Assessment of ecosystem functioning from space: Advancements in the Habitats Directive implementation

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Assessment of ecosystem functioning from space: Advancements in the Habitats Directive implementation

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ABSTRACT

The Habitats Directive (HD) and the Natura 2000 network establish a common framework for maintaining European natural habitats in a favourable conservation status and represent the main instrument used by conservation decision makers in the European Union. Habitat conservation status depends on the sum of the influences acting upon the habitat and its typical species that may affect its long-term natural distribution, structure and functions. Thus, ecosystem functioning is influenced by the diversity, number and functional traits of the species occurring in a habitat. Although the HD establishes that representative species should be selected to reflect favourable structure and functioning of the habitat type, it would not be realistic to associate species with all aspects of structure and functioning given the variability of Annex I habitats. This constraint led us to seek new approaches that allow a more direct assessment of the ecosystem functioning for natural habitats in space and time. We propose a remote sensing-based approach to characterize and assess the ecosystem functioning of habitats. As a case study, we applied our approach to three Mediterranean natural habitat types from the Iberian Peninsula included in Annex I of the Habitats Directive, i.e., Mediterranean sclerophyllous forest, Mediterranean deciduous forest and Sub-Mediterranean and temperate scrub. First, we estimated two key descriptors of ecosystem functioning derived from the Enhanced Vegetation Index and related them to primary production dynamics by using satellite images captured by the MODIS sensor for each year between 2001 and 2012. Second, we arranged these functional descriptors in two-dimensional space and calculated the distances from the habitats assessed to the reference sites, i.e., habitat patches that showed an optimal conservation status of composition and structure. Then, the distances were averaged over the period, and the habitats were categorized according to their mean distances as favourable or unfavourable-inadequate or unfavourable-bad, as outlined in the reporting guidelines under Article 17 of the Directive. Our approach provides new procedures to assess ecosystem functions across space and time, while complying with reporting obligations derived from the HD.

1. Introduction

The European Habitats Directive (HD) (Habitats Directive, 1992) and the associated Natura 2000 network comprise one of the most challenging conservation frameworks. Based on habitats, i.e., biodiversity elements identified at higher organizational levels than species, the HD represents a major instrument used by European conservation decision makers. It aims to maintain natural habitats in a favourable conservation status (FCS), which is periodically assessed (every six years) by the member states, under the legal obligation derived from Article 17. FCS occurs when the specific structure and functions that are necessary for a habitat's long-term maintenance exist and are likely to continue to exist for the foreseeable future (Art. 1e of the HD).Though ecosystem function is specifically considered a criterion for the FCS assessment; so far, most of the indicators used for this assessment have relied on compositional and structural attributes of habitats, such as species composition, presence/absence of typical species, or habitat spatial variation, as well as on environmental parameters (Lengyel et al., 2008). Nevertheless, the natural range of a habitat in terms of species composition may vary geographically and some characteristic species may even be entirely absent from certain areas and are still considered typical for that habitat (Mehtälä and Vuorisalo, 2007). In such cases, it would be beneficial to have more direct measures of ecosystem functioning.

The use of feasible indicators to inform about the functional dimension of a habitat's conservation status represents a major challenge

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for reporting obligations because functional indicators should be sensitive to both long-term and rapid environmental changes (Pettorelli et al., 2005; Cabello et al., 2012; Díaz et al., 2013). A rapid response to changes would be particularly useful for the monitoring programmes implemented into the Natura 2000 network because it would allow implementation of early-warning systems that enable conservation managers to actively manage in the short term (Cabello et al., 2012). As an example, the Autonomous Organization of National Parks of Spain is developing a remote sensing-based system for monitoring ecosystem functioning of national parks that informs managers of their conservation status at a fine temporal resolution (Cabello et al., 2016). In addition, Maes et al. (2012) highlighted the challenges of incorporating the monitoring of ecosystem functioning and services under current conservation schemes. These authors considered that the concept of ecosystem services has great potential in adding value to current conservation approaches. Although the quantitative relationship between ecosystem functioning and ecosystem services is still poorly clarified (Balvanera et al., 2014, 2016; Bastian, 2013), Maes et al. (2012) showed how habitats in a favourable conservation status had a higher potential to supply ecosystem services than habitats in an unfavourable conservation status. In this sense, functional indicators would help to assess the benefits provided by the Natura 2000 network (Brink et al., 2013) because they are conceptually linked to ecosystem services (Harrison et al., 2014).

To characterize the FCS, the HD promotes the identification of reference values for parameters, including range, area, structure and functions and future prospects. Reference values report the range of variability in ecological structures and processes, reflecting recent evolutionary history and the dynamic interplay of biotic and abiotic conditions and disturbance patterns (Morgan et al., 1994; Fulé et al., 1997). These conditions depict the baseline for comparative purposes and are a frame of reference for designing conservation actions (Bull et al., 2014). Therefore, an objective specification of such reference sites is crucial for properly determining a habitat's conservation status (Bull et al., 2014). To address this, long-term temporal series are necessary to determine past baselines and the extent of human-induced habitat change (Turvey et al., 2015).

Remote sensing, a cost-effective tool, can be particularly useful to address some challenges derived from the HD and can be related to ecosystem functioning dimension (Vanden Borre et al., 2011). The HD establishes that typical species should be selected to reflect favourable structure and functioning of the habitat type (Art. 1e). However, this is not realistic given the variability of the habitats included in Annex I of the Directive (Evans and Arvela, 2011) and the many species that characterize them. Beyond assessing changes in land-use or vegetation structure (Corbane et al., 2015; Schmidt et al., 2017), satellite images also provide repeated and synoptic information about the matter and energy exchanges between the biota and atmosphere, which support ecosystem functions and services. The translation of satellite spectral information into ecosystem functional attributes has been recognized as a valuable tool for conservation practice (Pettorelli et al., 2014; Cabello et al., 2012), and remote sensing-derived metrics related to changes in ecosystem functioning have been proposed as essential variables for monitoring biodiversity (Pereira et al., 2013; Alcaraz-Segura et al., 2017). Thus, remote sensing-derived functional attributes may be appropriate indicators for assessing the FCS of habitat functioning.

