Tracking Nature's Footprint: Uncovering NDVI Time Trends in Spanish High Mountain Biosphere Reserves

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Protecting Spain's mountain ecosystems is of great importance to preserve ecosystem services. Global warming is increasing the vulnerability of these habitats, especially in peninsular Spain. Biosphere Reserves are internationally protected areas that seek to protect biodiversity and, at the same time, promote sustainable development. Evaluating these protected areas is essential to verify environmental changes and establish priorities in their management. In this work, we have studied the time trends of NDVI in the high mountain Biosphere Reserves of Spain, in the period from 2001 to 2016, to check if the trend patterns are associated with: the Biosphere Reserves studied, surface temperature, water stress, altitude, slope, habitat type, biogeographic region, zonation, and distance to population centres. Significant differences were found between NDVI trends and high mountain Biosphere Reserves. First, significant positive trends in NDVI were observed when analyzing both reserves together. However, significant differences were found between the two reserves. The Ordesa-Viñamala Reserve shows higher positive NDVI trends and lower negative trends, while this pattern is reversed in the Sierra Nevada. Temperature and water stress affect the Sierra Nevada Reserve to a greater extent, increasing the number of negative NDVI trends. Habitat types show different patterns depending on the Reserve, with less resistance and, therefore, more vulnerable habitats. It has been observed that the zoning of the reserves significantly affects NDVI trends, following a pattern of increasing negative trends as we move away from the core. The height variable appears to substantially affect NDVI trends, with an increase in positive trends as we move in altitude. Finally, the distance to population centers has significantly influenced NDVI trends; generally, greater negative trends have been observed in areas closer to municipalities.

Keywords: NDVI, time series, remote sensing, Biosphere Reserve, high mountain, protected areas.

1. Introduction

Spain is one of the European countries with the greatest ecosystems, habitats and species diversity. It is home to more than half of the vertebrate and vascular plant species, a high number of endemic species and 65% of priority habitats in the European Union (OSE, 2010).

From the point of view of goods and services, these ecosystems fulfil three main functions: productive, environmental and social (Rodà et al., 2003). In their productive function, ecosystems provide renewable natural resources. Environmental services include the maintenance of biodiversity, climate regulation, water cycle regulation, biogeochemical cycles and soil conservation, among others. Finally, social services are related to the recreational, leisure, educational, or research uses that these ecosystems can provide and which, in some areas, are economic drivers for their development (Valladares et al., 2005).

Vegetation is conditioned by climate, specifically by radiation, temperature, precipitation and atmospheric humidity (Nemani et al., 2003). The great natural climatic variability present in the Iberian Peninsula makes some ecosystems particularly vulnerable to the effects of climate change. Mountainous areas are particularly relevant for water resource generation, particularly in temperate and semi-arid zones, including the Mediterranean zone. These mountainous areas are experiencing increased water stress caused by increased temperatures and reduced precipitation (García-Ruiz et al., 2011). In addition, these mountainous areas are one of the most vulnerable regions in the world, where temperature changes are more pronounced than in flatter areas (Pepin et al., 2015).

It has been shown that Mediterranean ecosystems are more vulnerable to climate change than other ecosystems in Europe (Schröter et al., 2005). These variations in climate have direct consequences on vegetation development and, thus, ecosystems and their services, resulting in ecological and economic losses (Field et al., 2012). In addition to climatic factors, these differences in vegetation growth can also be explained by anthropogenic (Fensholt et al., 2012) and topographic factors (Allen et al., 2010).

In order to protect natural diversity and ensure sustainable development, many countries worldwide have declared different types of protection (Dudley, 2008). Biosphere Reserves are areas designated by the United Nations Educational, Scientific and Cultural Organisation (UNESCO) in the People and Biosphere Programme (MaB Programme) framework. They are included in Law 33/2015 (BOE, 2015), of 21 September, which amends Law 42/2007 (BOE, 2007), of 13 December, on Natural Heritage and Biodiversity, in the section on Areas protected by international instruments. These areas of high natural value aim to reconcile nature conservation with sustainable development. The participation of the local population and other social sectors, such as economic agents and the scientific sector, is an essential part of this integrated approach.

Spain currently has 52 Biosphere Reserves, encompassing areas in both terrestrial and coastal/marine ecosystems, 4 of which are transboundary (three with Portugal and one with Morocco), making it the country with the highest number of Biosphere Reserves in the world (https:// miteco.gob.es).

The Biosphere Reserves consist of three areas, each with different functions but complementing each other and contributing jointly to achieve the objectives of the Reserve. These zones are:

- Core zone: this is the legally protected area in which conservation is prioritized.
- Buffer zone: the area surrounding or bordering the core zone, where activities compatible with conservation are allowed.
-Outer transition zone is dedicated to sustainable economic and human development.

Each country's government proposes the declaration of a new Biosphere Reserve and is responsible for proper functioning with the designated territories' competent entities. For example, in Spain, it depends on the Ministry for Ecological Transition and the Demographic Challenge (MITECO) and, in turn, on the Autonomous National Parks Organisation (OAPN) (https:// miteco.gob.es).

For the correct management of these areas, it is essential to know how the effects of climate change influence ecosystems. The Normalized Vegetation Index (NDVI) is useful for studying ecological responses to environmental changes (Pettorelli et al., 2005). In addition, the study of NDVI time series has proven effective in finding significant patterns or trends in vegetation (Bradley & Mustard, 2008).

NDVI is a vegetation index representing the fraction of photosynthetically active radiation intercepted by vegetation (fPAR) and primary productivity (Tucker & Sellers, 1986). It is calculated from the reflectance in the red (R) and near-infrared (NIR) according to the following formula: $NDVI = (NIR - R)/(NIR + R)$ (Tucker & Sellers, 1986). NDVI values range from -1 to 1. NDVI values close to zero are associated with diseased or sparse vegetation (presence of soil). Conversely, values very close to zero or negative NDVI values may indicate the presence of snow, clouds or water (Aguayo & CIREN, 2013). In this way, NDVI variations over time can show the vegetation's phenological dynamics and changes in ground cover.

NDVI is an index obtained by remote sensing. This technique is based on acquiring data from the Earth's surface through sensors carried on aircraft or satellites and their subsequent processing for analysis and interpretation (Chuvieco Salinero, 2002). Remote sensing has several advantages over other earth observation techniques, such as aerial photography or direct observation. Among its benefits are that it offers global and periodic coverage, allows information on regions of the non-visible electromagnetic spectrum, and enables images to be obtained at different scales. Besides, the different orbits traced by the satellites allow different time frequencies to be obtained over the same territory. Finally, recording information in digital format speeds up interpretation processes and facilitates data processing by geographic information systems (Martínez Vega et al., 2010).

Nowadays, remote sensing is a key technology for monitoring vegetation indices that give us an idea of the vegetative state of plant masses. In this respect, passive satellite platform sensors have provided free satellite images with adequate spatial and temporal resolution for over fifteen years. For example, the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor on board the AQUA and TERRA satellites of the National Aeronautics and Space Administration (NASA) records reflection data of the Earth's surface, which is stored in 36 bands of the electromagnetic spectrum. This sensor offers many products that can be used for land use and land cover mapping, including NDVI at different spatial resolutions. In addition, this sensor has been frequently used in vegetation time series studies to characterize vegetation (Busetto et al., 2010; Hmimina et al., 2013; Running et al., 2004).

These studies are key to deriving long-term habitat management guidelines under global change scenarios. In particular, this paper focuses on assessing high mountain Biosphere Reserves using remote sensing and time series. These protected areas are important because they are specially designated areas for assessing and managing natural and cultural resources and looking at their relationships in sustainable development scenarios (Batisse, 1982). However, although they can be vital from a research point of view for the management and management of the territories they contain, they have not been studied much to date, and even less so utilizing remote monitoring techniques, as proposed in this study.

In the framework of other NDVI studies carried out in Spanish mountain areas in the last decades (most of them protected areas) (Alcaraz-Segura, Liras, et al., 2009; P. Arrogante-Funes et al., 2018; Khorchani et al., 2018), in which positive trends of NDVI proved to be related to global warming, topographic factors and anthropogenic factors, the objectives of the present work are:

(1) To study the annual trends of NDVI in the Spanish high mountain Biosphere Reserves, i.e. the Ordesa-Viñamala and Sierra Nevada Biosphere Reserves; and (2) to study the possible association between NDVI trend patterns (from 2001 to 2016) and the Biosphere Reserves of interest, their zones (core, buffer and transition), the mean annual temperature trend, the annual water stress index trend, the elevation, and the distance to population centres.

2. Materials and Methods

2.1 Study Site

The study sites in the present work are the High Mountain Biosphere Reserves of Spain. These protected zones correspond to the Ordesa-Viñamala and Sierra Nevada Biosphere Reserves.

