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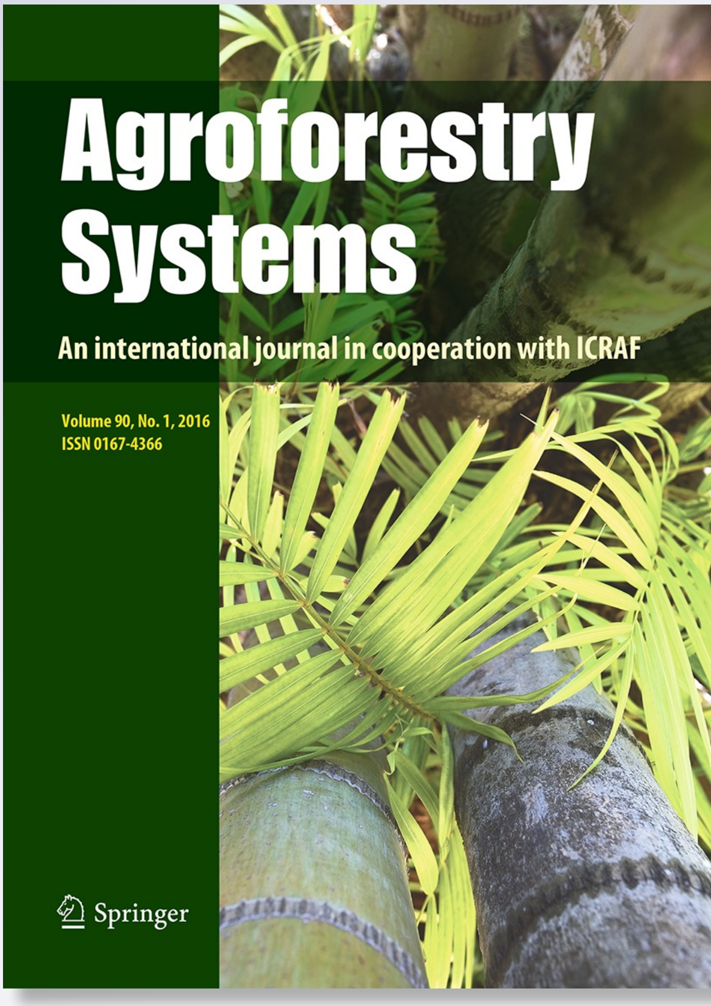

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Abstract Montados are silvo-pastoral systems, typical of the western Mediterranean Basin. When well managed, these ecosystems provide relevant ecosystem services and biodiversity conservation. In the northern part of the Mediterranean Basin, cork oak areas are mainly privately owned and a source of income to landowners, chiefly through cork and livestock production. Sustainable use is essential to maintain the ecological sustainability and socio-economic viability of these ecosystems. Biodiversity conservation and non-provisioning ecosystem services may generate additional incentives promoting sustainable use and conservation of montados, but require adequate mapping and identification. The high conservation value forest (HCVF) framework allows systematic inventory of biodiversity and non-provisioning ecosystem services and is widely applied in forest ecosystems. Here we exemplify the application of HCVF to the cork oak landscape of southern Portugal using a WebGIS tool that integrates the HCVF framework, in conjunction with Pareto optimization, to identify areas important for the conservation of biodiversity and ecosystem services. We present a case study using threatened bird and reptile species, as examples of biodiversity attributes, and carbon storage and water recharge rate of aquifers, as examples of ecosystem services attributes. We identify those areas in a cork oak landscape of southern Portugal where biodiversity and ecosystem services attributes are optimized. These areas can be prioritized for implementing conservation mechanisms, such as payment for ecosystem services, to promote sustainable forest management.