On the other hand, the HD establishes that reference values should be based purely on scientific grounds and adapt to changes in our knowledge of habitat types (Evans and Arvela, 2011). In addition, if knowledge is poor for a particular habitat, the reference values for each parameter can be adjusted by expert judgement using available information (Evans and Arvela, 2011). Remote sensing-derived information can help in defining reference conditions by providing temporal series at different spatial and temporal resolutions. In fact, satellite image-derived metrics related to ecosystem functioning have been used to define baseline and reference conditions in different ecosystems and regions (Stoms and Hargrove, 2000; Garbulsky and Paruelo, 2004; Dionisio et al., 2011). Some examples of remotely sensed ecosystem functions are food, water supply, and climate regulation monitored by primary production, evapotranspiration, and land surface temperature, respectively (for a review, see Pettorelli et al., 2017).

In this study, we propose a remote sensing-based approach to assess the ecosystem functioning dimension of the conservation status of habitats included in the HD. As a case study, we worked on three Mediterranean natural habitat types from the Iberian Peninsula that are included in Annex I of the Habitats Directive, i.e., Mediterranean sclerophyllous forest (code: 9340), Mediterranean deciduous forest (code: 9230) and Sub-Mediterranean and temperate scrub (code: 5120). To characterize the functional dimension of the conservation status of these habitats while adhering to the categories used in the reporting process under Article 17 of the HD (i.e., favourable, unfavourable-inadequate or unfavourable-bad), we first estimated two key descriptors of ecosystem function related to primary production and "greenness" canopy seasonality by using satellite images captured by the MODIS sensor. Second, we arranged these functional descriptors in two-dimensional functional space to calculate the distances from the assessed habitat to the reference sites identified through expert-criteria in terms of composition and structure. Finally, we categorized the habitats according to their mean distances, providing a spatially explicit characterization of the habitats in terms of the three reporting categories of conservation status.

2. Materials and methods

2.1. Study area

The study was conducted in the protected natural area of Sierra Nevada (37°09′N, 3°25′W), a Natura 2000 site that encompasses the three selected Mediterranean natural habitat types included in Annex I of the Habitats Directive (Fig. 1). The habitats differ in terms of the plant species composition and vegetation structure, the environmental conditions in which they occur, and the threats they are facing. Mediterranean sclerophyllous forest (habitat code: 9340) is dominated by the holm oak (*Quercus ilex*), a drought-resistant tree with perennial leaves. This habitat occurs between 700 and 1900 m a.s.l., and its main threats are fire, deforestation and anthropogenic reduction of habitat connectivity (Rodá et al., 2009). Mediterranean deciduous forest (habitat code: 9230) is dominated by the Pyrenean oak (*Quercus pyrenaica*), a deciduous tree that occupies humid and shadowed locations between 1000 and 2000 m a.s.l. Its presence in Sierra Nevada is considered relictic, showing an advanced state of degradation that is primarily due to deforestation and grazing (Camacho-Olmedo et al., 2002; García and Jiménez, 2009). Sub-Mediterranean and temperate scrub (habitat code: 5120) is dominated by the legumes *Genista versicolor* and *Cytisus purgans* and occurs between 1700 and 1900 m a.s.l. This habitat has shallow soils and is often associated with arborescent scrubs of *Juniperus sabina* and *J. communis*. Snow sport and leisure structures and grazing and fire have been identified as its main threats in Sierra Nevada (De la Cruz Rot, 2009).

2.2. Assessment approach

We proposed a remote sensing-based approach to characterize the ecosystem functioning dimension of habitat conservation status, using habitat patches that are considered to have an optimal conservation status in terms of composition and structure as reference sites. This is based on the fact that ecosystem functioning is influenced by species composition and structure. For example, Gross et al. (2017) have recently highlighted that diversity of the functional traits of the species occurring in a habitat maximizes ecosystem multifunctionality. In addition, structural vegetation characteristics such as plant species richness and the grass–shrub balance have also been found to play

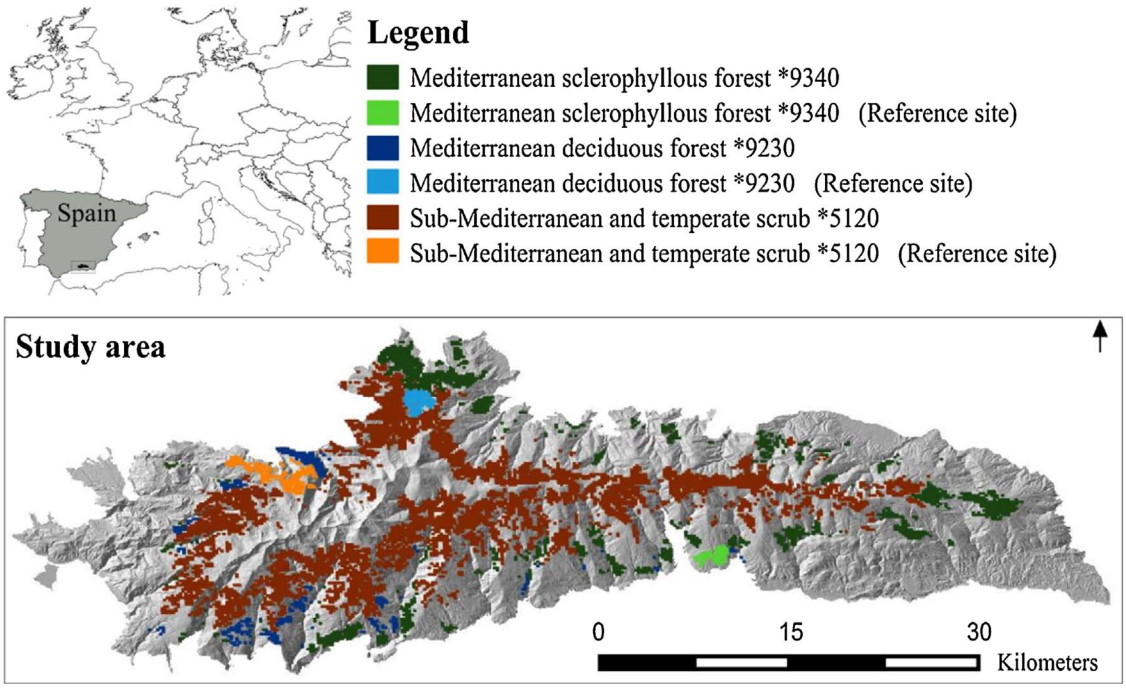

Fig. 1. Distribution of habitats and reference sites considered for the evaluation of conservation status in the protected natural area of Sierra Nevada. Cartography was downloaded from the Ministry of Agriculture, Food and Environment of Spain. (Available from: http://www.mapama.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/servidor-cartografico-wms-/).

important roles as drivers of ecosystem functioning (Eldridge et al., 2011; Maestre et al., 2012), in particular, in shaping primary production (Gaitán et al., 2014).