2.2.1 Ordesa-Viñamala

The Ordesa-Viñamala Biosphere Reserve (Figure 1) was declared in 1977 and is one of the first two announced in Spain. Later it underwent an extension in 2013. The Biosphere Reserve is in the Central Aragonese Pyrenees, Huesca province, in "Axial Pyrenees" and "Sierras Interiores". It has 117,364.1 ha, of which 13.71% correspond to the core zone, 37.28% to the buffer zone and 49% to the transition zone. Inside, it has a population of 5,639 inhabitants. The managing entity is the Ordesa-Viñamala Biosphere Reserve Consortium (Calvo, 2019).

In addition, within the Reserve, there are the following protection figures:

- Ordesa y Monte Perdido National Park

- World Heritage Site, natural and cultural "Pyrenees Monte Perdido", declared by UNESCO with mixed character (Spanish, French)
- Natural Monuments of the Pyrenean Glaciers
- Special Protection Areas for Birds (ZEPA)
- Places of Community Importance (SCI)
- Sobrarbe Geopark
- Viñamala and Circus Hunting Reserves

This Biosphere Reserve is one of the best representations of the Pyrenees Mountains ecosystems. Typical high mountain landscapes with glaciers and morphologies linked to glaciers give the landscape a significant relief (horns, ridges, cirques, basins with lakes). Besides, the altitudinal variable allows coexisting bioclimatic types, from sub-Mediterranean to mountainous ones. Also, some biogeographic units are established, finding mixed deciduous forests, black pine forests, fir trees, and high mountain pastures (OAPN, 2014). It is important to highlight that there are species of flora and fauna of great importance for conserving biological diversity. In Ordesa-Viñamala, local and regional endemism and thread species such as *Borderea pyrenaica, Leontopodium alpinum*, *Cochlearia aragonensis* or *Cypripedium calceolus*. There are also species of birds, such as the Bearded Vulture (*Gypaetus barbatus*) or the Grouse (*Tetrao urogallus*) or amphibians, such as the Ocellated Lizard (*Timon lepidus*).

Regarding the socio-economic characteristics of the Ordesa-Viñamala Biosphere Reserve, it is noticed that there is a clear example of sustainable development because it is possible to reconcile the use of goods and resources offered by the environment with ecosystem conservation. At present, the main productive activity is livestock to tourism. In addition, the main tourist activities are linked to mountaineering, hiking and mountain sports. Within the extension are 11 municipalities with a total population of 5,639 inhabitants.

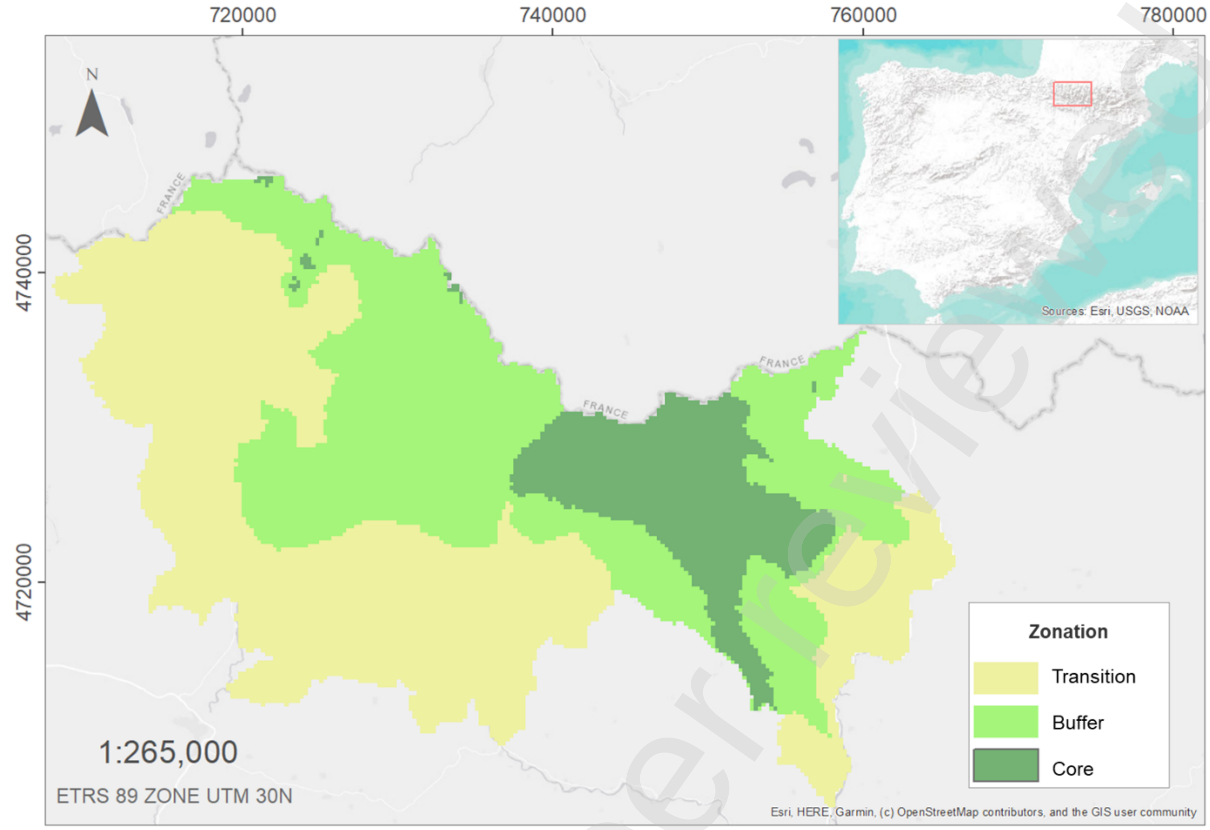

Figure 1. Ordesa-Viñamala Biosphere Reserve map

2.2.2. Sierra Nevada

Sierra Nevada Biosphere Reserve (Figure 2) is situated between Almería and Granada, in the Autonomous Community of Andalusia, located 30 km from the coast. It was declared in 1986. Sierra Nevada Biosphere Reserve has 172,238 ha, of which 50% belongs to the core zone, 40% to the buffer zone and 10% to the transition zone. It has a population of 10,760 inhabitants and 60 municipalities.

The managing entity is the Ministry of Environment and Spatial Planning (Calvo, 2019). Within this Biosphere Reserve, other protection figures are shown as follows:

- National Park
- Natural Park
- Natural Monument (Falla de Nigüelas)
- Natura 2000 Network of the European Union
- Special Conservation Area (ZEC)
- Special Protection Area for Birds (ZEPA)
- Place of Community Importance (SCI)
- List of RAMSAR wetlands (Humedales y Peberas de Padul)
- European Charter for Sustainable Tourism (CETS)

During the Quaternary, there were glaciers, which were the southernmost in Europe. Consequently, morphologies associated with glacial erosion can be seen, such as cirques, moraines, lagoons, and valleys. Sierra Nevada is the most important point of plant diversity in the western Mediterranean Region, representing almost 30% of the flora of mainland Spain. As for the fauna, there is a great diversity of fauna, highlighting the avifauna.

The area of socio-economic influence of the Reserve gathers about 98,000 inhabitants, of which only 10% live within the limits of the Natural Area. Agricultural and livestock crops represent 11% of land uses within the Reserve, although they have suffered a progressive decline in recent decades. The arboreal species (almond, cherry, olive tree, vineyards) represent 70% of the crops, while the irrigated herbaceous remains 30%. It is noteworthy in the industrial sector, meat industries for drying ham, wine, construction materials, renewable energies, and the mineral water bottling plant in Lanjarón. In addition, tourism is a fundamental source of income for the area's development.

