Long-term monitoring of NDVI changes by remote sensing to assess the vulnerability of threatened plants

L. Matas-Granados a, b, M. Pizarro b, L. Cayuela c, D. Domingo d, e, f, D. Gómez b, M.B. García b, *.

a Department of Biology, Faculty of Science, Autonomous University of Madrid, c/ Darwin 2, 28049 Madrid, Spain
b Pyrenean Institute of Ecology (CSIC), Avda. Montanauna 10005, 50059 Zaragoza, Spain
c Department of Biology and Geology, Physics and Inorganic Chemistry, Rey Juan Carlos University, c/ Tulipán s/n, 28933 Moisoles, Spain
d EiFAB-iuFOR, University of Valladolid, Campus Duques de Soria, 42004 Soria, Spain
e GEOFOREST, Department of Geography, University of Zaragoza, Pedro Cerbuna 12, 50009 Zaragoza, Spain
f Land Change Science Research Unit, Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Zürcherstrasse 111, 8930 Birmensdorf, Switzerland

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ABSTRACT

Little is known about how much continuous landscape transformation might affect the most vulnerable elements of biodiversity. In this study, we quantified changes in the normalized difference vegetation index (NDVI) over the past 35 years across locations with threatened plants and in Natura 2000 (N2000) protected areas, in an environmentally heterogeneous region of Southern Europe. First, we estimated the intensity and duration of NDVI gains and losses based on Landsat time series using the LandTrendr algorithm in Google Earth Engine. Then, we tested: 1) whether populations of threatened plants were located in more stable sites than non-threatened plants (i.e., lower NDVI changes); 2) whether NDVI changes around populations of threatened plants differed across habitats and inside/outside N2000 areas, and 3) whether lower NDVI changes occurred in N2000 areas than unprotected areas, thereby indicating their effectiveness at preserving biodiversity. Threatened plants tended to be concentrated in sites with less change irrespective of the habitat where they occurred and their location within protected areas. Occurrence in stable sites also reduced the risk associated with small-sized populations. N2000 areas were in line with the overall greening trend but they experienced less loss events than the unprotected areas, thereby supporting their role in slowing down human-induced land cover changes. Our approach demonstrates how long-term remote sensing monitoring can help to assess the effects of both slow processes and drastic landscape transformation events on priority plants in a comprehensive and rapid manner. This method can identify hidden patterns in extensive regions and guide effective conservation management.

1. Introduction

Landscape change is currently one of the main threats to biodiversity (Newbold et al., 2015), and it often results in faster and more dramatic effects than climate change (Titeux et al., 2016). Habitat fragmentation and destruction due to urbanization, agriculture, deforestation, or wildfires are relatively easy to detect, but other widespread and more subtle processes such as the invasion of grasslands by shrubs or afforestation may be responsible for population declines and species extinctions (e.g., Sirami et al., 2010). Those processes may occur anywhere and also affect the protected areas for habitats and species. Therefore, detecting “early warning” signs of changes linked to ecosystem structure or functions at large spatial and temporal scales is critical for allowing managers to implement conservation practices and policies in a timely manner.

Changes in the species compositions of communities or the abundances of certain species due to slow habitat transformation are particularly important for small or sedentary organisms such as plants, which are highly dependent on the surrounding environment (e.g., Deak et al., 2020). These changes are especially important for threatened plants, where their conservation status typically reflects a narrow distribution, small occupancy areas, or low population size. Describing the direction, strength, and speed of habitat transformation, and how it can affect highly vulnerable organisms may help to guide and optimize conservation efforts for the most fragile components of biodiversity. This type of information can be collected by ecological monitoring programs that aim to determine trends and identify threats, which are the two key requirements of adaptive management (Lindenmayer and

* Corresponding author.
E-mail address: mariab@ipe.csic.es (M.B. García).

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2. Methods

2.1. Study area and data collection

The present study was conducted in the Aragón region of Spain (SW Europe, Fig. 1), with an area over ca. 50,000 km². This territory contains two important mountain ranges comprising the Pyrenees in the north and Iberian System in the south, which are separated by the semidesert Ebro river valley. The study area covers wide altitudinal (from 40 to 3404 m a.s.l.) and ecological gradients, and contains more than 3000 native plant species according to the largest available plant database FLORAGON (Table 1), which account for almost one-fourth of all the European flora. In particular, 122 vascular plants are considered threatened according to regional, national, or international conservation lists (catalogues of threatened plants, Red Lists, and the Habitats Directive).