Keywords Silvo-pastoral systems · *montados* · *dehesas* · Forest management · Biodiversity · Ecosystem services · Pareto optimization

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Introduction

Cork oak (*Quercus suber* L.) ecosystems occupy 2.5 million ha in the western Mediterranean Basin both in

North Africa (Algeria, Morocco and Tunisia) and Europe (Portugal, Spain, France and Italy) (Aronson et al. 2009). They can have a closer or more open oak canopy, being structurally similar to forest or savannah type ecosystems, respectively. The typical silvo-pastoral system, called *montado* in Portugal and *dehesa* in Spain, has a relatively low density of trees (30–60 tree per ha) and an undercover of diverse shrub and grassland species (Diaz et al. 1997; Aronson et al. 2009). Dominant uses are cork and livestock production, frequently complemented with big and small game hunting and agricultural crops (Bugalho et al. 2009; Ferraz de Oliveira et al. 2013). Montados have considerable conservation value harboring several threatened and endemic vertebrate species (Diaz et al. 1997; Bugalho et al. 2011a, b) and are a classified habitat under the pan-European network of protected areas Natura 2000 (Berrahmouni et al. 2009). There have been different revisions on the importance of these ecosystems for the conservation of biodiversity (Diaz et al. 1997; Joffre et al. 1999; Bugalho et al. 2011a) although fewer revisions address non-provisioning ecosystem services (sensu MEA 2005) delivered by these systems (for non-provisioning services delivered by montados see, for example: Berrahmouni et al. 2009; Bugalho et al. 2011a; Caparrós et al. 2014). Montados are human-shaped, socio-ecological systems maintained through management. Favoring adequate oak regeneration and a tree cover distributed over different age classes, clearing shrubs over long-term rotation cycles and maintenance of open grassland areas within the shrub matrix may contribute to the conservation of the system and its biodiversity (Rey-Benayas et al. 2008; Bugalho et al. 2011b; Santana et al. 2012). Mismanagement, including abandonment, endangers the ecological sustainability of the ecosystem. Overuse, namely over-grazing, can cause oak regeneration failure, induce even age class structure of the oak cover with a dominance of old trees and a simplified undercover with absence of shrubs (Pulido et al. 2001; Plieninger et al. 2003). Conversely, lack of management can lead to shrub encroachment which affects the whole ecology of ecosystems (Eldridge et al. 2011). Effects of encroachment on the ecology of montados, namely facilitation or competition with oak seedlings can vary with shrub species identity (Rivest et al. 2011; Rolo et al. 2013). Shrub encroachment however usually increases the risk of severe wildfires (Acacio et al. 2007) and may cause loss of habitat heterogeneity and of biodiversity at certain scales (Bugalho et al. 2011a, b). For example, the species diverse grasslands (Díaz-Villa et al. 2003) can be lost to the dominant shrub cover. The system may even fall under a cycle of arrested succession, in which fire and shrub encroachment hinder ecological succession and woodland formation (Acacio et al. 2007).

In Europe, montados have the largest area of distribution in Iberian Peninsula, where they are mainly privately owned. Cork, a non-timber forest product harvested between 9 and 12 years without felling the trees, is the main source of income to cork oak landowners. Maintaining a healthy oak canopy is not only essential to assure cork production but to ensure oak regeneration and the ecological sustainability of the system (Caldeira et al. 2014). The socio-economic and ecological components are closed interlinked in montados. Economic incentives, based on valuation of biodiversity and ecosystem services, may complement cork and other provisioning services economic returns, and contribute to the sustainable use and conservation of montados. For example, compensating landowners for ensuring biodiversity conservation and delivery of non-provisioning services (sensu MEA 2005) is the basis of mechanisms such as payment for ecosystem services (PES) (Wunder 2005; Engel et al. 2008). However, implementation of such mechanisms requires the systematic inventory and mapping of areas important for the conservation of biodiversity and ecosystem services.