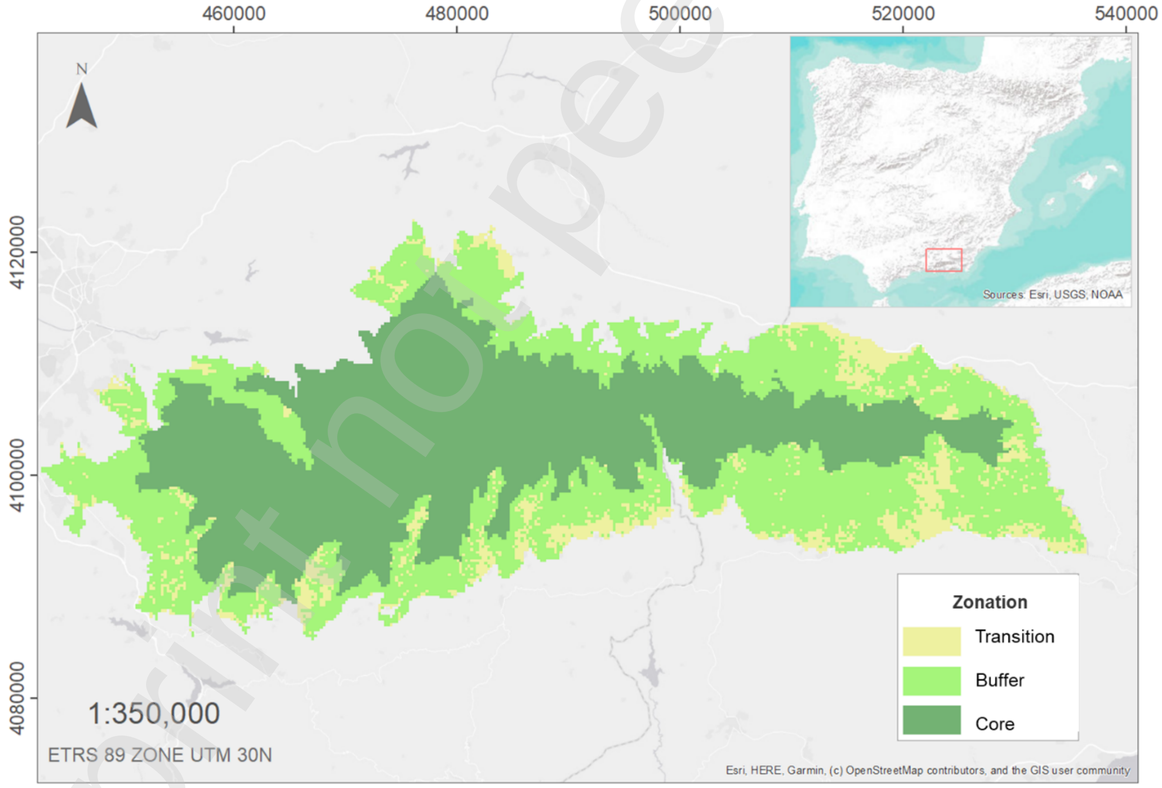

Figure 2. Sierra Nevada Biosphere Reserve map

2.2 Data input

Table 1 shows the data input used for the present work.

Table 1. Input material

Material	Product	Original spatial resolution	Source
NDVI	MOD13Q1	250 m	*Google Earth Engine-NASA (last Access: 1 September 2020, Google Earth Engine Datasets Catalog)*
Biosphere Reserve zonation layers			*MITECO (Spain) (last access: 1 September 2020, http://www.miteco.gob.es/)*
Land Cover	Land Cover CCI 2001	300 m	*ESA (last access: 1 September 2020, https://www.esa-landcover-cci.org)*
Annual mean temperature	MOD11	1 km	*Google Earth Engine-NASA (last Access: 1 September 2020, Google Earth Engine Datasets Catalog)*
Drought index	MOD16	500 m	*Google Earth Engine-NASA (last Access: 1 September 2020, Google Earth Engine Datasets Catalog)*
MDT (Digital Terrain Model)	MDT 200	200 m	*IGN (Spain) (last access: 1 September 2020, http://centrodedescargas.cnig.es/)*

- MODIS and MOD13q1 product

The product developed by the MODIS team to obtain the Vegetation Index is MOD13Q1. This product has been generated from the daily surface reflectance product. After applying an algorithm (Maximum Value Compositing), it is possible to obtain the best pixel value and a clean image for 16 days (Huete et al., 1999). Thus, the NDVI data is generated every 16 days with a 250-pixel-meter resolution. From 2001 to 2016 (inclusive), 368 images were collected (Didan, 2015).

- CCI Land cover cartography

Climate Change Initiative (CCI) is a program dependent on the European Space Agency (ESA) whose objective is to group and understand all the information collected from Earth observation by ESA during the last 40 years to contribute to improving the databases required by the United Nations Framework Convention on Climate Change. The maps are free and can be downloaded from the ESA website within the CCI program (ESA, 2017).

The land cover layer has been used to observe changes in land use within our time series (2001-2016). Therefore, the land occupation layers were obtained for 2001 between 2001 and 2016, and the pixels that have remained stable throughout that period are considered for the present work.

- Reserves Biosphere layers

The Nature Bank of the Ministry has provided these layers for Ecological Transition and the Demographic Challenge (MITECO). It includes the zonation of each Reserve, i. e., the core area, the buffer zone and the outer transition area, at a scale of 1: 50,000.

- EUNIS Habitat Classification

EUNIS Habitat Classification is a European reference classification based on the habitat types listed in Annex I of the European Habitats Directive. Ecosystems are mapped by interpreting different available land cover information according to the European habitat classification. The EUNIS habitat classification covers the whole of Europe's terrestrial and marine areas of Europe and establishes a total of 10 habitat types.

Generally, the scale used in this classification covers habitats of at least 100 m^2. However, microhabitats (those below 1 m^2) have also been described, and even combinations of mosaics of several individual habitats can cover an area of at least 10 ha. EUNIS habitats are grouped hierarchically into three levels, specifically the higher ones. To make this classification, keys are used, which follow different criteria to categorize each habitat (Davies et al., 2004). In the present work, only terrestrial habitats have been recorded for both Biosphere Reserves, and the classification used is EUNIS level 1 (Table 2).

Table 2. EUNIS Level 1 habitats used in this study and the number of pixels belonging to each class.

EUNIS Level 1 categories		Total number of pixels
C	Inland surface waters	140
D	Mires, bogs and fens	6
E	Grasslands and land dominated by forbs, mosses or lichens	8475
F	Heathland, scrub and tundra	15799
G	Woodland, forest and other wooded land	22789
H	Inland unvegetated or sparsely vegetated habitats	4977
I	Arable land and market gardens	1382
J	Constructed, industrial and other artificial habitats	234

- Average annual temperature of the Earth's surface

The annual mean temperature data have been obtained using the MOD11 product of the MODIS sensor for the 2001-2016 time series (both inclusive). The MOD11A1 Version 6 product records the Earth's surface temperature daily with a spatial resolution of 1 km. The temperature value per pixel is derived from the MOD11L2 product, which performs daily measurements every 5 minutes using the split-window algorithm (Wan et al., 2015). To facilitate the processing of these data, Google Earth Engine software was used, which allows an average of all the images available to obtain an annual average of temperature for all years from 2001 to 2016, both inclusive.

- Annual average evapotranspiration

The annual mean evapotranspiration was obtained through the MOD16 product of the MODIS sensor. The spatial resolution of the measurements for this product is 1 km. According to Mu et al. (2011), the MODIS team uses the evapotranspiration algorithm. For this product, the actual and potential evapotranspiration data have been used, during the period 2001-2016, which will be used to calculate the drought index explained later. In the same way as to obtain the mean annual temperature, the evapotranspiration data were processed using Google Earth Engine, thus bringing a yearly mean for each year of the time series under study.

- Digital model terrain

The elevation of the land has been obtained from the MDT200 cartography elaborated by the National Geographic Institute (IGN) and downloaded through its website (see Table 1).

This Digital Terrain Model (DTM) has a mesh pitch of 200 m and has been obtained by interpolation from the terrain class of LIDAR flights of the first coverage of the National Plan for Aerial Orthophotography (PNOA) (García Asensio & Lumbreras Crespo, 1992).

2.3 Data processing

2.3.1 NDVI Pixel Curve Smoothing and NDVI trend categories

The annual mean NDVI values per pixel were smoothed using the Gaussian algorithm of the TIMESAT software (Jönsson & Eklundh, 2002) so that no "spikes" of outliers are found and the vegetation time series for the study area can be worked with. In addition, TIMESAT provides a weighting mechanism such that some values in the time series may be more influential than others. Therefore, high weights are assigned for higher quality MODIS shots and low weights for lower quality. In this way, pixels with a lower given weight have a lower weight in the curve fit (Jönsson & Eklundh, 2002). Finally, the mean of each pixel included in the study area was obtained for 2001-2016. Those pixels where the NDVI was less than zero were ignored because they are areas of bare rock or soil without vegetation. Based on the annual mean NDVI values per pixel obtained by smoothing, we analyzed the NDVI trends for the time series (2001-2016).

Taking as a reference the studies published by Arrogante et al. (2018) and Novillo et al. (2019), Theil-Sen regressions were used to examine the trend. Thus, a positive slope implies a growth in the NDVI value, while a negative slope indicates a decrease in the NDVI value.

Subsequently, a Mann-Kendall test was applied to corroborate whether this observed trend is significant. A significant trend between 2001 and 2016 was considered for those pixels where the Mann-Kendall statistic had a p-value of less than 0.1 (90%

confidence interval). The Mann-Kendall test and Theil-Sen regression were performed using the Clark Labs TerrSet Earth Trends Modeler (ETM) (Eastman, 2015). ETM is an integrated set of tools for analyzing image time series data associated with remotely sensed Earth observation imagery.

The result was a raster layer with significant trends generated with Mann-Kendall and another with slopes generated with Theil-Sen. Then, using ArcGIS software, a single layer was obtained with pixels with a significant positive NDVI trend (code = 1), pixels with a significant negative NDVI trend (code = -1) and pixels with no significant trend where the p-value was less than 0.1 (code = 0). Subsequently, the data from the significant trend layer were crossed with the layer presenting the boundaries of the high mountain Biosphere Reserve zones (Sierra Nevada and Ordesa-Viñamala) to obtain the pixels within the study areas.

