associated to an increase on breeding success.

The requirement of breeding sites with little disturbance, high level of naturalisation and major stability, that promote breeding success, is illustrated by those preferences. But the increasing adaptation to the current declining in the quality and availability of native trees for nesting is also noteworthy and seems to favour the use of exotic eucalyptus trees.

Despite the current positive trend of the population, the current decline of large potential nest trees, as mature eucalyptus trees, is directly related to habitat degradation and is one of the major threats to the tree-nesting breeding population of Bonelli's eagle in Portugal (CEAI, 2011a). This decline may contribute to reduce the reproductive potential of the population in a medium or long term.

Natural mortality of cork oaks, pines trees and eucalyptus, wildfires, mismanagement of tree cover by forest activities and the logging of large trees (sometimes supporting nests) are responsible for the decline (CEAI, 2011a). Mortality of cork oaks occurs throughout the Southwest uplands due to several causes including physiological stress associated with drought (Sousa et al. 2007), and is particularly relevant in terms of long-term economic viability of cork oak forests, that are the key habitat for the eagles in this region (Palma 1995). In addition, hydric stress may be responsible for gradual damage on large *Eucalyptus globulus* (Palma 1995) and the pine wilt disease for the fast negative impact on maritime pine along the western mountains of Alentejo (Sousa et al. 2001). Besides tree loss, wildfires results in the conversion of forests into shrublands and in the decrease of tree recovery because of lower tree resprouting success and higher seed mortality (Acácio et al. 2009). Forestry activities create persistent or permanent changes on nesting habitat, as arboreal and shrubby cover removal and the cutting of large trees may cause temporary or permanent abandonment of nesting sites (Palma 1995).

The National Action Plan for the tree-nesting Bonelli's Eagle population (CEAI, 2011a) defined, among other measures, (a) the inclusion of species conservation measures in forest management plans and (b) the establishment of mechanisms to encourage and promote the conservation of large trees in current and potential distribution areas of the tree-nesting population, as actions of high priority in a short- and medium-term, respectively. Among other variables, PBH (perimeter at breast height) measurements obtained in this study were used to define the minimum DBH (diameter at breast height) of large trees that should be protected, which were included in the Forestry and Hunting Best Practice Guide for the conservation of Bonelli's eagle (CEAI 2011b). Land managers must respect these and others forest structure thresholds in order to maintain, create or enhance nesting habitat for the Bonelli's eagle, which consequently promotes species conservation.

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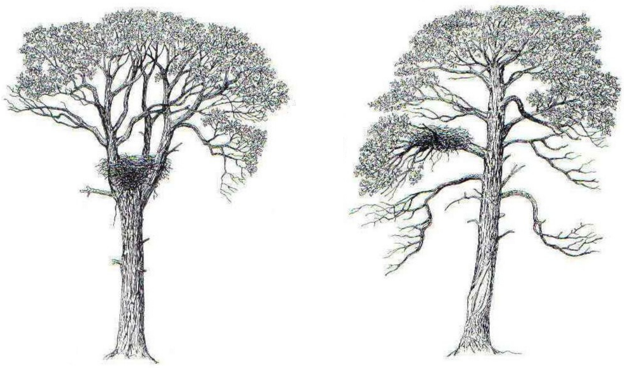
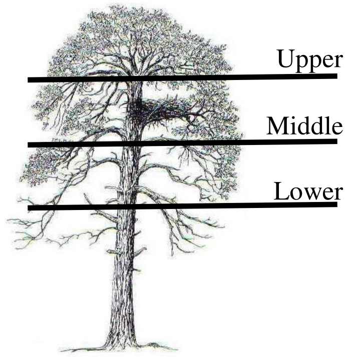
S1. Tree ramification types and location of Bonelli's eagle nests at the tree crown

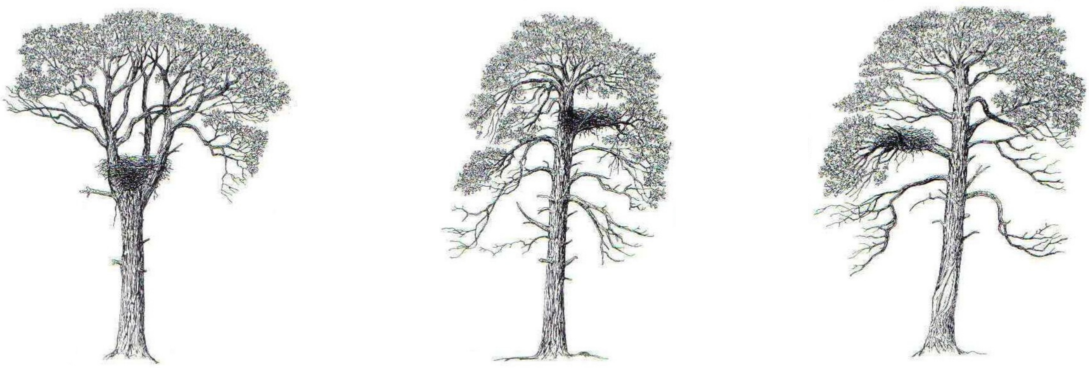


Radial Alternate

Type of supporting ramification of the nest, except for cork oak (RAMIF variable). Adapted from Mebs & Schmidt (2006).