Thus, we compared the assessed habitat patches with the reference patches to determine their conservation status and classified them according to the three Habitats Directive categories of conservation: favourable, unfavourable-inadequate and unfavourable-bad. Specifically, we assessed the ecosystem functioning component of the conservation status in four steps.

2.2.1. Selection of habitat patches and reference sites

We selected pixels that included habitat cover above 50% (Fig. 1). For that, we visually analysed the cartography using orthoimages, ensuring only the target habitats were evaluated. To define reference sites, the HD states that the conservation status of a habitat should be considered favourable when the specific structure and functions that are necessary for its long-term maintenance currently exist and are likely to persist for the foreseeable future, and the conservation status of its typical species is favourable (Art. 1e). Thus, we selected habitat patches that showed a suitable composition, structure and conservation status, and then, we characterized their ecosystem functioning by using remote sensing-derived information related to primary production dynamics. The selection of these habitat patches was made purely through expert judgement (as Evans and Arvela (2011) recommend when scientific knowledge is poor or absent) by consulting the Sierra Nevada National Park staff and based on both composition (e.g., species diversity and richness) and structural attributes (e.g., canopy cover fraction and structural diversity). The area selected as the reference site for Mediterranean sclerophyllous forest covered 4% (i.e., 3.94 km^2) of this habitat in Sierra Nevada (Fig. 1). For Mediterranean deciduous forest, this reference area covered 18% (i.e., 6.06 km^2) of this habitat, while for Sub-Mediterranean and temperate scrub, this reference area covered 3.2% (i.e., 10.81 km^2) of this habitat.

2.2.2. Ecosystem functioning characterization

Ecosystems are structurally organized as food webs within which energy is transmitted between trophic levels and dissipated into the environment (McNaughton et al., 1989). Primary production represents the base level and is considered as the principal integrator and indicator of functional processes in food webs. For this reason, it has been widely used as one of the most integrative descriptors of ecosystem functioning (Virginia and Wall, 2001; Alcaraz-Segura et al., 2006). For example, descriptors of the primary production dynamics have been proved very useful in monitoring different spatiotemporal aspects of the ecosystem functioning in protected areas networks (Alcaraz-Segura et al., 2009b) or in predicting habitat quality of species (Requena-Mullor et al., 2014; Requena-Mullor et al., 2017). Remotely sensed indicators of ecosystem functioning, such as those derived from the vegetation indices (VIs), are conceptually and empirically linked with primary production (Paruelo et al., 1999). Monteith's model (Monteith, 1972) states that carbon gains of vegetation are a function of the quantity of incoming photosynthetically active radiation (PAR), the fraction of this radiation intercepted by vegetation (fPAR), and the light use efficiency (LUE). The flux estimated using the Monteith's model included net and gross primary production and net ecosystem exchange (Ruimy et al., 1994). In particular, the VIs are linearly related to net primary productivity through the fraction of photosynthetically active radiation intercepted by green vegetation and represents the vegetation "greenness" (Ruimy et al., 1994). Among the VIs, the Enhanced Vegetation Index (EVI) has been widely used to derive descriptors of ecosystem functioning (Alcaraz-Segura et al., 2013; Huete et al., 1997; Huete et al., 2008; Ma et al., 2013; Ma et al., 2014). Specifically, we estimated two functional descriptors expressed as average temporal summaries: the annual mean EVI (*meanEVI*) as a surrogate of mean annual primary production (i.e., per year) and the seasonal coefficient of variation (*cvEVI*) as an indicator of seasonality or annual temporal variation (Alcaraz-Segura et al., 2013). These functional descriptors were derived from satellite images captured by the MODIS sensor onboard the NASA TERRA satellite (www.modis.gsfc.nasa.gov/). We used the MOD13Q1 EVI product, which consists of 16-day maximum value composite images (23 per year) of the EVI at a pixel size of 250 × 250 m. This product has atmospheric, radiometric and geometric corrections. We first used the product's Quality Assessment (QA band) information to filter out values affected by high content of aerosols, clouds, shadows, snow or water.