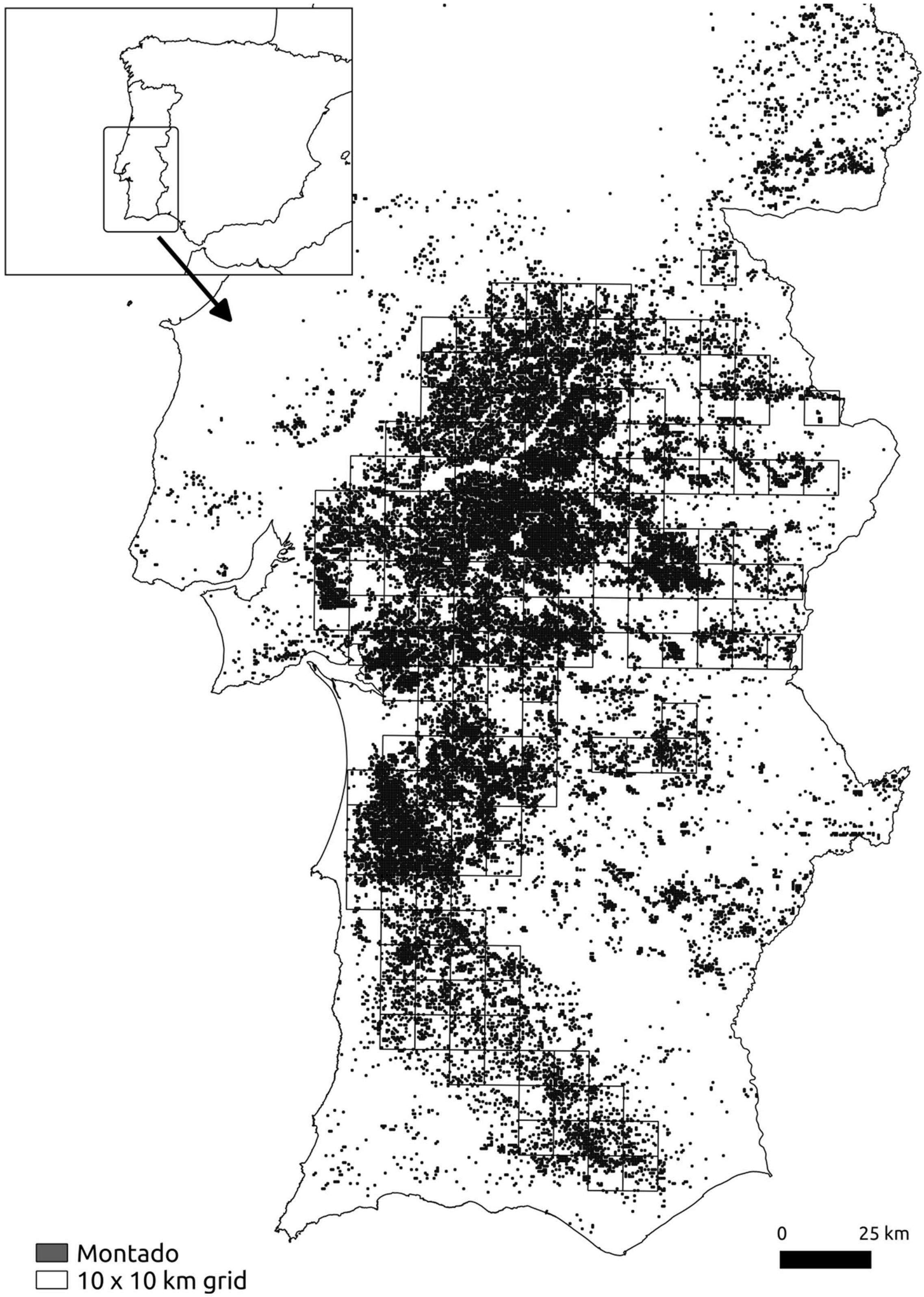
The high conservation value forest (HCVF) is an international standardized framework (Senior et al. 2014; www.hcvnetwork.org) used to systematically identify biodiversity and ecosystem services delivered by forest ecosystems (Branco et al. 2010) which was developed under the Forest Stewardship Council (FSC) certification (Auld et al. 2008; Senior et al. 2014), a voluntary certification scheme which aims to promote the responsible management of the worlds forests. HCVF is covered by one of the FSC environmentally principles: Principle #9 “Maintenance of high conservation value forests” (www.fsc.org), which requires landowners to “maintain or enhance the high conservation value attributes” (HCVs) identified within their properties. HCV attributes cover biodiversity values and ecosystem services, including cultural services, identified at a particular forest management unit (Senior et al. 2014; Auld et al. 2008). HCV attributes also explicitly address the "human needs of local people whose subsistence depends directly on forest resources" and recognizes the importance of active management for maintaining or enhancing HCV attributes (www.hcvnetwork.org). HCVF, therefore, moves beyond conservation based on biodiversity values *per se* and away from "fortress conservation" approaches (e.g. Sarkar and Montoya 2011). By explicitly listing ecosystem services and including "human needs" attributes into its framework, HCVF also relates to the Millennium Ecosystem Assessment classification of ecosystem services (MEA 2005). Additionally, HCVF is an international standard adapted to the national and regional specificities through public interpretation of HCV attributes by multiple stakeholders (e.g. farmer and forest associations, public administration bodies, non-governmental environmental organizations, research entities or private forest companies) which increases its power and legitimacy as a conservation tool.