The N2000 network encompasses over 19.1% of the regional surface and it is distributed across 156 areas (Fig. 1). N2000 areas contain 94% of all the plant species in the region and 87% of the threatened plant species. In addition, 44% of all plant records in the region are located inside N2000 areas, as well as 44% of the records of threatened species. Very similar values are outside the N2000 areas (Table 1), although the N2000 areas only occupy less than one-fifth of the region.

As part of a citizen science plant monitoring program, we collected highly precise information in 229 monitoring units (MUs), 70% of which were located inside N2000 areas (Fig. 1). In the MU sites, the population size of several plant species was estimated and the trend of the abundances were monitored in fixed sampling units. The total number of plant populations included in the network was 343, which belonged to 174 different species (36 threatened). In addition, 39% of the MUs contained at least one threatened species and the remainder comprised habitat indicator plants for European Habitats listed in the Habitats Directive, or common plants. We recorded the following information for each MU: 1) altitude; 2) georeferenced centroid of sampling units; 3) habitat type according to six classes comprising forest, wetland, shrubland, grassland, rocky, and cliff (the reason for separating the latter two classes is explained in the following); and 4) estimated population sizes of monitored plants according to the number of individuals and/or area of occupancy as: small (< 100 individuals or < 100 m²), medium (500–1000 individuals and > 1000 m², or > 1000 individuals and 500–1000 m²), or large (> 1000 individuals and > 1000 m²). In order to explore whether detection of the NDVI changes in plant populations was scale dependent, we used each centroid to establish three circular buffers defined by a radius of 50, 300, and 3000 m (B50, B300, and B3000 respectively; Fig. 1). The smallest buffer (B50: 7850 m²) completely covered small and intermediate sized populations, whereas the largest (B3000: 28,274,300 m²) allowed us to evaluate changes around populations of any size. Given the vertical positions of particular MUs located on cliffs, moderate resolution Landsat imagery had great difficulty detecting changes with the smallest buffer, and thus we assumed no change at B50.

Nevertheless, given the restrictions on activities that might be detrimental to biodiversity inside N2000 protected areas, we expected them to have played a protective role for threatened species. Thus, we specifically tested: 1) whether populations of threatened plants tended to occur in more stable areas compared with non-threatened areas (i.e., lower NDVI changes); 2) whether threatened plant populations in different habitats had experienced lower NDVI changes inside than outside N2000 protected areas; and 3) whether N2000 areas had experienced lower changes in NDVI (gains as well as losses) than unprotected areas over the last 35 years, thereby indicating their effectiveness at preserving biodiversity.

Our study aims to demonstrate how monitoring changes in vegetation indices using long-term remote sensing imagery can address the challenge of assessing slow and unnoticeable landscape transformation processes in a comprehensive, rapid, and objective manner. Although our analysis focused on external threats to priority plants, it covered a large range of populations and habitats, and we conducted evaluations at three different spatial scales, so the results should provide guidelines for more effective conservation management practices in other environmentally heterogeneous regions of Europe.
On the other hand, the study area is divided into a grid of 48,862 1-km² cells according to Universal Transverse Mercator (UTM) coordinates, which is the most frequent geolocation unit employed by botanists in recent decades. In total, 394,414 plant records are stored in FLORAGON at this resolution and 1.1% correspond to threatened species (Table 1, Fig. 1). Each record of threatened plants was associated with one type of habitat (the same as listed above), and scored as inside or outside the N2000 area (more than half of the UTM area was required to fall within the N2000 area to be classified as inside).

### 2.2. Landsat data and processing

Landsat image processing was performed using the GEE platform (Gorelick et al., 2017). We computed a time series containing cloud-free images from January–December each year between 1984 and 2018. In total, we used 2274 scenes from Landsat 5, 1500 from Landsat 7, and 706 from Landsat 8 (Fig. A1). The calibrated and corrected surface reflectance “USGS Landsat Surface Reflectance Tier 1” collection from Landsat 5, 7, and 8 was selected. The data were atmospherically corrected and they included a cloud, shadow, water, and snow mask produced using CFMASK (for more details, see Zhu et al., 2015; Kennedy et al., 2018).