In addition, to eliminate the effect that could occur in the time trend of NDVI as a result of variability in land occupation, the raster layer data were crossed with the CCI layer of land occupations of each of the Biosphere Reserves to eliminate the pixels that have undergone changes over the time series and thus obtain pure occupation pixels, i.e., the same occupation code in 2001, 2008 and 2016 cartography. For this purpose, the different raster maps were combined to assign a single output value to each unique combination of input values.

2.3.2 Temperature trend

The process of obtaining the time temperature trend was carried out in the same way as that described in the previous section with the NDVI from the annual mean temperature data obtained from the MOD11 product of the MODIS sensor. The only difference is that we did not apply a smooth process.

2.3.3 Drought index

The actual and potential evapotranspiration data for the Drought Index has been obtained from the MOD16 product from MODIS.

This drought index has been found by applying the Vapor Stress Index (ESI), which allows the real evapotranspiration to be compared with the potential evapotranspiration obtained by remote sensing using geostationary satellites. This index does not require data on precipitation or subsurface soil characteristics (Anderson et al., 2011). The process to trend the drought index was the same as for the NDVI and temperature trends.

2.3.4 Euclidean distance from population centres

To examine how the distance to population centers impacts certain factors, the analysis proceeded as follows:

Selection of Population Centers: The CCI raster layer from 2001 was utilized, specifically identifying population centers with a designated class value (Class = 190). This selection process aimed to pinpoint areas classified as population centers within the raster data.

Assumption of Stability: It was assumed that population centers would remain intact throughout the studied time series of 16 years. This assumption is grounded in the expectation that urban areas typically maintain their category without significant changes over this relatively short duration.

Calculation of Euclidean Distance: Using GIS software, the Euclidean distance was computed from the chosen population centers. The Euclidean distance metric measures the straight-line distance from each pixel or point to the nearest population center. This analysis provides insights into the spatial relationship between various locations and their proximity to the closest population center.

By conducting this analysis, valuable information can be obtained regarding the influence of distance on different aspects or phenomena, such as land use patterns, accessibility, or socio-economic characteristics.

All the variables were projected to ETRS 1989- UTM Zone 30 North, the official projection in Spanish databases. The layers were resampled to 250 meters pixels, the resolution from the MOD13q1 product, obtaining a total of 53,802 samples, of which 32,095 correspond to the Sierra Nevada Reserve, and 21,707 remain within the Ordesa-Viñamala Reserve.

2.4 Data analysis

First, before performing the statistical analysis of the data, a descriptive study was carried out where the distribution of frequencies between the explanatory variables and the variable to be explained (NDVI trend) was examined. Then, bar graphs were made for categorical variables, and box and whisker plots were used for numerical variables.

Statistical tests were performed using R software to test for statistically significant relationships between the different variables. First, the Chi-square test was performed between NDVI trends and categorical variables. Then, the Kruskal-Wallis test (see Table 2), analogous to an analysis of variance (ANOVA) but non-parametric, was performed to assess whether there is a significant association between NDVI trends and numerical variables. The Kruskal-Wallis test identifies substantial differences between the median values of the numerical variable of a pair of categories of the variable to be explained (positive, negative or no NDVI trend), so the post-hoc Wilcoxon signed-rank test was carried out to identify which pairs differ.

Finally, for the categorical variables, a frequency analysis was carried out by creating contingency tables in which the difference in percentage between the observed and expected NDVI was calculated, with both significant positive and negative trends and no trend in the classes of each categorical variable, and graphs were made based on these differences.

Table 3. Input variables and tests performed for each analysis

Analysis	**Explained variable**	**Explanatory variables**	**Test**
Analysis 1	NDVI trends	Reserve	Chi-square
Analysis 2	NDVI trends	Reserve zone	Chi-square
Analysis 3	NDVI trends	EUNIS Habitats	Chi-square
Analysis 4	NDVI trends	Annual mean temperature trend	Chi-square
Analysis 5	NDVI trends	Annual mean hydric stress trend	Chi-square
Analysis 6	NDVI trends	Elevation	Kruskal-Wallis
Analysis 7	NDVI trends	Distance to population centres	Kruskal-Wallis

3. Results

3.1. NDVI trends of the reserves

Figure 3 shows the geographical distribution of NDVI trends from 2001 to 2016 for each Reserve. In general, significant positive NDVI trends are more frequent, accounting for 11.7%, while significant negative trends account for 6%, and there is 82.3% with no trend.

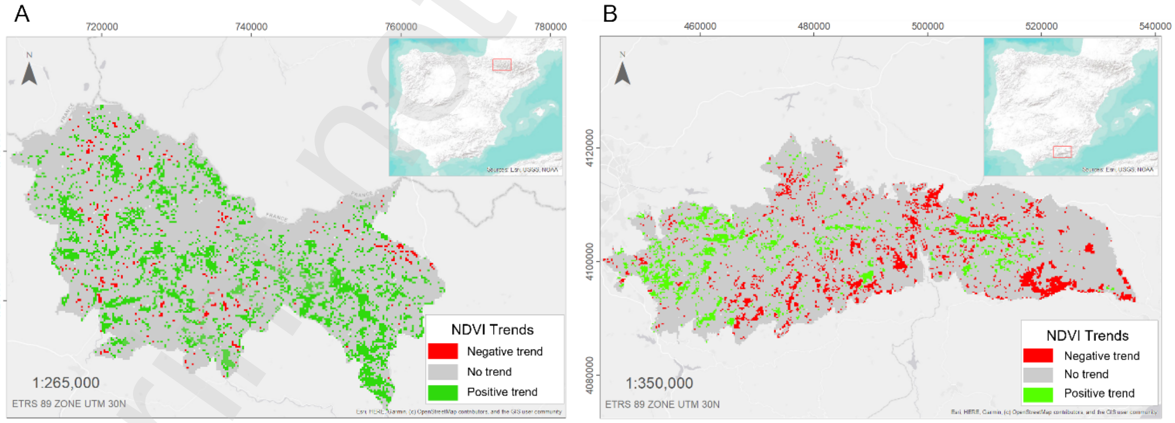

Figure 3. NDVI time trends in each Reserve. A. Ordesa-Viñamala Biosphere Reserve; B. Sierra Nevada Biosphere Reserve.

Figure 4A reveals the percentages of pixels with significant positive, negative and no significant NDVI trends, for the 2001-2016 time series and each Reserve. Ordesa-Viñamala is the Reserve with the highest percentage of pixels with significant trends, 20.15%, while the Sierra Nevada has 16.02% of pixels with significant trends. On the other hand, in Ordesa-Viñamala, significant positive NDVI trends predominate at

18.47%, while significant negative trends represent only 1.68%. On the contrary, Sierra Nevada shows higher values in the negative NDVI trend with 9.02%.

Furthermore, when comparing the values of the difference between the observed and the expected number of pixels with positive, negative and no NDVI trend (Figure 4B), we observe that in the Sierra Nevada, the values of significant negative NDVI trend are more frequent than expected, while in Ordesa-Viñamala the frequency of negative NDVI trend is lower than expected; on the contrary, there are more positive values of NDVI trend than expected. In the latter case, it should be noted that the differences between observed and expected values are higher than 50% for positive and negative NDVI trends.