Although the application of HCVF concept has been criticized, particularly in tropical plantations (Edwards et al. 2012; Edwards and Laurance 2012), available data suggest that HCVF and FSC certification can deliver environmental benefits (Arbainsyah et al. 2014; Medjibe et al. 2013; Dias et al. 2014). HCVF has now been applied independently of forest certification and extended to other aims such as land-use and conservation planning, advocacy, or for developing responsible purchasing policies in forest and non-forest ecosystems (Senior et al. 2014; www.hcvnetwork.org).

In the present work we exemplify the use of HCVF framework in conjunction with HCVs information and Pareto optimization (Pardalos et al. 2008), to identify areas important for the conservation of biodiversity and ecosystem services in cork oak landscapes of southern Portugal. We present a case study using threatened bird and reptile species as examples of biodiversity attributes and carbon storage and aquifer recharge rates as examples of ecosystem services attributes.

Methods

We used Pareto optimization, which defines a state in which resources are allocated in the most efficient manner (Pardalos et al. 2008), and data from the online geographic information system (WebGIS) "Hotspot Areas for Biodiversity and Ecosystem Services" (HABEaS) (www.habeas-med.org; Branco et al. 2010; Bugalho and Silva 2014) to identify areas optimizing a set of HCV attributes in the main area of cork oak distribution in Portugal. HABEaS WebGIS uses HCVF framework and provides free access to HCV attributes on biodiversity and ecosystem services in Portugal. The study area covers approximately 736,000 ha of cork oak landscapes including 500,000 ha located in the water basin of rivers Tagus and Sado (Fig. 1). Data on cork oak distribution was taken from the Portuguese forest inventory (PFI) (Autoridade Florestal Nacional 2010). PFI data is based on photo-interpretation data (500 $\times$ 500 m resolution) collected at national scale between 2005 and 2006 (Autoridade Florestal Nacional 2010). PFI data discriminates land cover classes including forest cover, scrublands and agricultural areas with data on forest cover referring to tree cover only. The study area was formally defined using a 10 $\times$ 10 km UTM grid, commonly used in Portugal for national biodiversity surveys, by selecting the cells of this grid with a percentage of cork oak cover $\geq$10 %. We followed the Food and Agriculture Organization (FAO) criteria of classifying an area of Mediterranean forest if it has a canopy projection $\geq$10 % (FAO 2006). We used data on threatened birds and reptiles occurring in cork oak ecosystems, as biodiversity attributes, and above ground carbon storage and aquifer water recharge rates, as ecosystem services attributes. We choose these attributes as bird species are frequently used as surrogates for biodiversity in different ecosystems (Larsen et al. 2012) and carbon storage and water regulation are frequently referred forest ecosystem services (MEA 2005). We also included information on threatened reptiles as an additional biodiversity attribute. WebGIS data were originally gathered from publicly available information on biodiversity and ecosystem services. Data on bird distribution and bird species conservation status was gathered from the Portuguese Atlas on bird distribution (Equipa Atlas 2008) and the Red Book for Portuguese Vertebrates (Cabral et al. 2005). We followed previous work (Dias et al. 2013) and selected those bird species that spend part or their whole life cycle in the cork oak montado. This includes 172 bird species from which ten are