### 2.3. Quantification of changes in NDVI

NDVI changes were estimated during 1984–2018 in the whole region as the baseline for overall change, and we then explored their effect on elements of three different data sets: 1) 229 MUs containing species of interest (threatened, or characteristic of habitats of interest); 2) 1529 1-km² UTMs with records of threatened plants, where each was associated with one of the habitats mentioned above, and scored as inside/outside the N2000 areas; and 3) 156 areas of the N2000 network (Fig. 1). For the N2000 network analysis, we separately compared the gains and losses of spectral indices (G and L, respectively), whereas we focused on the

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**Table 1**

Number of plant species, plant records, and 1-km² UTM cells in the Aragón region as a whole, and inside and outside Natura 2000 (N2000) areas (in percentages). Values are given for all plants and threatened species.

<table>
<thead>
<tr>
<th></th>
<th>Aragón (%)</th>
<th>N2000 (%)</th>
<th>Unprotected (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of plant species</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>3087</td>
<td>93.7</td>
<td>96.6</td>
</tr>
<tr>
<td>Threatened</td>
<td>122</td>
<td>86.9</td>
<td>86.6</td>
</tr>
<tr>
<td>Number of plant records</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>394,414</td>
<td>44.1</td>
<td>55.9</td>
</tr>
<tr>
<td>Threatened</td>
<td>4527</td>
<td>43.8</td>
<td>56.2</td>
</tr>
<tr>
<td>Number of 1-km² UTM cells</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>48,862</td>
<td>19.1</td>
<td>80.9</td>
</tr>
<tr>
<td>Containing plant species records</td>
<td></td>
<td>12,329</td>
<td>29.4</td>
</tr>
<tr>
<td>Containing threatened species records</td>
<td></td>
<td>1529</td>
<td>46</td>
</tr>
</tbody>
</table>

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*Fig. 1.* Left: Study area in the NE Iberian Peninsula showing the area covered by the Natura 2000 network (N2000, green shadows), 1-km² cells (UTMs) with records of 122 threatened vascular plant species according to regional, national, and European lists (red squares), and the locations of the 229 monitoring units (MUs) for plants and habitats of interest (MUs, black dots). Right upper row: habitat and buffers with different sizes (B50, B300, and B3000) used to analyze vegetation changes in one population of the threatened *Cypripedium calceolus*. Bottom: aerial images (orthophotos) showing vegetation changes from 1956 to 2000 and 2018 for the three buffers, and pixels with gain of vegetation (end of each row) after processing Landsat images using the *LandTrendr* algorithm (1984–2018; see the text for a detailed description of the process). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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dominant change (i.e., gains, G) for the UTM and MU analyses because the sample sizes were much smaller.

We used the LandTrendr (Landsat-based Detection of Trends in Disturbance and Recovery) temporal segmentation algorithm implemented in GEE to assess changes in vegetation (Kennedy et al., 2010, 2018). LandTrendr captures short-duration events and smooths long-term trends using the original satellite bands or spectral indices by segmenting the spectral trajectory (Kennedy et al., 2010). The algorithm was tuned to avoid over- and under-fitting as well as allowing better adjustment to the potential types of changes within the study area (Table A1). We considered the Standard change scenario, which provides a balance between disturbances and moderate events in the long term (Kennedy et al., 2010; Kennedy et al., 2012). The mode value along a year of NDVI derived from Landsat data was selected to determine changes at the pixel level (30 m) over 35 years.

Important changes identified by LandTrendr (events) were defined by their magnitude (M, difference between the spectral value in the year when the change started and the year after the change multiplied by 1000), duration in years (D), and the relative ratio between the magnitude of change (Kennedy et al., 2018). We then identified gain (G) and loss (L) events irrespective of the length of the change detected (2 to 35 years) (Fig. A1). The mean magnitude of change by all of the pixels within each buffer area (B50, B300, and B3000) and UTM was used to estimate the changes in vegetation in MUs, and inside/outside N2000 areas respectively. We found that the correlation was very good between the magnitude of gain changes (GM) estimated from B300 and 1-km² UTM cells where each MU was included (N = 229 MUs), thereby indicating that both approaches produced similar results.