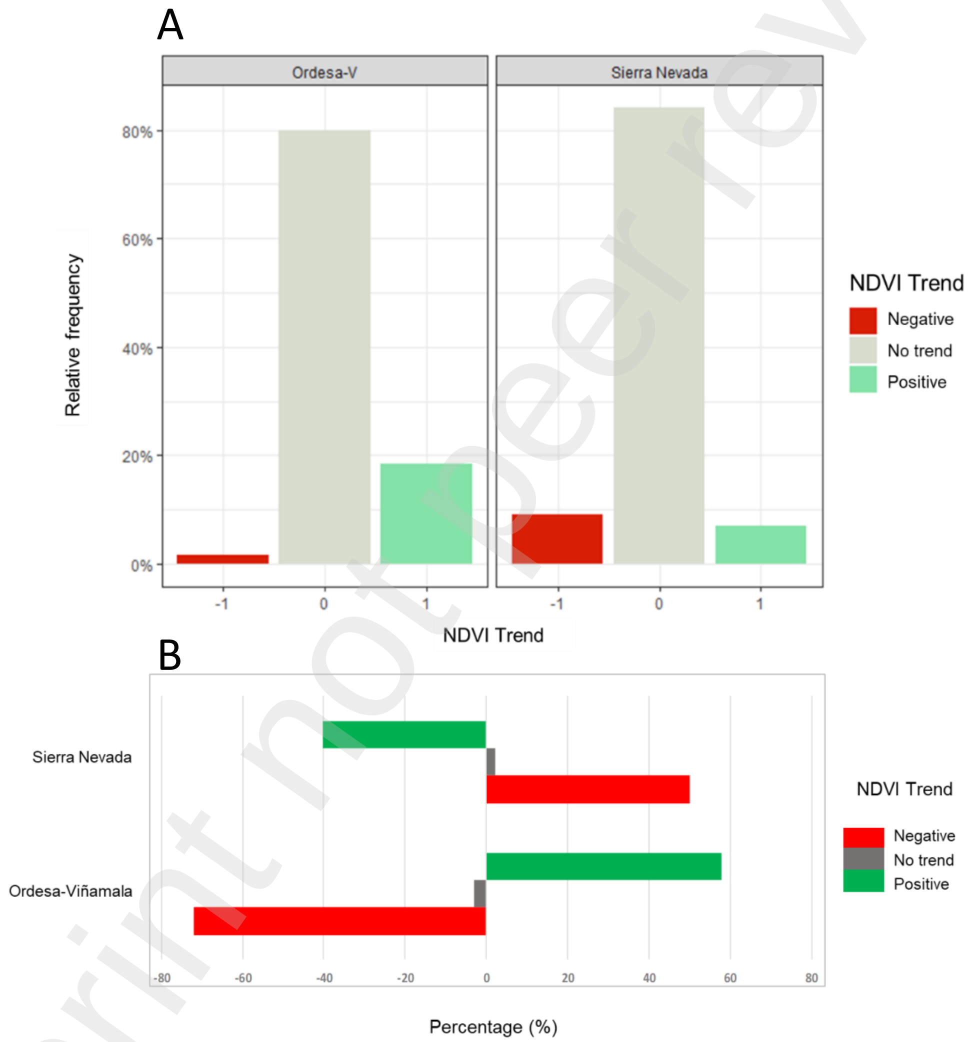

Figure 4. A. Proportions of each category of NDVI trend in both reserves and B. Deviation of actual trend values from expected trend values in both reserves.

3.2. Time trends of NDVI by important variables

3.2.1. Trend of NDVI according to reserve zonation

Figure 5.1 shows how Ordesa-Viñamala has a higher percentage of pixels with positive than negative NDVI trends. In addition, the number of pixels with significant negative NDVI trends is lower in the core, slightly higher in the buffer zone and somewhat higher in the transition zone (0.48%, 1.48% and 2.14%, respectively). On the other hand, Sierra Nevada has a higher percentage of pixels with a negative NDVI trend in the transition zone than in the core zone, increasing from 7.72% in the core zone to 19.42% in the transition zone. On the contrary, a decrease in the percentage of pixels with a positive trend is observed as we move towards the transition zone, with values of 8.32% in the core zone and 2.82% in the transition zone.

In addition, to verify this pattern, Figure 5.2 shows that in Ordesa-Viñamala, there is a lower percentage of negative NDVI trend than expected (less than 60%) for the core zone. The core zone of Sierra Nevada also reveals a lower rate of negative NDVI trend than expected (less than 10%) and a higher positive NDVI trend than expected (19%). Both reserves have more negative NDVI trends and less than-expected positive trends for the transition zone. Still, the high values observed in the Sierra Nevada stand out, with a 115% higher-than-expected negative trend and a 60% lower-than-expected positive trend.

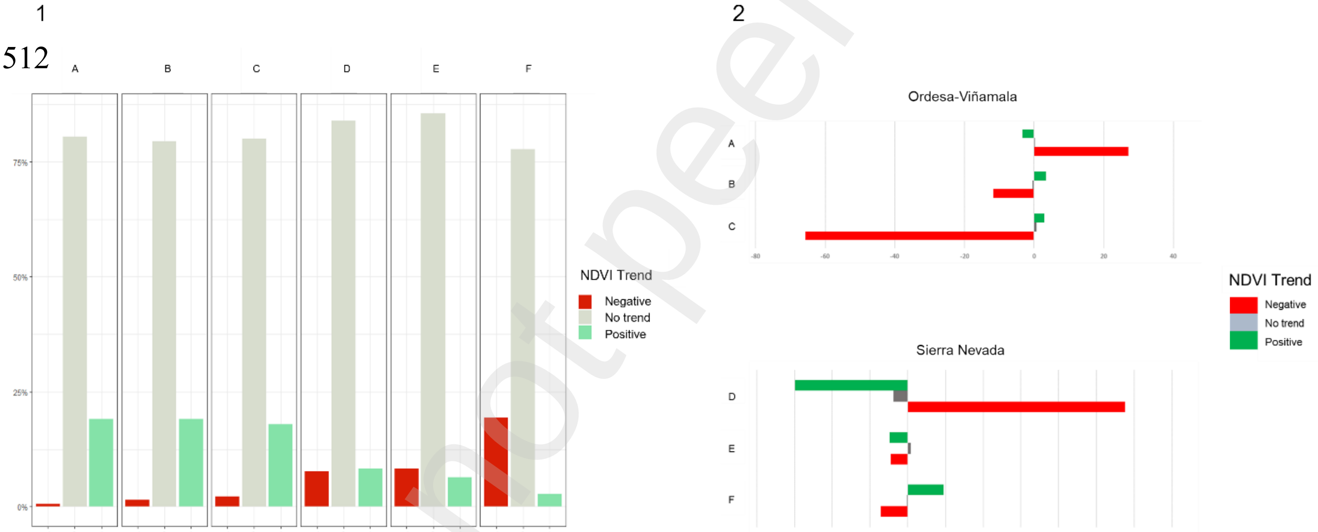

Figure 5. 1. Proportion of each category of NDVI trend in each zone of both reserves. A. Core area of Ordesa-Viñamala; B. Buffer zone of Ordesa-Viñamala; C. Transition area of Ordesa-Viñamala; D. Core area of Sierra Nevada; E. Buffer zone of Sierra Nevada; F. Transition zone of Sierra Nevada. 2. Deviation of actual trend values from expected trend values in each zone of both reserves. A. Transition area of Ordesa-Viñamala; B. Buffer zone of Ordesa-Viñamala; C. Transition area of Ordesa-Viñamala; D. Core area of Sierra Nevada; E. Buffer zone of Sierra Nevada; F. Core area of Sierra Nevada.

3.2.2. Trend of NDVI according to the trend of temperature

No significant decreasing trends in surface temperature over 2001-2016 were found for both reserves. However, Sierra Nevada is the Reserve with the highest increasing temperature trend for the time series, with 55% of pixels with such a trend. On the other hand, Ordesa-Viñamala has only 13% of pixels with a rising temperature trend. In both reserves, there is a decrease in the positive NDVI trend from areas without significant temperature variation trends to regions with a significantly increasing temperature trend, as seen in Figure 6.1.

Figure 6.2 shows the difference between the observed and expected NDVI time trend pixels as a function of the temperature time trend within each Reserve. The difference in NDVI trend values between pixels with increasing temperature trends and pixels where no significant temperature trends were found is remarkable. The same pattern is observed in both reserves for growing temperature trends, where the positive NDVI trend values are lower than expected. Furthermore, there is a higher percentage of negative NDVI trends in the Sierra Nevada than expected. Notably, positive trends increased more than expected, with no significant temperature trends recorded. On the contrary, in Ordesa-Viñamala, positive and negative NDVI trends are lower than expected when there is a positive temperature trend. In contrast, when there are no significant temperature trends, there are higher positive NDVI trends than expected, although in a lower proportion than in the Sierra Nevada.