Montado
10 x 10 km grid
0
25 km

◀**Fig. 1** Map of the study area showing the distribution of cork oak (*Quercus suber*) montado in southern Portugal in a superimposed 10 × 10 km cell grid. Data on cork oak distribution was taken from the Portuguese forest inventory which is based on photo-interpretation data (500 × 500 m resolution) collected at the national level

classified as critically endangered, 13 as endangered and 23 as vulnerable (Dias et al. 2013). Data on distribution of reptiles was collected from the Atlas of amphibians and reptiles of Portugal (Loureiro et al. 2008) which describes 22 reptiles occurring in cork oak ecosystems, from which two species are classified as "Vulnerable" and another two species are classified as "Endangered". The number of threatened species of birds and reptiles was computed for each 10 × 10 km cell within the grid of the study area.

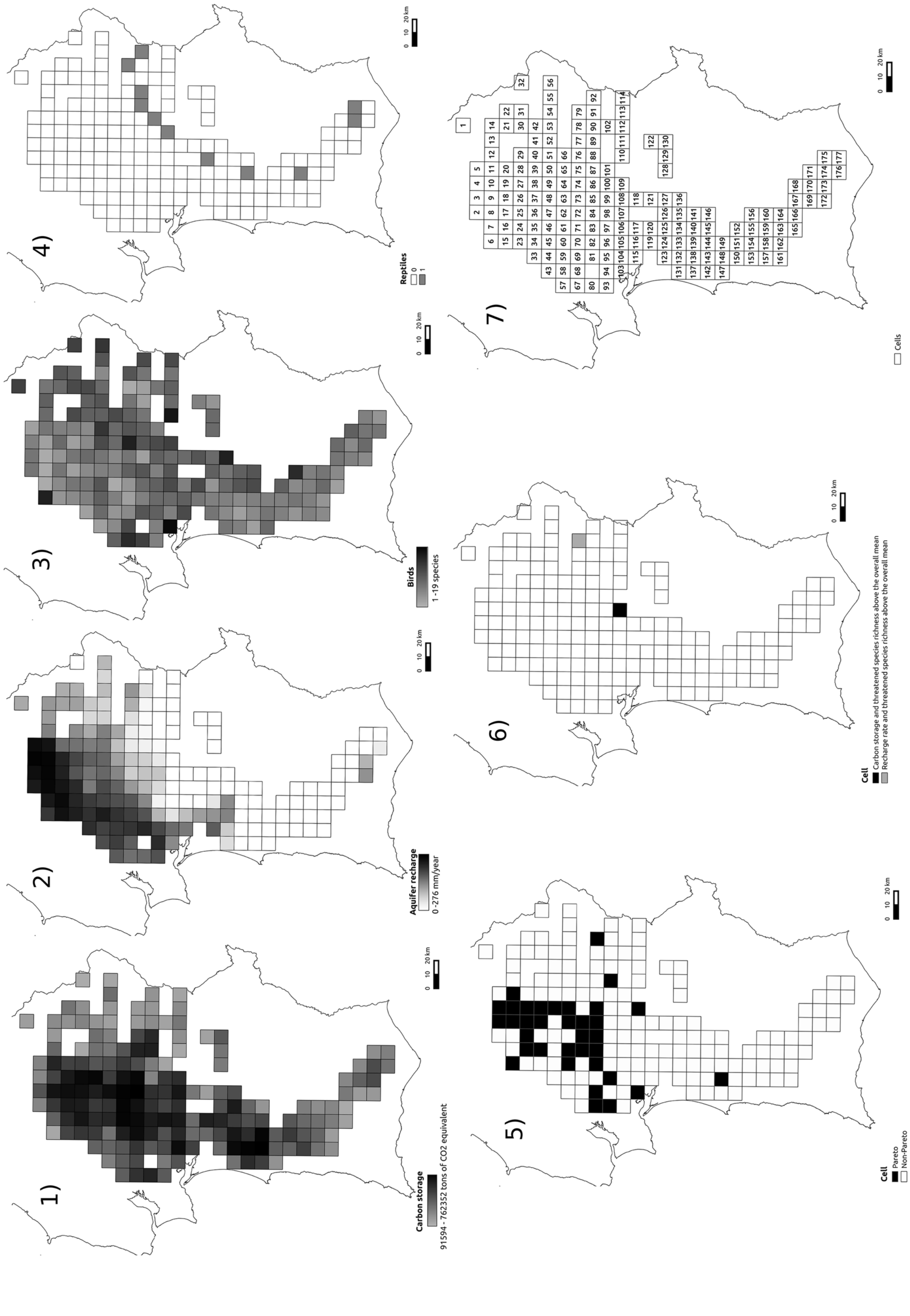
Data on cork oak forest biomass was also collected from the PFI (Autoridade Florestal Nacional 2010). Forest inventories were initially established to assess the commercial value of existent timber in stands but are currently being used worldwide as others sources of information, namely for quantification and analysis of carbon pools regionally (Ciais et al. 2008). In the case of the PFI, aboveground biomass and carbon of montados is estimated through allometric equations that predict individual tree biomass per tree component (e.g. leaves, branches, stem, cork, wood and roots) (Autoridade Florestal Nacional 2010; Palma et al. 2014). We gathered from the PFI, a 500 × 500 m vector grid mapping the distribution of montado in Portugal. Each of these grid cells is classified under PFI as "pure montado stands", "mixed stands where montado is dominant" and "mixed stands where montado is not dominant" and has an associated average carbon storage (Autoridade Florestal Nacional 2010). We used this information to estimate the amount of carbon stored in each 10 × 10 km cell of the study area by summing carbon storage values associated with different montado classes occurring in this grid. Carbon storage data refers to biomass of cork oak trees only, not including information on other carbon pools such as the soil.