2.4. Data analysis

In the analysis focused on MUs, we used generalized linear mixed models (GLMMs) with a binomial error distribution and a logit link function to test whether the occurrence of populations of threatened plant species (a binary response variable, where “0” denoted the absence and “1” indicated the presence of threatened plant populations) was affected by the intensity of NDVI change, habitat type, and population size at each buffer size. The most complex model included the interaction between all three predictors. Altitude was not included as a predictor because habitats tend to be altitudinally segregated, and thus these two predictors were highly collinear. MU was included as a random factor to account for the potential correlations between threatened or not threatened species that clustered together. To test for the effect of MUs, we compared GLMMs with the most complex fixed factors structure and their equivalent GLMs using Akaike’s information criterion corrected for small sample size (AICc). GLMs performed better than GLMMs in all cases, and thus we used to analyze the effects of fixed factors by building alternative models with different subsets of predictors. Model residuals were explored using a simulation-based approach to obtain readily interpretable scaled (quantile) residuals for the fitted GLMs (Harting, 2020). The explained deviance (D²) and theoretical pseudo-R² for best-fit models were used as measures of goodness of fit. Tukey post-hoc analyses were conducted to explore differences between types of habitats and population sizes whenever these factors were included in the best-fit models. Models were tested for each buffer size independently to determine whether the relationship was scale dependent. We used Moran’s I test to explore the existence of spatial autocorrelation in the model residuals (see the correlograms in Fig. A2).

In the analysis focused on UTM cells containing threatened plants, we checked for the suspected existence of spatial autocorrelation due to the aggregation of some of the UTM cells (see Fig. 1) by analyzing Moran’s I in the model residuals. To avoid the resulting spatial autocorrelation, we conducted 100 stratified random samplings of UTMs by habitat type at minimum distances of 15 km from each other (lower minimum distances did not remove spatial autocorrelation). We then fitted a generalized linear model (GLM) with a Gaussian error distribution to test for the effects of habitat type, inclusion within N2000 protected areas, and their interaction on the magnitude of the most frequent NDVI change (GM). Finally, we computed the mean magnitude and duration of gains and losses for the 48,862 UTMs within the whole region, and calculated the mean ± standard deviation values inside and outside N2000 areas. Statistical analyses were conducted in R (R Development Core Team, 2020), including the lme4 (Bates et al., 2015), DHARMA (Harting, 2020), MuMIn (Barton, 2020), spdep (Bivand and Wong, 2018), ncf (Bjornstad, 2020), and multcomp (Hothorn et al., 2008) packages.

3. Results

Comparisons of alternative models to investigate the relationship between the probability of occurrence of threatened plants in MUs and the magnitude of change considering the effects of habitat and population size demonstrated consistent effects of all three explanatory variables for the three buffers (Table 2, Table A2). The best model predicted that when the change in NDVI was smaller, the probability of occurrence of threatened species was higher irrespective of the habitat type or population size (Fig. 2a–f). The probability of finding threatened plant populations was highest in cliffs and forests, but lowest in wetlands, and the probabilities were similar in the remaining habitat types (Fig. 2g). The probability of occurrence of threatened species was significantly higher for small and medium sized populations than large populations (Fig. 2h).

The results obtained for the 100 GLMs with different random subsets of the original set of UTMts of threatened plants demonstrated: i) no statistically significant effect of the interaction between N2000 and habitat type on the changes in NDVI (p-value range: 0.074–0.972); ii) no statistically significant effect of being inside/outside the N2000 areas (p-value range: 0.053–0.999); and iii) statistically significant effects of habitat type in 55% of the models (p-value <0.05), whereas habitat had no effect in 45% of the models (p-value: 0.052–0.894). In 91% of the models where habitat type had an effect on changes in vegetation, the gains were significantly higher in forests than wetlands, but there were no significant differences among other habitat types (Fig. A3). Overall, these results demonstrate that the occurrence of populations of threatened plants was not related to their inclusion in N2000 areas, and that there were no significant differences in the changes in NDVI, except when we compared forests (greatest change) with wetlands (smallest