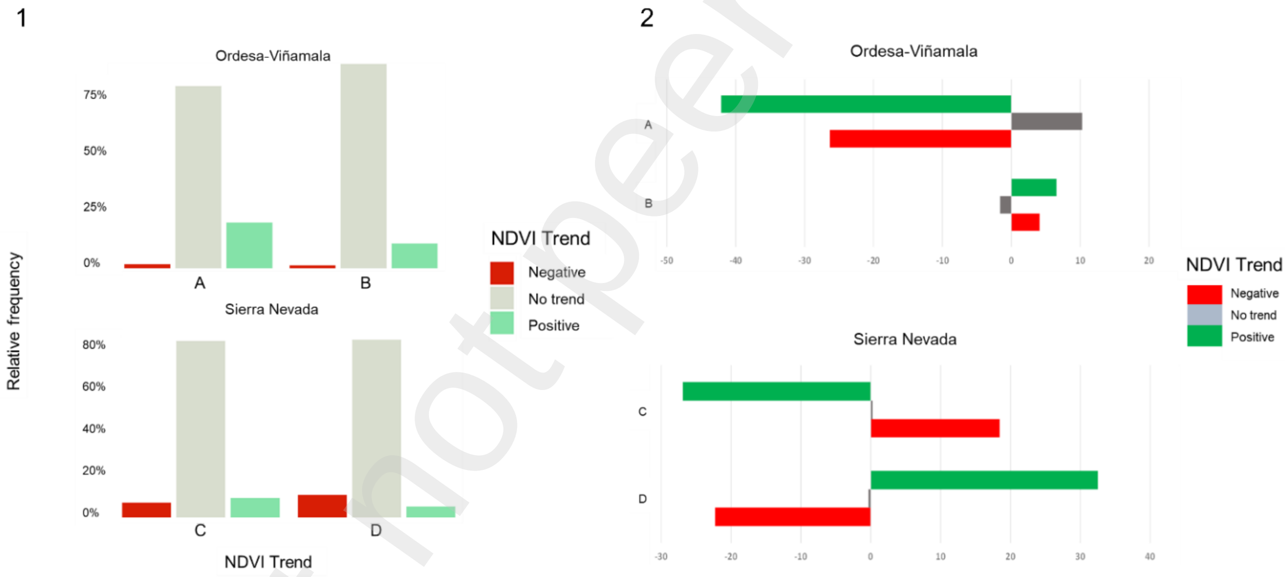

Figure 6. 1. Proportion of each category of NDVI trend according to the time temperature trend in both reserves. A. No significant temperature trend in Ordesa-Viñamala Reserve; B. Significant positive temperature trend in Ordesa-Viñamala Reserve; C. No significant temperature trend in Sierra Nevada Reserve; D. Significant positive temperature trend in Sierra-Nevada Reserve. 2. Deviation of actual temperature trend values from expected temperature trend values in both reserves. A. Significant positive temperature trend in Ordesa-Viñamala Reserve; B. No significant temperature trend in Ordesa-Viñamala Reserve; C. Significant positive temperature trend in Sierra-Nevada Reserve; D. No significant temperature trend in Sierra Nevada Reserve.

3.2.3 Trend of NDVI according to the time trend of hydric stress

Both reserves have similarities regarding the percentages of NDVI trend pixels as a function of significant water stress trends for 2001-2016 (Figure 7.1). For pixels with a positive water stress trend, i.e. lower water stress, there is a higher percentage of pixels with a positive NDVI trend, around 20% positive NDVI trend in both reserves. While the highest rates of negative NDVI trends in both reserves are found in areas with a negative trend of water stress, i.e., greater water stress, Ordesa-Viñamala has 6% of negative NDVI trends. At the same time, in the Sierra Nevada, we observe a percentage of 46% of negative NDVI trends. Therefore, there are differences between reserves: Ordesa-Viñamala has higher percentages of significant positive NDVI trends, while Sierra Nevada has higher rates of negative NDVI trends.

On the other hand, for negative water stress trends, a higher percentage of negative NDVI trends than expected was observed in both reserves (Figure 7.2). However, the rates were more elevated in the Sierra Nevada. For areas with positive water stress trends, higher positive NDVI trends and lower negative NDVI trends than expected were recorded in both reserves. Still, here, however, the positive NDVI trends were higher in the Sierra Nevada.

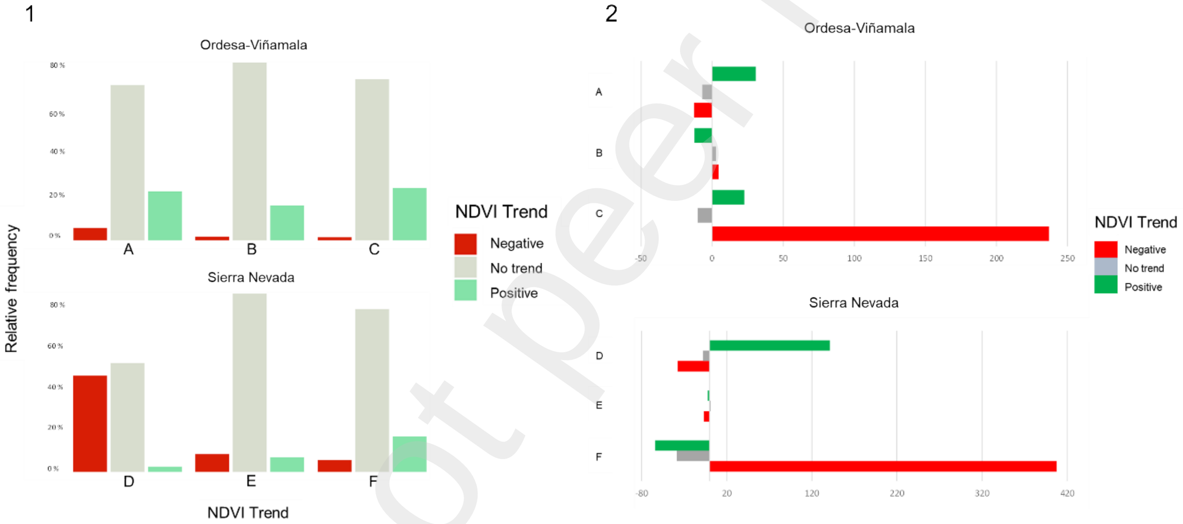

Figure 7. 1. Time NDVI trends according to time hydric stress trends in both reserves. A. Significant negative hydric stress trend in Ordesa-Viñamala Reserve; B. No significant hydric stress trend in Ordesa-Viñamala Reserve; C. Significant positive hydric stress trend in Ordesa-Viñamala Reserve; D. Significant negative hydric stress trend in Sierra Nevada Reserve; E. No significant hydric stress trend in Sierra Nevada Reserve; F. Significant positive hydric stress trend in Sierra Nevada Reserve. 2. Deviation of actual hydric stress trend values from expected hydric stress trend values in both reserves. A. Significant negative hydric stress trend in Ordesa-Viñamala Reserve; B. No significant hydric stress trend in Ordesa-Viñamala Reserve; C. Significant positive hydric stress trend in Ordesa-Viñamala Reserve; D. Significant negative hydric stress trend in Sierra Nevada Reserve; E. No significant hydric stress trend in Sierra Nevada Reserve; F. Significant positive hydric stress trend in Sierra Nevada Reserve.

3.2.4. Time trend of NDVI according to EUNIS habitats

Figure 13 shows significant differences in the NDVI trends according to habitat type in each Reserve. In Ordesa-Viñamala, positive NDVI trends are higher than negative ones for all habitat categories. The highest percentages of positive NDVI trends were observed in the habitats corresponding to grasslands and lands dominated by herbaceous, mosses or lichens (E) and heathlands, shrublands and tundra (F), with 23.34% and

20.65%, respectively. These were followed by habitats C and G, which are inland surface waters and woodland, forest and other wooded land, respectively. On the contrary, agricultural habitats (I) and urban, industrial or artificial areas (J) showed the highest percentage of negative trends. The most frequent habitats, i.e. the ones that concentrate the highest number of pixels, are wooded areas (G), with 43% of the total number of pixels, and habitat E, with 25%.

In the Sierra Nevada, there are more negative significant trends than positive trends in five of the eight identified habitats. Notably, 100% of the pixels belonging to wetlands (D) show negative NDVI trends for the period 2001-2016. This habitat is followed in the percentage of negative NDVI trends by habitats I and J, representing agricultural habitats and built and artificial areas, as in Ordesa-Viñamala. On the other hand, the habitats with the highest percentage of positive NDVI trends are habitats E and F, as in Ordesa-Viñamala. Finally, the most frequent habitats are G, as in Ordesa-Viñamala, and F, which correspond to woodland and heathland, scrub and tundra, representing 41.92% and 40.92% of the total number of pixels.

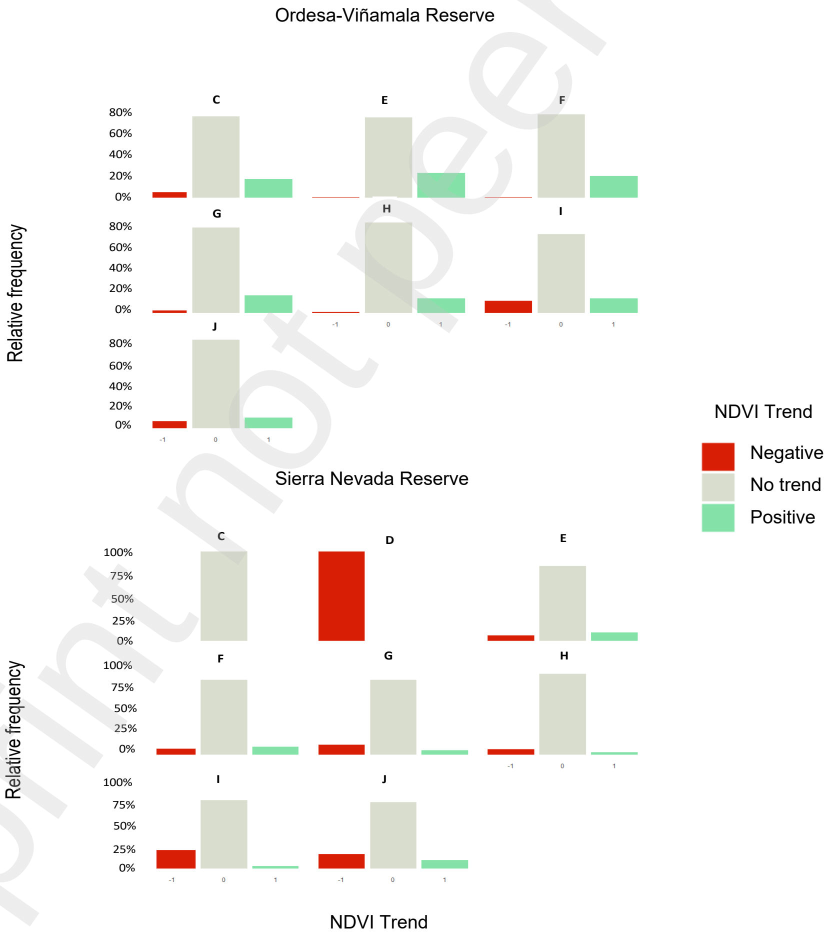

Figure 8. NDVI time trends distribution of frequencies according to EUNIS Habitats categories in both reserves.