We gathered data on aquifer water recharge rates from the management plans of the Tagus and Sado river basins and other river basins occurring in the study area (Lobo Ferreira et al. 1999; Oliveira et al. 2008; Agência Portuguesa do Ambiente 2012). This data consists on polygon vector layers which have associated mean aquifer water recharge rates. For each 10 × 10 km cell of the study area the weighted average of aquifer water recharge rates was computed using the area of each polygon as weight. We used QGIS 2.6 (QGIS Development Team 2014) to perform these calculations.

To identify areas that are important for biodiversity and ecosystem services we used the concept of Pareto optimality (Pardalos et al. 2008) which can be expressed as follows: consider a set of points in an n-dimensional space where each axis is associated to some (measurable) criterion. Each point can be viewed as a particular *state* with respect to the n criteria. A point P dominates point Q if P is at least as *good* as Q with respect to every criterion, and strictly better for at least one criterion. A point that is not dominated by any other point is called non-dominated or Pareto optimal. The concept of Pareto optimality has been increasingly applied to environmental management (Kennedy et al. 2007) and in different ecosystems including the montado (Porto et al. 2014). We identified the set of cells that are Pareto optimal regarding maximum values for four criteria: species richness of threatened birds, species richness of threatened reptiles, the amount of carbon stored in montado and the mean aquifer water recharge rates. We implemented this using the function "psel" from package "rPref" (Rooks 2014) of the software R (R Core Team 2014). Although Pareto optimal cells may not have high values on every criterion, they may be viewed as the most suitable cells regarding the four criteria combined. Indeed, for every given non Pareto cell there is a Pareto optimal cell that is at least as good, or better, than that cell in representing every of the conservation attributes analyzed. To evaluate the relative importance of Pareto cells, the value of each criterion can then be compared with a reference value. In our example, we used the average and the median of particular attributes.