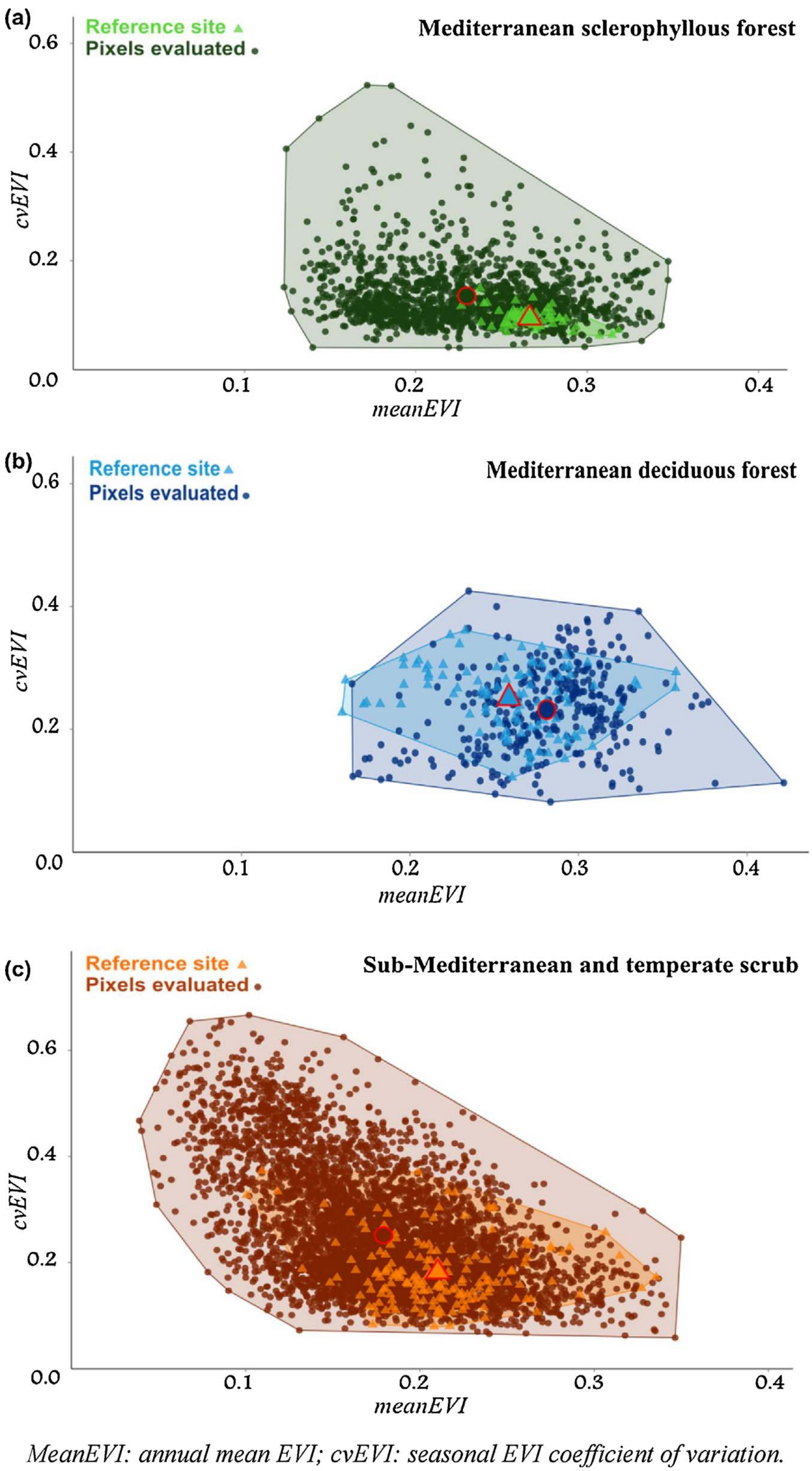

Fig. 2. Functional characterization of three Mediterranean habitats in the protected natural area of Sierra Nevada. Pixels were arranged in two-dimensional space in terms of their *meanEVI* and *cvEVI* values, using the year 2012 as an example. Small circles and triangles represent evaluated and reference pixels, respectively. Large circles and triangles with red borders depict the centroids (i.e., means) of the functional spaces of evaluated and reference habitat patches, respectively. Polygons represent the functional space, i.e., the minimum area containing all evaluated and reference pixels. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Next, we calculated *meanEVI* as the mean of the 23 images within a year and *cvEVI* as the intra-annual standard deviation divided by *meanEVI*. Both descriptors capture important features of ecosystem functioning for temperate ecosystems such as primary production and its temporal dynamics (Pettorelli et al., 2005; Alcaraz-Segura et al., 2009a).

2.2.3. Ecosystem functional descriptor analysis

The *meanEVI* and *cvEVI* values of each pixel and year were arranged in two-dimensional space for the period between 2001 and 2012, and functional spaces were estimated (Alcaraz-Segura et al., 2009a) (Fig. 2). For that, we enclosed all pixels by connecting the outer pixels in such a way as to create a convex polygon (Mohr, 1947). Then, for these two descriptors, we calculated the mean of the pixels belonging to reference patches and the mean of the pixels belonging to assessed patches per year. Finally, we explored the relationship between *meanEVI* and *cvEVI* over the period by calculating their Spearman rank correlation for each