3.2.5. Time trend of NDVI according to altitude and population centres

The results in Figure 8 have shown that positive NDVI trends occur at higher altitudes than negative NDVI trends in both reserves. The variability of the negative NDVI trends in Ordesa-Viñamala is lower than those recorded for positive NDVI trends, which have a wider range of dispersion. These negative NDVI trends occur at lower altitudes than the positive trends. In the Sierra Nevada, the negative NDVI trends show a greater altitude variability, but they are still observed at lower altitudes than the positive NDVI trends.

Concerning distance to population centres, the results have confirmed that the distance is generally less in the Sierra Nevada than in Ordesa-Viñamala. In Ordesa-Viñamala, negative NDVI trends are found in areas closer to population centres, and positive trends are greater at greater distances from population centres. In contrast, in the Sierra Nevada, positive NDVI trends are found at shorter distances from population centres than negative trends (Figure 8).

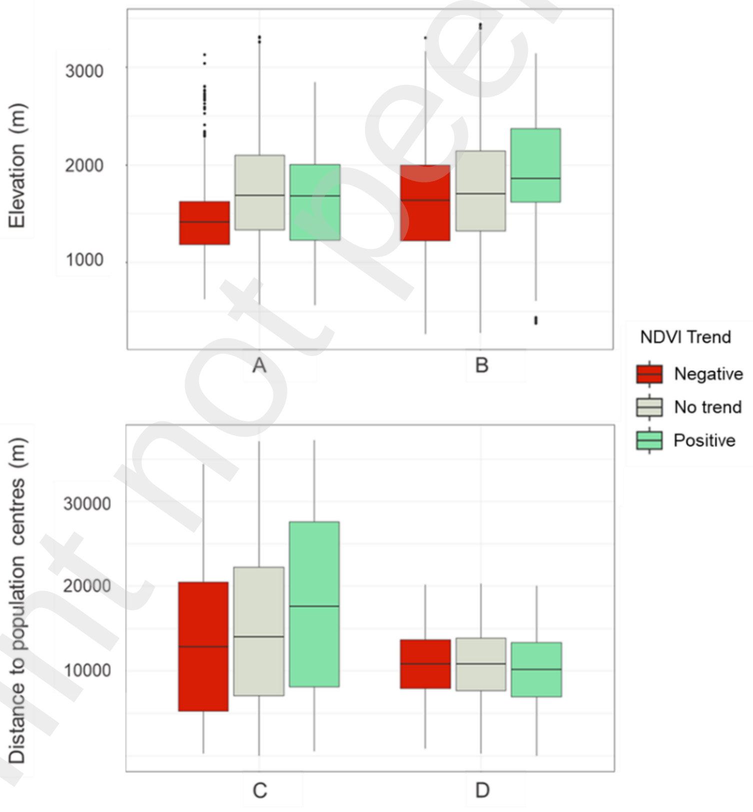

Figure 9. NDVI time trends distribution of frequencies according to elevation and distance to population centres in each zone of both reserves.

3.3. Results of the Chi-square and Kruskal-Wallis analysis

Tables 3 and 4 show the results obtained for the statistical tests applied for categorical (Table 3) and numerical variables (Table 4).

Table 4. Chi-square test results. SN: Sierra Nevada Reserve; OV: Ordesa-Viñamala Reserve

Test number	Explained variable	Explanatory variable	Biosphere Reserve	p value	Degrees of freedom	Chi-square value
1	NDVI trend	Reserves	Todas	<0.05	2	2599.68
2	NDVI trend	Reserve zone	SN	<0.05	4	40.77
3	NDVI trend	Reserve zone	OV	<0.05	4	527.40
4	NDVI trend	Annual mean temperature trend	SN	< 0.05	2	306.06
5	NDVI trend	Annual mean temperature trend	OV	<0.05	2	142.55
6	NDVI trend	Annual mean hydric stress trend	SN	<0.05	4	2682.00
7	NDVI trend	Annual mean hydric stress trend	OV	<0.05	4	143.50

Table 5. Kruskal-Wallis test results. SN: Sierra Nevada Reserve; OV: Ordesa-Viñamala Reserve

Test number	Explained variable	Explanatory variable	Biosphere Reserve	p value	Degrees of freedom	H value	Post-hoc Wilcoxon Ranks
8	NDVI trend	Elevation	OV	< 0.05	2	172.42	All pairs are differentiated
9	NDVI trend	Elevation	SN	< 0.05	2	432.21	All pairs are differentiated
10	NDVI trend	Distance to population centres	OV	< 0.05	2	302.25	All pairs are differentiated
11	NDVI trend	Distance to population centres	SN	< 0.05	2	38.37	0 is not differentiated from -1

A statistical association was found between NDVI trends and all the categorical variables analyzed in each Reserve. For the numerical variables, significant differences were found for all variables except for the slope variable in Ordesa-Viñamala, where no significant differences were found for the negative and positive NDVI trend categories. Also, there were no significant differences between areas with no NDVI trend and regions with a negative NDVI trend regarding the distance to population centres variable.

4. Discussion

The statistical results show a significant association between NDVI trends and the reserves studied. In general, it has been observed that significant positive NDVI trends are more frequent than negative trends in high mountain Biosphere Reserves for the period from 2001 to 2016. These results coincide with those obtained by Arrogante et al. (2018) for the same period and in the Pyrenees and Southern Baetic mountain regions, where the Reserves under study are located. These results have also been observed in continental Spain (Novillo et al., 2019). This general increase in photosynthetic activity also occurs globally (Nemani et al., 2003). According to different studies, this is related to the rise in mean annual temperature, favouring plant development, especially in spring and summer (Myneni et al., 1997).

NDVI trend results for the two Reserves have followed different patterns. In Ordesa-Viñamala, more positive NDVI trends have been observed than negative ones. Moreover, the positive trends recorded are higher than expected, while the negative trends are lower than expected. However, this pattern is reversed in the Sierra Nevada, where negative NDVI trends are predominant and higher than expected, while positive trends occur less frequently. These differences can be explained by climatic factors, such as temperature, precipitation and radiation, although anthropogenic factors may also play a role (Liu et al., 2015).

According to Papagiannopoulou et al. (2017), the limiting factors on vegetation in the north of the Peninsula are temperature and solar radiation received. In the south, the limiting factor is precipitation. Khorchani et al. (2018) state that when energy is the limiting factor, an increase in temperature results in positive NDVI trends; however when precipitation is the limiting factor, this increase in temperature causes a decrease in the NDVI trend.

In Ordesa-Viñamala, vegetation growth has a high seasonality, the limiting factor of this growth being temperature, especially in winter, but the availability of water and solar energy received, especially in summer, allows vegetation development (Alcaraz-Segura, Cabello, et al., 2009). The increase in mean annual temperatures is causing this seasonality to be lower, which could be favouring vegetation development. However, the climatic conditions of Sierra Nevada mean that the main limiting factor is precipitation (Alcaraz-Segura, Cabello, et al., 2009). In addition, rising temperatures are causing an increase in the frequency of summer droughts (Sergio M Vicente-Serrano et al., 2014). On the other hand, altitude may also be causing the temperature to be a limiting factor in winter.

No significant decreasing surface temperature trends have been found from 2001 to 2016. This fact makes sense in the current global warming scenario (IPCC, 2014). A significant association was found between surface temperature trends and NDVI trends, and it was observed that Sierra Nevada Reserve has the highest percentage of increasing temperature trends. Besides, when the temperature trend has grown for both reserves, the positive NDVI trends have decreased compared to areas where no significant temperature trends were found. However, when comparing the negative NDVI trends, there are differences between the reserves: in the Sierra Nevada, the negative NDVI trends increase from areas with no significant temperature trend to places where there has been an increase in temperature, while in Ordesa-Viñamala, there is no such increase in the negative NDVI trends, there is even a slight decrease. These differences highlight the vulnerability of the Mediterranean region to rising temperatures, which could explain why we find more negative and less positive NDVI trends than expected in the Sierra Nevada and the opposite in Ordesa-Viñamala (García-Ruiz et al., 2011).