Results

The HCVF framework and the data gathered from HABEaS WebGIS allowed us to use Pareto optimization to identify areas maximizing biodiversity and ecosystem services in the study area (Fig. 2). Among the Pareto cells we identified those areas of cork oak landscapes associated with high levels of biodiversity and carbon storage and those areas that are


1)
Carbon storage
91594 - 762352 tons of CO2 equivalent
0 10 20 km
2)
Aquifer recharge
0-276 mm/year
3)
Birds
1-19 species
4)
Reptiles
0
1
5)
Cell
Pareto
Non-Pareto
6)
Cell
Carbon storage and threatened species richness above the overall mean
Recharge rate and threatened species richness above the overall mean
7)
Cells

◀**Fig. 2** Map of the study area showing **1** carbon storage, **2** aquifer recharge rates, **3** number of threatened bird species, **4** number of threatened reptile species, **5** Pareto cells, **6** Pareto cells for which carbon storage and aquifer recharge rates, combined with number of threatened bird and number of threatened reptile species, are above the overall mean and median and **7** grid cell numbering for facilitating description of results. Data is represented on a 10 × 10 km grid cell and was obtained from different sources. Data on aboveground carbon storage was computed from the Portuguese Forest Inventory (Autoridade Florestal Nacional 2010). Data on aquifer recharge rates was taken from river basin management plans (Lobo Ferreira et al. 1999; Oliveira et al. 2008; Agência Portuguesa do Ambiente 2012). Data on threatened bird species and threatened reptile species was collected from the Portuguese Atlas on bird distribution (Equipa Atlas 2008) and Atlas of amphibians and reptiles of Portugal (Loureiro et al. 2008), respectively

biodiversity rich and associated with high aquifer water recharge rates.

When simultaneously considering the number of threatened species of birds and reptiles, carbon storage and aquifer water recharge rates, 35 Pareto optimal cells could be identified in the study area (30 % of the study area or, approximately, 140,000 ha) (Fig. 2). That is, when considering each of the identified Pareto cells individually, no alternative cells can be find in the study area that optimize the four considered conservation attributes as well as that cell. When considering each attribute individually, the mean and median of Pareto cells were (with the exception of number of threatened bird species) higher than the overall mean and median of the attributes for the overall of the study area (Table 1). Pareto cells may have low values in some criteria but, in these cases, they will also be associated with high values in other criteria. For example, Pareto cell number 6 has a below average value for carbon storage and has no threatened reptile species, however it records one of the highest number of threatened bird species (15 species) in the study area (Table 1). In general, the highest values for each attribute do not coincide in the same cells. For example, Pareto cell 4 has the highest water recharge rate in the study area but harbors no reptile species and has below average values for carbon storage and threatened bird species. Conversely, Pareto cell 14 has one of the highest carbon storage values in the study area but also a below average value of threatened bird species (4 species only) and it is located within an area of no aquifer influence (associated water recharge rate is nil) (Table 1). We could find one Pareto cell showing equal or above average values for carbon storage and threatened bird and reptile species (species richness) and another cell with equal or above average values for water recharge rates and species richness (Fig. 2).

Discussion

The HCVFs framework and data provided by HABEaS WebGIS, provides a simple and coherent way of inventorying and systematizing data on biodiversity and ecosystem services. This, associated with Pareto optimization, shows potential for identifying conservation priority areas through optimization of HCV attributes. Here we focused on four HCV attributes (2 biodiversity and 2 ecosystem

Table 1 Mean and median values for carbon storage, aquifer recharge rates, number of threatened bird species and number of threatened reptile species for all cells (overall) and for Pareto cells in the study area. Number (and percentage) of Pareto cells with values equal or above the overall mean and median of each conservation attribute is also shown

Conservation attribute	Mean for Pareto cells	Overall mean	Number and % of Pareto cells ≥ overall mean	Median for Pareto cells	Overall median	Number and % of Pareto cells ≥ overall median
Carbon storage (tons of CO_2 equivalent)	404,443	307,218	145 (82)	407,873	276,884	156 (88)
Aquifer recharge rate (mm/year)	154	87	156 (88)	188	50	156 (88)
Number of threatened bird species	6	7	62 (35)	6	6	62 (35)
Number of threatened reptile species	0.09	0.06	10 (6)	0	0	10 (6)

services attributes). The approach however allows identification of sites optimizing multiple combinations of biodiversity and ecosystem services attributes.