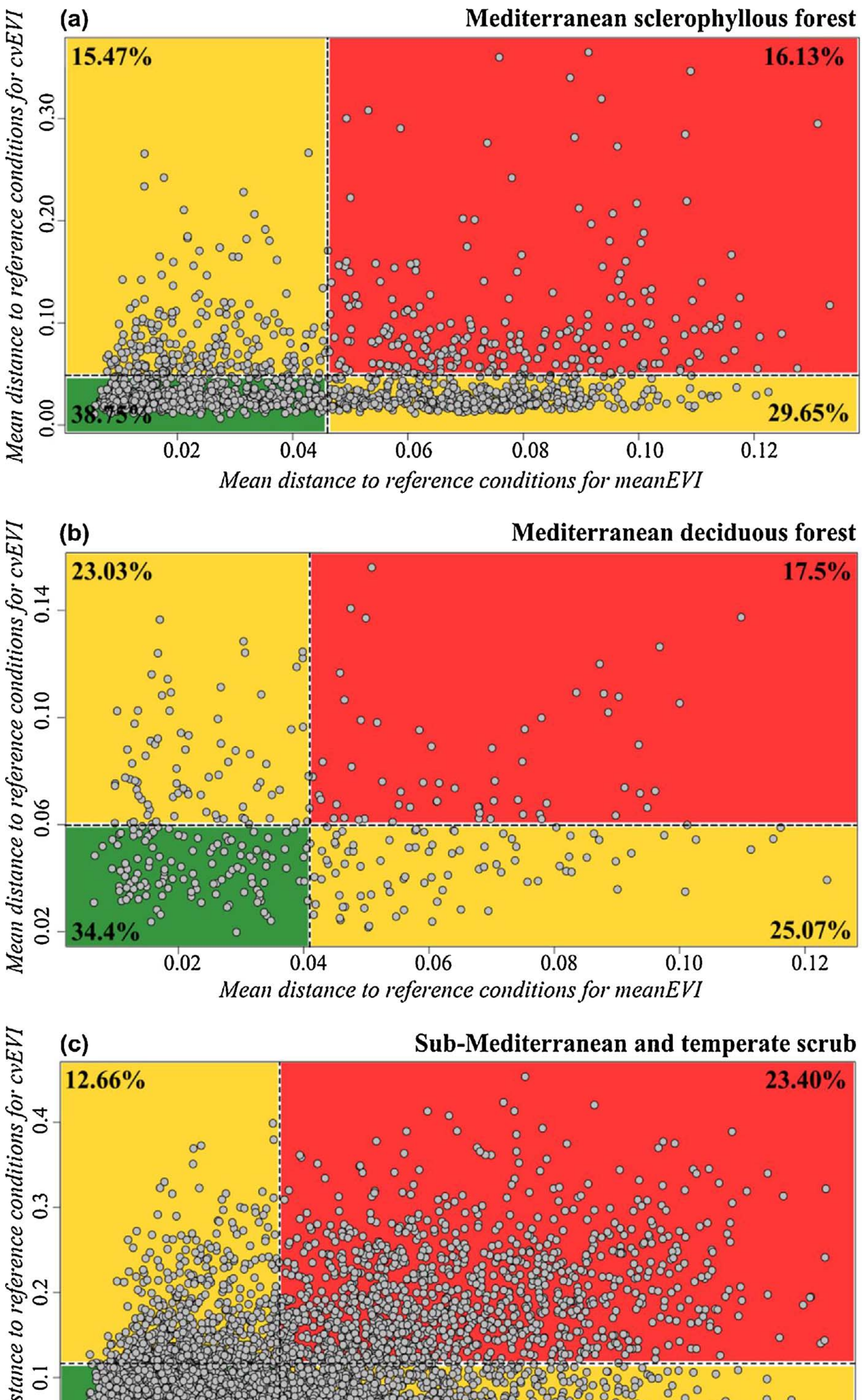

Fig. 3. Assessment of ecosystem functioning state of three Mediterranean natural habitats in the protected natural area of Sierra Nevada. Dashed lines represent the inter-annual means of the distances between *meanEVI* and *cvEVI* values of each pixel and their corresponding reference centroids over the period 2001–2012. Green: favourable; yellow: unfavourable-inadequate; and red: unfavourable-bad (see "Conservation category classification" subsection). Percentages refer to area occupied by each conservation category.

year and then summarizing them by the mean. How the correlation varies can offer interesting information, such as whether similar behaviours may be expected from both functional attributes in response to the same environmental changes.

2.2.4. Conservation category classification

MeanEVI and *cvEVI* values of each pixel can be treated as spatial coordinates in the functional spaces, and their centroids represent their mean values. Thus, the distance from each evaluated pixel to the reference centroid represented the deviation from the functional reference sites. We used such deviations to classify the pixels into conservation categories. The distances were calculated as the absolute value of the differences between the *meanEVI* and *cvEVI* values of each pixel and their corresponding reference centroids in each year. Then, the distances were averaged over the entire time period and arranged in two-dimensional space, where the abscissa axis represented the distances to the *meanEVI* centroid and the ordinate axis represented the distances to the *cvEVI* centroid. Finally, we estimated the mean distances for all pixels over the time period and delineated four quadrants by crossing the lines that passed through the means and ran parallel to both axes (Fig. 3); this method provided the thresholds necessary to classify pixels into conservation categories. The pixels were categorized based on the quadrant they occupied: favourable (bottom left) had distances lower than both the *meanEVI* and *cvEVI* means; unfavourable or inadequate (upper left and bottom right, respectively) had distances higher than *meanEVI* or *cvEVI* means, respectively; unfavourable and bad (upper right) had distances higher than both *meanEVI* and *cvEVI* means.

Finally, the local conditions of the reference sites, such as those related to aspect, altitude, etc., could potentially affect the conservation status assessment. To explore this, we calculated the spatial auto-correlation Moran's Index of the conservation categories by using the spatial coordinates of the pixels as weights in R (package *ape* and function *Moran.I*) (Paradis et al., 2004).

3. Results

Fig. 2 shows the arrangement of the evaluated and reference pixels in their functional spaces in terms of their *meanEVI* and *cvEVI* values, using the year 2012 as an example. These charts allow visual examination of the functional state of habitats based on their proximity to reference sites. In the sclerophyllous forest, the centroid of reference site was in the extreme of the functional space delimited by the assessed pixels (Fig. 2a), while in the deciduous forest, the reference centroid was situated more towards the middle of the functional space both in terms of *meanEVI* and *cvEVI* (Fig. 2b). In the Sub-Mediterranean and temperate scrub, the reference site was centred only in terms of *meanEVI* (Fig. 2c). In general, dispersion around the centroids was lower in the reference sites than in the evaluated habitats, except in the deciduous forest (see Table 1). The averaged pairwise Spearman correlation between *meanEVI* and *cvEVI* estimated over the period was very low for Mediterranean sclerophyllous forest and Mediterranean deciduous forest ($rho = -0.044 \pm 0.014$ SE and 0.047 ± 0.019 SE, respectively) but was higher for Sub-Mediterranean and temperate scrub ($rho = -0.542 \pm 0.051$ SE). Accordingly, it would be expected that both functional attributes respond in the opposite way to the same environmental changes.

The pixel classification into conservation categories for Mediterranean sclerophyllous forest showed that 16.13% of its area was considered unfavourable-bad, and 38.75% favourable (Fig. 3a). Because the expected seasonality of homogeneous holm oak forest is low, the increase in *cvEVI* (i.e., 31.6% = 15.47% + 16.13%; Fig. 3a) compared to the reference conditions may be interpreted as an increment of heterogeneity by colonization of vegetal species (such as native species expanding its range; field observation) that showed different temporal dynamics in terms of primary production. The pixels classified as unfavourable were mainly located in the east and north regions of Sierra Nevada (Fig. 4a). For Mediterranean deciduous forest, 65.6% of its area was far from the averaged reference conditions for the time period analysed (Fig. 3b), in terms of *meanEVI* values, *cvEVI* values, or both. No manifest spatial pattern was observed for pixels with an unfavourable status (Fig. 4b). The largest percentage of pixels classified as favourable status was found in Sub-Mediterranean and temperate scrub (46.39%) (Fig. 3c), mainly located at the lowest altitude for this habitat type (Fig. 4c). However, 23.40% of its area was far from reference conditions, both in terms of primary production and seasonality. It is noted that most of those pixels were situated at the upper limit of its altitudinal range. This habitat experiences frequent snow events (Molero and Fernández, 2010) in Sierra Nevada, and therefore, this spatial pattern may be related to snow cover dynamics.