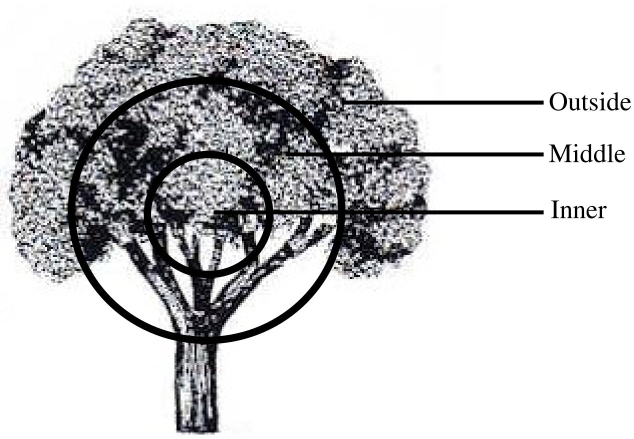


Vertical location of the nest at the tree crown, except for cork oak (VERT variable). Adapted from Mebs & Schmidt (2006).



Central Lateral Eccentric

Horizontal location of the nest at the tree crown, except for cork oak (HORI variable). Adapted from Mebs & Schmidt (2006).



Nest location at the crown tree of *Quercus suber* (NEST_QS variable).

S2. Nest trees of Bonelli's eagle in Southwest Portugal

Blue gum (*Eucalyptus globulus*)

Blue gum (*Eucalyptus globulus*) on a plantation stand

River red gum (*Eucalyptus camaldulensis*)

Cork oak (*Quercus suber*)

Maritime pine (*Pinus pinaster*)

Maritime pine (*Pinus pinaster*)

Monterey pine (*Pinus radiata*)

S3. Nest trees by tree species, and nest and nest sites features of 52 Bonelli's eagle nests.

Nest trees and nests features

	PBH	Tree height	Height of the first branch	Nest height	Number of branches
All species					
Mean ± SD	2,16 ± 0,83	23,85 ± 7,58	4,02 ± 2,4	14,86 ± 5,66	3,94 ± 1,32
Range	0,94-4,10	12-44	0,39-11	5,5-31	2-8
Cork oak (*Quercus suber*)					
Mean ± SE	2,18 ± 0,62	16,04 ± 3,27	4,63 ± 1,18	8,47 ± 2,34	4,45 ± 1,92
Range	1,48-3,28	12-23,5	2,75-6,5	5,5-12,5	2-8
Maritime pine (*Pinus pinaster*)					
Mean ± SE	1,48 ± 0,39	19,89 ± 3,4	4,28 ± 1,9	13,52 ± 3,2	3,58 ± 1,31
Range	0,94-2,26	13,5-26	1,8-7	8-21	2-6
Monterey pine *(Pinus radiata)*					
Mean ± SE	1,3 ± 0,19	23,6 ± 3,42	2,24 ± 1	14,7 ± 2,05	5 ± 1
Range	1,05-1,55	20,5-28	1,5-4	12,5-16,5	4-6
Blue gum (*Eucalyptus globulus*)					
Mean ± SE	2,74 ± 0,73	30,01 ± 6,75	4,08 ± 3,09	18,85 ± 5,48	3,64 ± 0,9
Range	1,42-4,10	18,5-44	0,56-11	11,5-31	2-6
River red gum (*Eucalyptus camaldulensis*)					
Total	2,71	24,00	5,50	14,00	4,00

Nest site features

Variables	Mean ± SD	Range
SLOPE	36,64 ± 10,22	13,8-67,2
ALTI	312,25 ± 119,76	112-580
DIS_W	41,35 ± 42,66	0-176,7
DIS_HFT	1795,03 ± 2169,71	38,95-7878,08
DIS_HF	7049,32 ± 3334,05	3435,17-18910,72
RICH	3 ± 1,5	0-7
HEIG_C	5,91 ± 2,98	0,42-14,17
PBH_C	0,57 ± 0,26	0,14-1,13
DENS_T	297,15 ± 282,67	0-1461,68
DENS_Q	81,19 ± 86,77	0-468,55
COV_I	78,39 ± 19,36	17,92-100
COV_II	47,69 ± 16,66	8-78,33
COV_III	30,74 ± 12,14	5-57,92
COV_IV	23,41 ± 14,16	2,75-50
DIS_H	1027,07 ± 413,8	312,37-2596,08
DIS_NH	754,04 ± 429,18	130,80-2327,39
DIS_PR	1674,35 ± 775,17	350,16-3349,07
DIS_URF	865,78 ± 447,47	168,71-1786,85
DIS_URO	76,67 ± 54,51	5,36-267,48
DIS_V	2288,08 ± 1278,69	521,45-6714,56
DIS_PL	1540,45 ± 895,43	146,36-4289,27
DIS_PLH	4394,35 ± 2801,63	274,32-12960,04
HUMAN	1577,6 ± 538,23	684,43-2722,62