Identification of areas important for the conservation of biodiversity and ecosystem services is essential to prioritize areas for setting up conservation mechanisms promoting sustainable ecosystem management, such as payments for ecosystem services (PES) (Wunder 2005; Engel et al. 2008). For example, companies willing to invest in conservation could be viewed as potential buyers of services on which their core business depends and fund sustainable management practices in areas important for the conservation of biodiversity and ecosystem services. Different PES schemes can be find worldwide (Engel et al. 2008). For example, in Portugal, the World Wide Fund for Nature (WWF) leads a conservation initiative which aims to promote the sustainable use of cork oak landscapes by seeking donors willing to compensate landowners that commit to sustainable management practices (Bugalho and Silva 2014). This initiative uses information provided by HABEaS WebGIS to identify areas where biodiversity and particular ecosystem services overlap. Pareto optimization, coupled with this information, will contribute to prioritize areas according to donor main interests. For instance, companies willing to mitigate their carbon footprint may be willing to invest in areas important for carbon storage and biodiversity, whilst bottling industry companies may be more interested in investing in areas important for biodiversity and water conservation. Electing conservation areas according to a set of optimized attributes is possibly more appealing to attract conservation funds. Our results imply that in approximately 20,000 ha of the study area there are locations where biodiversity and carbon storage are high and locations where biodiversity and water recharge rates are high. This suggests that implementation of conservation schemes promoting sustainable management in these locations may favor biodiversity and ecosystem services simultaneously.

Similarly, identifying areas that optimize particular conservation attributes may be used to delimit and select conservation areas within forest certification schemes (Auld et al. 2008). Information provided by HABEaS WeGIS, has been used by forest landowner associations in Portugal (e.g. Forest Producer Association of Coruche, Forest Producer Association of Vale do Sado) to identify areas for conservation within their properties, as required by FSC certification. Pareto optimization may further increase the information on conservation attributes of particular locations and thus contribute to delimitation and selection of conservation areas in certified estates.

In the case of silvo-pastoral systems, such as montados, HCVF targets the forest component of the system. There are other conservation frameworks which target the farming component of these systems and which may benefit from the analytical approach presented here. An example is the high natural value farmland systems (HNVF) (EEA 2004). HNVF are low-input, extensive farming systems which generate habitat hosting species of conservation concern (EEA 2004). In Europe, for example, much of the biodiversity values depend on the maintenance and conservation of these low-input farming systems (Kleijn et al. 2009). More than 50 % of Europe's most highly valued biotopes occur on low-intensity farmland (Bignal and McCracken 1996) and over 20 % of the European countryside qualifies as HNVF (Pointereau et al. 2007) including the cork and holm oak (*Q. rotundifolia* L.) silvo-pastoral systems (montados and dehesas) of the Iberian Peninsula (EEA 2004; Pointereau et al. 2007; Pinto-Correia and Carvalho-Ribeiro 2012). Other HNVF systems include semi-natural grasslands, steppes and extensive cereal fields (Pointereau et al. 2007; Paracchini et al. 2008; Ribeiro et al. 2014). HNVF areas are frequently classified according to management intensity such as grazing pressure or levels of fertilizers and herbicides used (EEA 2004) which may vary widely within these areas. In montados, for example, management intensity may vary with grazing regimes and animals species used (e.g. cattle, sheep, game species) or with varying amounts of land allocated to grasslands, pastures, shrublands or complementary agricultural crops (Bugalho et al. 2009). This means that, provided information is available, indicators of management intensity could be analyzed using Pareto optimization to discriminate levels of farming intensity within HNVF systems, such as the montado. Such approach would allow prioritizing areas for of application of agri-environmental schemes in areas classified as HNVF (Kleijn et al. 2009).

Using the HCVF or similar conservation frameworks, together with optimization approaches, to identify priority conservation areas in montados or similar ecosystems, is a line of research that deserves further work in the future.

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