Table 1
Dispersion around the centroids of functional space for the three habitats assessed in the year 2012. Dispersion was estimated in terms of standard deviation of the means of *meanEVI* and *cvEVI,* respectively.

	Mediterranean sclerophyllous forest		Mediterranean deciduous forest		Sub-Mediterranean and temperate scrub	
	MeanEVI	*cvEVI*	*MeanEVI*	*cvEVI*	*MeanEVI*	*cvEVI*
Assessed pixels	0.05	0.06	0.04	0.07	0.05	0.11
Reference site	0.02	0.02	0.04	0.05	0.04	0.06

The spatial auto-correlation reached by the conservation categories of the three habitats was close to zero (Mediterranean sclerophyllous forest: n = 1484, Moran's I = -0.043, *p*-value $\ll 0.05$; Mediterranean deciduous forest: n = 343, Moran's I = -0.01, *p*-value $\ll 0.05$; Sub-Mediterranean and temperate scrub: n = 5064, Moran's I = -0.013, *p*-value $\ll 0.05$), which means that they were randomly distributed. Therefore, we considered the effect of the location of the reference sites on conservation status assessment as negligible.

4. Discussion

4.1. Assessment of the ecosystem functioning from space in sierra nevada

In this study, we proposed characterizing and assessing ecosystem functioning by using remote sensing-derived indicators related to primary production dynamics. According to the guidelines for assessing structure and functions of habitats at the biogeographical level, when more than 25% of the area is unfavourable (both inadequate and bad combined), the conservation status should be assessed as unfavourable-bad (Evans and Arvela, 2011). Following this approach, our results showed that the functional state of Mediterranean sclerophyllous forest, Mediterranean deciduous forest and Sub-Mediterranean and temperate scrub in Sierra Nevada should be considered as unfavourable-bad, since they had less than 75% of their area in a favourable state. This assessment contrasts with that reported over the period 2007–2012 for these three habitats at both biogeographical and national level, which was unfavourable-inadequate, unknown and favourable, respectively (European Environment Agency; Spanish Ministry of Environment, 2013). The conservation status reported by Spain was supported by field data-based protocols (Spanish Ministry of Environment, 2009) that use different amounts and types of parameters depending on habitat (Table 2). Three of these parameters may be indirectly related to primary production, i.e., herbivory (estimated by ungulate density), defoliation and canopy health (both estimated by visual observation). However, the two EVI-derived functional attributes used in our study inform more directly about vegetation greenness dynamics, and therefore, we suggest incorporating them to the protocols used by the Member States. This would allow assessing the same habitat in different countries using the same criteria and filling gaps in functional parameters, such as in Sub-Mediterranean and temperate scrub, in which no parameter was proposed for the Spanish protocol. In general, field data-dependent monitoring schemes are difficult to support economically and given the economic limitations in many European countries, the incomplete implementation of such protocols and the lack of information for some habitats (e.g., Mediterranean deciduous forest) may come from unsustainable monitoring strategies (Vihervaara et al., 2017). In this sense, remote sensing-derived information allows to conduct efficient monitoring schemes for biodiversity conservation by offering broad scale automated and repeatable methods for monitoring indicators of vegetation condition across a variety of habitats (Pereira et al., 2013; Lawley et al., 2016). In addition, the growing amount of freely available remote sensing data enables the maintenance of realistic habitat monitoring schemes at a relatively low cost over time (Vihervaara et al., 2017), which is key to member states adhering to