Concerning the above, the increase in temperatures and the decrease in precipitation has led to a rise in the severity of droughts, especially in the Mediterranean area (García-Ruiz et al., 2011; Sergio M. Vicente-Serrano et al., 2014), so it would be expected that in areas with negative trends of water stress, we would observe higher negative and lower positive trends of NDVI than expected. Again, these trends would be accentuated in the Sierra Nevada.

The results demonstrate this, although the common trend in both reserves is to find more negative NDVI trends than expected for areas with an increase in water stress and more positive trends than expected where there has been a decrease in water stress. Sierra Nevada seems to be more affected by this variable, which could indicate that water stress is a more limiting factor for vegetation development in the Mediterranean bioregion than in the alpine (Alcaraz-Segura, Cabello, et al., 2009). It is noteworthy that in the areas of Sierra Nevada where there has been a decrease in water stress, higher positive NDVI trends than expected have been found than for the same regions of Ordesa-Viñamala, which seems to explain how, when neither water availability nor temperature is limiting factors, vegetation growth is favoured.

Regarding EUNIS habitats, in Ordesa-Viñamala, grasslands and shrublands are the habitats with a higher percentage of positive NDVI trends since they could be benefiting from the increase in temperatures, which would allow attenuating the effect of low temperatures in winter, as explained Alcaraz-Segura et al. (2009) and Khorchani et al. (2018). On the contrary, the habitats with the most NDVI negative trends are agricultural habitats and built and constructed areas, the same as in Sierra Nevada. These trends could be explained by the abandonment of traditional practices on farmland, which, together with unfavourable climatic cycles, hinder vegetation development (Valladares et al., 2004).

In the Sierra Nevada, the whole wetlands area shows negative NDVI trends, which indicates how temperature increases and lack of precipitation affect the vegetation associated with these habitat types. Agricultural and built areas also host more negative trends than positive ones, as in Ordesa-Viñamala. The latter could be because agricultural areas are suffering a widespread impact due to climate change (Anderson et al., 2020; Pathak et al., 2018). These habitats are followed in the percentage of negative trends by woodlands and unvegetated lands. On the contrary, the habitats with the highest percentage of positive NDVI trends are shrublands and grasslands. The latter mentioned could indicate that land abandonment is triggering the development of woody vegetation in these areas (Lasanta et al., 2017).

On the other hand, the most extensive habitats in the Sierra Nevada, woodlands and forests, which are composed mostly of coniferous forests and evergreen broadleaved forests, and heathland, shrubland and tundra are the most extensive ones in Ordesa-Viñamala as well. It indicates how, despite being high mountain Reserves and having the same habitat types, there are significant differences depending on the bioregion where the Reserve is located.

In this sense, habitats in the Ordesa-Viñamala Biosphere Reserve, located in the north of Spain, have a much more favourable evolution than the habitats of the Sierra Nevada located in the south. Ordesa-Viñamala is not in arid conditions of the Mediterranean zone, so the progressive increase in temperatures favours vegetation growth and, therefore, generates positive NDVI trends (Martínez-Vilalta et al., 2008). In this lower latitude, they endure conditions of higher average temperatures and water stress (Lamprecht et al., 2021) and, therefore, potential aridification in the face of climate change (Oliva et al., 2011; Ramos-Román et al., 2018).

In addition, it has to be taken into account that Biosphere reserves represent a dynamic conservation concept, different from other protected areas, whose main purpose is conservation. In addition to preserving ecosystems, biosphere reserves seek to maintain harmony between human action and the natural environment and, therefore, the cultural landscapes created by anthropic activity (Vericad Corominas & Balcells Rocamora, 1981).

However, within the biosphere reserve concept, there are different approaches or objectives. It should be noted that the Ordesa-Viñamala biosphere reserve has a great environmental value and a more purely conservation focus (González González, 2020) than the Sierra Nevada biosphere reserve, which hosts recreational activities, like tourism, occupying a considerable area (Moreno-Llorca et al., 2020). It is possible that the preservation of the state of the ecosystems in Ordesa-Viñamala, together with its latitudinal situation and, thus, its climatic characteristics, has led to a significantly higher proportion of positive NDVI trends and a lower proportion of negative trends than in the Sierra Nevada reserve in general, which translates into a better situation of tree stands.

On the other hand, a significant statistical association was found between the protection zones of each Reserve. The same trend has been observed in both reserves, i.e. negative NDVI trends increase, and positive trends decrease as we move away from the core area. However, both trends remain more stable in Ordesa-Viñamala. These results make sense, since the objective of these protected areas, according to UNESCO's MaB Programme, is precisely to offer greater protection in the core area, to allow the development of environmentally compatible activities in the buffer zone and to allow the development of activities that favour socio-economic development in the buffer zone (Batisse, 1982). Furthermore, this is evident because both reserves also show the same differences in observed and expected NDVI trends. The results obtained by Arrogante et al. (2018) for the mountainous area of Sierra Nevada show more negative and less positive trends than expected in protected areas and suggest that the configuration and management in this area could also explain the NDVI trends found.

Regarding the orographic variables studied, the statistical results show significant differences between altitude and NDVI trends in both reserves. These differences are due to the distribution of vegetation, which is partly dependent on topography (Peco et al., 1998). Positive NDVI trends occur at higher altitudes than negative ones in both reserves. These results coincide with those obtained by Pauli et al. (2012), where it is stated that the increase in temperatures induces the altitudinal ascent of vegetation in search of more temperate zones and greater water availability. Regarding slope, no significant differences were found between negative and positive NDVI trends in Ordesa-Viñamala, i.e. slope does not seem to be associated with finding significant positive or negative NDVI trends in the area. On the other hand, in Sierra Nevada, significant associations were found between NDVI trends and slope, although the proximity of the medians seems to indicate that this variable does not have a great influence on NDVI trends.

NDVI trends were significantly associated with distance to population centres in Ordesa-Viñamala. In this Reserve, negative NDVI trends have been observed at distances closer to population centres, and positive trends have been recorded in more distant areas. These results are logical since the greater the distance from population centres, the less anthropogenic activity capable of causing disturbances to the vegetation can be expected. In the Sierra Nevada, no significant differences were found between the distance to population centres and areas with negative and no NDVI trends. However, there are significant differences between negative and positive NDVI trends. Notably, positive trends were observed in the Sierra Nevada at a shorter distance from population centres than negative trends. The latter mentioned could be explained by the fact that the Sierra Nevada has 60 municipalities within the reserve boundary and, in addition, its elongated and irregular shape means that the central zone is not very isolated from the outer zones (Shafer, 2008), which would mean that the municipalities are closer to the core and transition zones, which are precisely where the highest NDVI trends have been recorded.

In summary, global warming is increasing the vulnerability of these habitats, especially in peninsular Spain. Studying and understanding environmental changes in these protected areas is crucial for taking appropriate conservation measures and preserving their services. Biosphere Reserves are internationally protected areas that seek to protect biodiversity and promote sustainable development. Evaluating these protected areas is essential to verify environmental changes and establish priorities in their management. In addition, these studies, like the one shown here, help identify threats and pressures they face and sites requiring greater attention and conservation efforts. Finally, by studying the temporal trends of the Normalized Difference Vegetation Index (NDVI) in a spatially continuous manner and their relationship with different factors such as temperature, water stress, altitude, slope, habitat type, biogeographic region, zonation, and distance to population centres, valuable information can be obtained about the factors influencing the health and resilience of mountain ecosystems. The latter allows for a better understanding of environmental processes and helps establish more effective conservation strategies.

5. Conclusions

This study assessed NDVI trends for 2001-2016 in the high mountain Biosphere Reserves: Sierra Nevada and Ordesa-Viñamala. The main conclusions are the following:

- Generally, there are more significant positive NDVI trends in the high mountain Biosphere Reserves analyzed as a whole. These results are similar to other studies carried out both in Spain and globally.

- Significant differences in NDVI trends were found between the two reserves. However, the Ordesa-Viñamala Biosphere Reserve has shown higher significant positive NDVI trends and fewer negative trends, while this pattern is reversed in the Sierra Nevada.

- The analysis of the variables has allowed us to explain the differences found between the reserves, and it has been observed that temperature and water stress affect Sierra Nevada Reserve to a greater extent.

- The NDVI trends analyzed according to the zonation of each Reserve show the same pattern in both reserves, with higher positive trends around the core and lower positive trends around the transition zone.

- Altitude is highly related to vegetation development in both reserves.

- The significant association between the distance to population centres and the NDVI trend shows that anthropogenic factors limit vegetation development.

- Remote sensing and GIS are essential for this kind of study as they provide access to spatial data, enable long-term monitoring, facilitate spatial analysis, and support decision-making. By analyzing trends in NDVI and integrating environmental factors such as distance to population centers, altitude, and habitat type, valuable insights are gained regarding the health and resilience of mountain ecosystems. In addition, these tools help understand the effects of global warming, identify conservation priorities, and plan sustainable development within Biosphere Reserves. Therefore, remote sensing and GIS are crucial in assessing environmental changes and informing effective management strategies for high mountain areas.

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