<table>
<thead>
<tr>
<th>Model</th>
<th>Probability of containing a threatened species</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B50</td>
</tr>
<tr>
<td>No explanatory variables</td>
<td>310.1</td>
</tr>
<tr>
<td>NDVI change</td>
<td>311.7</td>
</tr>
<tr>
<td>NDVI change + habitat</td>
<td>304.6</td>
</tr>
<tr>
<td>NDVI change + habitat + size</td>
<td>301.9</td>
</tr>
<tr>
<td>NDVI change + habitat + size*</td>
<td>288.9</td>
</tr>
<tr>
<td>NDVI change + habitat + size*+ size</td>
<td>298.5</td>
</tr>
<tr>
<td>NDVI change + habitat + size*+ size*+ size</td>
<td>300.4</td>
</tr>
<tr>
<td>NDVI change + habitat + size*+ size*+ size*+ size</td>
<td>291.6</td>
</tr>
<tr>
<td>NDVI change + habitat + size*+ size*+ size*+ size*+ size</td>
<td>314.1</td>
</tr>
<tr>
<td>(D²)</td>
<td>0.1</td>
</tr>
<tr>
<td>(pseudo-R²)</td>
<td>0.2</td>
</tr>
<tr>
<td>Number of estimated parameters</td>
<td>8</td>
</tr>
</tbody>
</table>
Our analysis of the whole region showed that the overall dominance of NDVI increased over the last 35 years (Fig. 3). Gains were widely distributed across the region and they were four times more frequent than losses (Fig. A4). On average, this greening trend was very similar inside rather than outside the N2000 areas (GM: 91.2 ± 34.8 and 91.8 ± 21.6, respectively). By contrast, losses were much lower inside N2000 areas than outside (LM: 11.2 ± 23.8 and 21.8 ± 21.1, respectively) (Fig. 3). Gains and losses also differed in terms of the length of the events, where they were much longer in the former (GD: 19.5 ± 6.8 years) than the latter (LD: 1.5 ± 1.9 years). Therefore, we concluded that gains occurred at a lower annual and relatively constant rate over long periods, whereas losses were more abrupt and they lasted for a shorter period. In terms of duration, the N2000 areas experienced longer gains and shorter losses than unprotected areas (Fig. 3).

4. Discussion

The main aim of this study was to evaluate the gains and losses of NDVI (a proxy of changes in vegetation) experienced by threatened plants in an environmentally heterogeneous region of South Europe over the last 35 years, because strong changes would result in additional vulnerability for the most fragile plant diversity components. In particular, we determined the effects of being located in areas under protection, the type of associated habitat, and specific population sizes. Our analysis of information gathered from Landsat imagery processed using GEE and the LandTrendr algorithm revealed two interesting patterns: 1) threatened plants tended to occur in areas with smaller changes regardless of whether they were inside or outside N2000 protected areas and the habitat where they occurred, which may have counterbalanced the risk of occurring frequently in small and medium sized populations; and 2) N2000 areas had an important role in sheltering threatened plants and buffering them against drastic losses of vegetation.

The overall greening pattern inferred from the increase in NDVI in our study region is in agreement with the widespread greenness of Earth’s terrestrial vegetation attributed mainly to increased CO₂ levels (Zhu et al., 2016; Pei et al., 2019). This pattern is also compatible with the abandonment of traditional land use and the migration of rural society to urban areas over recent decades in Southern Europe (MacDonald et al., 2000; Vicente-Serrano et al., 2000). In the study region, the abandonment of crops in lowlands and summer pasturages in the highlands, as well as the replacement of the use of wood by electricity in the 1950s had important impacts on plant biomass increases, and thus on the greening pattern (García-Ruiz and Lasanta, 2018). Land abandonment is considered a major threat to biodiversity and rare plants, particularly in northwestern Mediterranean ecosystems because of their association with open habitats (Sirami et al., 2010). However, our analysis showed that threatened plants were located in areas with less transformation (NDVI change) regardless of the habitat where they occurred even though they also tended to be concentrated in open...
habitats (almost 80% of all records in UTM occurred in wetlands, rocky areas, cliffs, or grasslands). Interestingly, a recent study detected a similar pattern for forests at the global scale despite the worldwide decrease in forests in conservation areas, where those with the least deforestation were the most critical for the conservation of the rarest species (Tracewski et al., 2016). It could be argued that threatened plants are more abundant in the least transformed (currently protected) areas because they have persisted better in these places. However, other reasons must be involved, as most N2000 areas were declared in the 20's, and the study region is not highly populated as to have suffered drastic transformations that confined threatened species to protected areas. Besides that, threatened plants are also located in areas with low NDVI changes outside the N2000 network, such as often being present in remote and rugged landscapes where anthropogenic pressure has been at a historically lower level. The occurrence of threatened species in areas with lower magnitudes of NDVI change is particularly important because of their tendency to be part of small or medium sized populations in this region (García et al., 2021), and the associated higher risk of extinction due to demographic stochasticity (Pimm et al., 1988; Matthies et al., 2004). Occurring in these stable areas clearly increases the chance of long-term persistence.