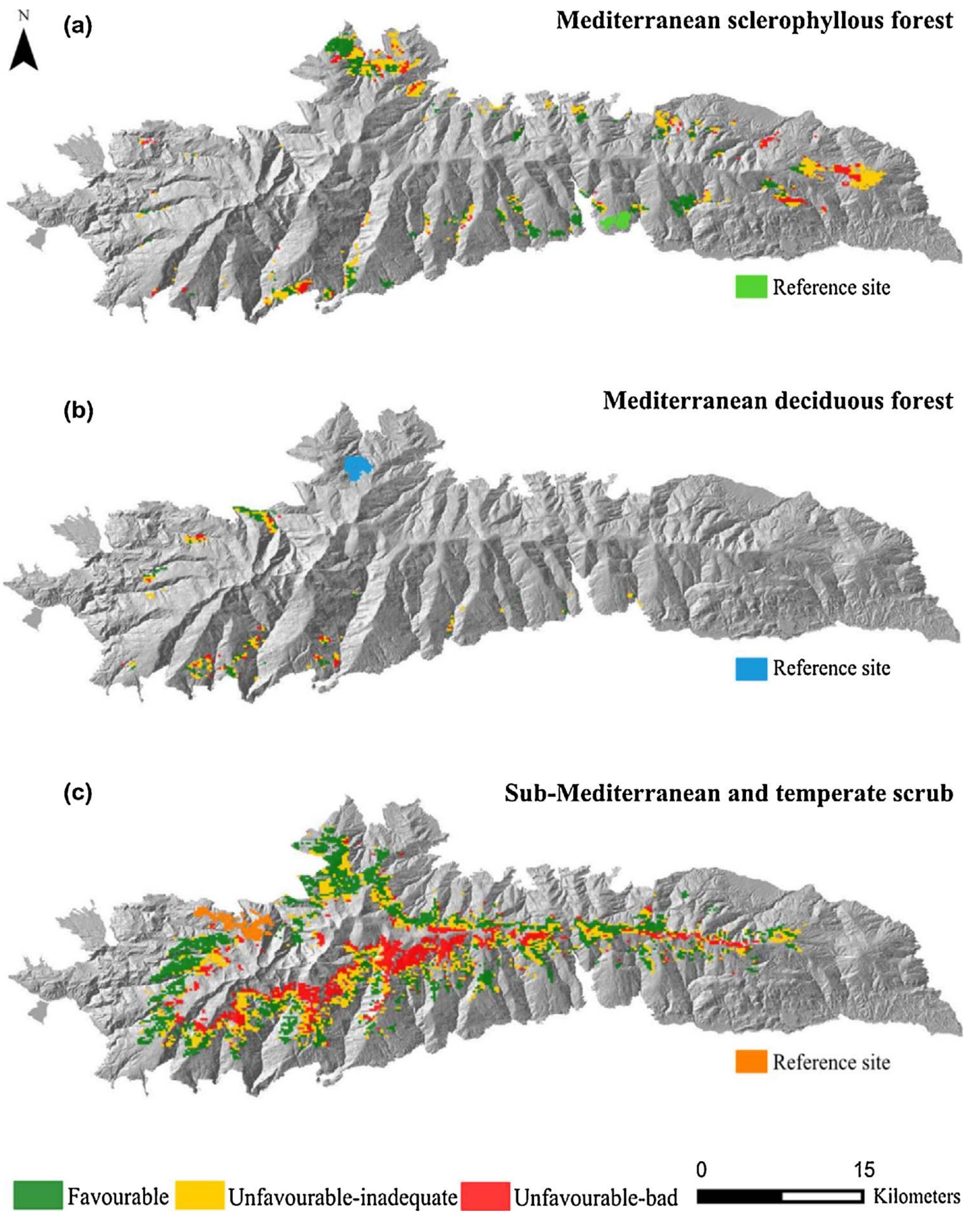

Fig. 4. Spatial distribution of three Mediterranean habitats in Sierra Nevada classified by their conservation status. The pixels were mapped according to their conservation category.

Table 2
Parameters proposed to characterize the ecosystem functions of the three habitats assessed in the field-data based protocols used by Spain. Since structure and functions are evaluated together, but using different numbers and types of parameters, we also show the ratios between such parameters in order to highlight potential imbalances in the conservation status assessment.

Habitat	Functional parameters	Applicability	Ratio between structural and functional parameters
Mediterranean sclerophyllous forest (habitat code 9340)	Herbivory Defoliation	Recommended Obligatory	2/2
Mediterranean deciduous forest (habitat code 9230)	Dead wood Growth pattern Canopy health Radial growth	Obligatory Recommended Obligatory Recommended	5/4
Sub-Mediterranean and temperate scrub (habitat code 5120)	No functional parameters proposed		8/0

reporting obligations on a six-yearly basis.

The spatial patterns of the conservation status of Mediterranean sclerophyllous and deciduous forest were discontinuous, which may be due to causes that affect at a local scale. Conversely, the pattern was more regular in Sub-Mediterranean and temperate scrub, showing an altitudinal gradient through its spatial range of distribution, and hence, the underlying factors, such as changes in the dynamics of snow cover (Zamora et al., 2017), may be operating at a regional scale. As a result, this habitat could be more susceptible to the effects of climate change (Bonet et al., 2016; Pérez-Luque et al., 2016).

Functional space differences among the studied habitats were determined by the dispersion of their *meanEVI* and *cvEVI* values, i.e., proxies of primary production and "greenness" canopy seasonality, respectively. Such dispersion is conditioned, in turn, by intrinsic features of habitats and climate controls, such as rainfall in Mediterranean environments (Nemani et al., 2003). Sclerophyllous forest showed the lowest dispersion in terms of *cvEVI*, while in deciduous forest and sub-Mediterranean scrub the dispersion was higher. Holm oak (i.e., the dominant species in sclerophyllous forest) has perennial leaves, which determines its low seasonality. However, Pyrenean oak, which is dominant in deciduous forest, has deciduous leaves. Regarding sub-

Mediterranean scrub, this habitat had the highest values of *cvEVI* dispersion, either in assessed pixels or in reference site. The vegetation of this type of habitat depends directly on snow-cover extent and duration, and both factors are widely variable in terms of altitude and latitude in Sierra Nevada (Zamora et al., 2017; Pérez-Luque et al., 2016). Remote sensing-derived metrics related to changes in ecosystem functioning, such as the functional attributes used by us, show faster responses to environmental changes (Pettorelli et al., 2005; Díaz et al., 2013); changes in climate controls could be detected rapidly by monitoring programmes based on these functional descriptors. However, despite the recognized usefulness of remote sensing products to address conservation tasks (Cabello et al., 2012), their use in Natura 2000 habitat monitoring has been very limited beyond visual interpretation of airborne or satellite imagery (Vanden Borre et al., 2011). Although potential users of remote sensing products do not want to be burdened with the large variety of imagery and methodologies available, Vanden Borre et al. (2011) highlighted that habitat monitoring experts are willing to use readily useful products that integrate seamlessly with existing workflows. In this regard, our approach is completely aligned with the legal requirements derived from the HD implementation and helps conservation decision makers adhere to reporting obligations, as required under Article 17 of the Directive.

4.2. How remote sensing can help address challenges arising from the HD

Proper identification of reference sites is one of the main challenges in implementing the HD must address. Determining such sites is not easy and requires identifying threshold values to discriminate between favourable and unfavourable areas. The HD states that the conservation status shall be classified as favourable when the specific structure and functions necessary for habitat long-term maintenance exist and are likely to persist for the foreseeable future and the conservation status of its typical species is favourable (Art. 1e). When direct indicators of ecosystem functioning or structure are absent, the HD recommends using presence of typical species. However, it is not realistic to associate species with all aspects of structure and functioning given the variability of Annex I habitats (Evans and Arvela, 2011); therefore, these authors recommend that, in the absence of data regarding typical species, reference sites should be selected via expert judgement. Nevertheless, the proper definition of reference sites is a not-yet-solved issue in the conservation biology research agenda (Rick and Lockwood, 2013). Different approaches have been suggested; for example, the LIFE project RedBosques (http://www.redbosques.eu/) aims to define reference sites based on shared criteria and protocols. In this sense, remote sensing offers a large variety of imagery related to different aspects of ecosystem functioning, such as those that we proposed here, which enable the identification of common indicators and methodologies to assess ecosystem functioning (Vanden Borre et al., 2011; Díaz-Varela et al., 2007; Dionisio et al., 2011; Garbulsky and Paruelo, 2004; Stoms and Hargrove, 2000). By following the guidelines indicated by the HD and because it is widely recognized that both composition and structure influence ecosystem functioning processes such as primary production dynamics (Mehtälä and Vuorisalo, 2007), we propose the integration of both dimensions to determine conservation status.