Our results showed that the areas of conservation interest (N2000), which contain a high proportion of the regional flora and threatened plants, have experienced less NDVI loss events than the region overall. In particular, in Ordesa and Monte Perdido National Park, which is included in the N2000, García et al. (2019) found little evidence of detrimental effects of vegetation changes on threatened populations over 46 years based on comparisons of pairs of aerial orthophotos because most occurred in areas that underwent little transformation. However, we did not expect all of the N2000 areas to follow a uniform trend or changes with a similar intensity. By comparing the temporal evolution of ecosystem functions across the network of National Parks in the Iberian Peninsula, Alcaraz-Segura et al. (2009) found little evidence of divergent results among nearby protected areas or areas with similar biogeographical affinity. Therefore, the value of N2000 areas as refuges for

![Fig. 3. Maps of magnitude (a, b) and duration (number of years, d, e) of NDVI gain (a, d) and loss events (b, e) obtained by applying the LandrTrendr algorithm for the period of 1984-2018 in the study area. Mean magnitude (c) and duration (f) of gains and losses (SD) inside and outside N2000 areas are also shown.](image-url)
threatened species from global change drivers probably varies across the region, which should be investigated in future research.

Site-based protection is an essential conservation management action because it is assumed that avoiding drastic disturbances is the best way of maintaining a habitat’s functions (except for prescribed fires in particular ecosystems), and it helps to address the limited capacity to undertake in situ field monitoring programs at large scale. Site-based protection is considered to be appropriate for over 80% of threatened birds, mammals, and amphibians (Boyd et al., 2008), and it is relatively effective for the endemic fauna in the Iberian Peninsula (Rosso et al., 2017). In the present study, we demonstrated its important role for threatened plants in an environmentally heterogeneous European region given the lower rate of NDVI loss. Eichenwaldb et al. (2020) applied comparative analysis to determine the roles of federal and private lands in the protection of endangered vertebrates in the US and found that habitat loss was reduced more effectively in the former than the latter. However, these authors demonstrated that all listed vertebrates experienced a net loss of habitat, whereas the threatened plants in our study appeared to stay safer in places with reduced vegetation changes inside and outside areas designed specifically for conservation. It is important to note that organisms with little or no capacity for mobility (e.g., soil arthropods and herbs) are highly dependent on habitat transformation because small landscape modifications (e.g., light conditions) may totally change their microenvironment.

In order to effectively address generalized biodiversity loss, we require coherent global biodiversity monitoring variables, and links between pressures and trends (Butchart et al., 2010). Identifying population trends and threats are the best methods for critically evaluating the conservation status and vulnerability of endangered or threatened species. Monitoring population trends in field surveys is ideal (e.g., de Bello et al., 2020) and threats have been historically identified based on in situ observations of ongoing processes. However, remote sensing may complement this approach and provide an effective method for addressing conservation problems when the collection of field information is not feasible. Our study provides an example of the use of satellite remote sensing to record essential biodiversity variables (SRS-EBVs sensu Pettorelli et al., 2016). EBVs identify measurable variables to allow the rate and direction of change to be quantified for some aspect of the biodiversity state over time and across space, and they may belong to different frameworks such as ecosystem structures and functions (Skidmore et al., 2015; Pettorelli et al., 2016). SRS-EBVs aim to facilitate the integration of remote sensing and biodiversity monitoring by expanding the set of data that can support monitoring, providing global coverage at low cost, and allowing data collection at multiple spatial and temporal resolutions. In the future, according to the current scenario of limited conservation resources, it may be pragmatic to use effective “early-warning” signs of concern for the most vulnerable components of biodiversity and test the beneficial roles of conservation areas. A highly efficient approach could involve the combination of field and remote sensing data based on optimized sampling, verified upsampling of field findings, and monitoring land cover changes and vegetation parameters in unsampled areas.

Remote sensing technology has great potential for use in monitoring and building global indicators of change (O’Connor et al., 2015; Pasquarella et al., 2016), but conservation biologists need to engage in “joined-up thinking” to effectively respond to clearly oriented questions (Lindenmayer et al., 2018). In the present study, we demonstrated the utility of applying a large-scale passive data collective system in conservation biology by determining how changes in vegetation indices might affect threatened plants according to the direction, duration, and magnitude of change in these indices. We found that threatened plants were located in more stable locations than others, and this finding may help policy makers to evaluate the impacts of landscape change and to prioritize efforts in a holistic framework for preserving threatened organisms.

CRediT authorship contribution statement


Maria B García: conceptualization, data curation, funding acquisition, writing- review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2021.109428.

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