In addition, reference sites should encompass the range of environmental variability found in the study area to avoid assessments that are based on environmental conditions rather than conservation status (Bull et al., 2014). To address this, we evaluated habitat patches that were distributed along the same altitudinal range to ensure that the environmental variability was relatively homogeneous. In this sense, functional spaces, shown in Fig. 2, are a useful tool to check if specific pixels are far from the rest in terms of their functional state. Thus, potential "outliers", which could derive from out-of-date or erroneous habitat cartography, can be detected. In Sierra Nevada, the habitat functional spaces of both evaluated and reference pixels showed high overlap, and the spatial distribution of their conservation status did not show any pattern related to the location of reference sites according to Moran's Index, which supports that the influence of the locations in the assessment of conservation status was negligible.

Another key point in the evaluation process derived from the HD is the suitable selection of thresholds and cut-off points used to classify habitat patches into conservation categories. What measures should be employed to summarize deviations from the reference sites? Though it depends on whether dispersion deviations over time are low or high, measures of central tendency, such as mean, mode or median, or measures of non-central tendency, such as quartiles, could be used, respectively. Besides these, dispersion metrics, such as range, could be also advisable. The selection of cut-off points is a required decision driven by the HD. In ecology, deciding what cut-off point should be used to classify elements in categories is not always an easy task. For this reason, we suggest using the charts shown in Fig. 3 and expanding the conservation categories by defining new subcategories nested within the general conservation categories, i.e., favourable, unfavourable-inadequate and unfavourable-bad, thus making them less restrictive (see Fig. A1 in Supplementary material). The new subcategories would help management decision makers detect habitat patches close to the threshold between two conservation categories. Such habitat patches should be assessed with caution.

One of the most important issues to consider when assessing ecosystem functioning is that reference conditions are dynamic, not static, over time (Hessburg et al., 1999; Moore et al., 1999; Nicholson et al., 2009). Remote sensing information provides temporal series that include such fluctuations. Thus, we calculated the deviations of evaluated habitat patches across years and then summarized them. In this manner, we assumed that the conservation status could change every year in parallel to reference sites. Additionally, habitat dynamism over time offers multiple possibilities for conservation status monitoring by analysing the trajectory of the centroids. If we consider the centroid to be representative of the average functional behaviour of habitat patches, the analysis of their movements, trajectories and attractors (Morelli and Tryjanowski, 2016) may provide new metrics for assessing and monitoring conservation status. When the centroids were observed in a sequence generated as a movie by integrating one chart per year (see Videos 1a, 1b and 1c in the Supplementary material), the direction of movement and distances covered were different in the three habitats analysed. However, all the habitats showed a severe decrease in primary production and seasonality in 2005. Such a decrease could be due to the extreme drought that occurred that year (Valladares et al., 2008). The monitoring of extreme conditions would enable more reliable assessments of conservation status, and therefore, less prone to erroneous conclusions due to anomalous events. Finally, the HD requires assessing habitat conservation status at both biogeographical and member-state levels every six years. Given the large range of satellite-images covering the entire globe at different spatial-temporal resolutions, remote sensing is an adequate tool to meet this requirement. Likewise, with the aim of assessing future trajectories of ecosystem structure and functions, the Directive recommends using a percentage of the area in a favourable condition as the threshold for the favourable reference value. Such a percentage can be calculated from maps where habitat patches are mapped according to their conservation category, as shown in Fig. 4.

4.3. Future perspectives

Future efforts should be made to explore (1) the effect of the reference sites selected, (2) the use of other remote sensing products related to ecosystem functioning on the assessment of functional state, and (3) to upscale the approach to larger areas (preferably an entire member state). To address the first goal, studies should assess habitat conservation status at a regional scale using common reference sites for habitats belonging to the same biogeographical region but located in different member states. To address the second and third goals, the

European Space Agency has launched a family of missions called Sentinels belonging to the Copernicus Programme that are providing new remote sensing products, such as multispectral images at high spatial-temporal resolutions. These products could improve the functional characterization of habitats by capturing ecosystem functioning dynamics at very fine scales (Turner et al., 2003).

Finally, new conservation strategies adopted by the EU employ the ecosystem services framework (Millennium Ecosystem Assessment, 2005), with the aim of informing and protecting the benefits that the Natura 2000 network provides to society and the economy (European Commission, 2013). Likewise, Maes et al. (2012) highlighted that conservation efforts of the HD should be oriented to assess habitat conservation status, as well as their capacity to supply ecosystem services. In this sense, Paruelo et al. (2016) proposed the ecosystem service provision index (ESPI) to estimate and to map ecosystem services related to carbon, water dynamics and biodiversity. The ESPI is a function of two remote sensing-derived attributes related to the seasonal dynamics of vegetation indices, like those we have used here. According to these authors, the ESPI can be used as an aggregated indicator of the status of ecosystem services supplied at large spatial scales. Thus, improving our understanding of the relationship between different satellite-derived functional descriptors and ecosystem services would help to assess the capacity of habitats to supply ecosystem services through the use of remote sensing information.

5. Conclusions

There is an urgent concern to elucidate the impacts of human-driven global changes on ecosystem functioning to adjust conservation policies. For that, a proper assessment of the conservation status is crucial. However, an evaluation based solely on composition may be unrealistic (Evans and Arvela, 2011) and insufficient. In the present work, we suggested a remote sensing-based approach that aimed at more directly assessing the functional dimension of habitat conservation status, while still adhering to reporting obligations derived from the HD. In the interest of moving from ecological theory to applied ecological management and conservation, different challenges, such as a more direct assessment of the ecosystem functioning for natural habitats in space and time, have arisen. Future research should be oriented to tackle these challenges by taking advantage of the capabilities derived from remote sensing and exploring new approaches that monitor the spatial and temporal evolution of habitats and their capacity to supply ecosystem services.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ecolind.2017.12.036.

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