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NUMERICAL SIMULATIONS OF RECENT AND FUTURE EVOLUTION OF MONTE PERDIDO GLACIER

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ABSTRACT. Glaciers are globally retreating due to climate change, and the Pyrenees Mountain range is no exception. This study uses the Open Global Glacier Model (OGGM) to explore the dynamics of the Monte Perdido glacier, one of the largest remaining glaciers in the Pyrenees. We explored three calibration approaches to assess their performances when reproducing observed volume decreases. The first approach involved mass balance calibration using terrestrial laser scanning data from 2011 to 2022 and climate data from a nearby weather station. The second approach used terrestrial laser scanning calibration with default climate data provided by OGGM (GSWP3-W5E5). The third approach used default geodetic mass balance calibration and default climate data. By comparing these calibration strategies and analysing historical data (terrestrial laser scanning and ground penetrating radar), we obtain insights of the applicability of OGGM to this small, mild conditions, Pyrenean glacier. The first calibration approach is identified as the most effective, emphasising the importance of selecting appropriate climate data and calibration methods. Additionally, we conducted future volume projections using an ensemble of General Circulation Models (GCMs) under the RCP2.6 and RCP8.5 scenarios. The results indicate a potential decrease in total ice volume ranging from 91.60% to 95.16% by 2100, depending on the scenario. Overall, this study contributes to the understanding of the Monte Perdido glacier's behaviour and its response to climate change through the calibration of the OGGM, while also providing the first estimate of its future melting under different emission scenarios.

Simulaciones numéricas de la evolución reciente y futura del glaciar Monte Perdido

RESUMEN. Los glaciares están retrocediendo globalmente debido al cambio climático, y la cordillera de los Pirineos no es una excepción. Este estudio utiliza el modelo Open Global Glacier (OGGM) para explorar la dinámica del glaciar Monte Perdido, uno de los glaciares actuales de mayor tamaño de los Pirineos. Se exploran tres enfoques de calibración para evaluar sus rendimientos al reproducir las disminuciones de volumen observadas. El primer enfoque consistió en calibrar el balance de masas utilizando datos de escaneo láser terrestre de 2011 a 2022 y datos climáticos de una estación meteorológica cercana. El segundo enfoque utilizó la calibración de escaneo láser terrestre con datos climáticos predeterminados proporcionados por OGGM (GSWP3-W5E5). El tercer enfoque manejó la calibración geodésica predeterminada del balance de masas y los datos climáticos predeterminados. Al comparar estas estrategias de calibración y analizar los datos históricos (escaneo láser terrestre y radar de penetración en el suelo), se obtiene información sobre la aplicabilidad del OGGM a este pequeño glaciar pirenaico. Se considera que el primer método de calibración es el más eficaz, haciendo hincapié en la importancia de seleccionar los datos climáticos y los métodos de calibración adecuados. Además, se realizaron proyecciones de volumen futuras utilizando un conjunto de modelos de circulación general (GCMs) bajo los escenarios RCP2.6 y RCP8.5. Los resultados indican una disminución potencial en el volumen total de hielo que va del 91,60% al 95,16% para 2100, dependiendo del escenario. En general, este estudio contribuye a la comprensión del comportamiento del glaciar Monte Perdido y su respuesta al cambio climático a través de la calibración del OGGM, al tiempo que proporciona la primera estimación de su futura fusión bajo diferentes escenarios de emisión.

Keywords: Mountain glacier, OGGM, in-situ surface observations, climate change.

Palabras clave: Glaciar de montaña, OGGM, observaciones superficiales in-situ, cambio climático.

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1. Introduction

Glaciers are highly sensitive indicators of recent climate variations (Beniston, 2003; Grunewald and Scheithauer, 2010). Current assessments of the Intergovernmental Panel on Climate Change (IPCC) have highlighted that changes in temperature and precipitation have resulted in global glacier retreat since the 1950s that is unprecedented in the last 2000 years (IPCC, 2021).

Glaciers in the Pyrenees are currently in a critical situation, with clear evidence of very advanced stages of degradation (Rico *et al.*, 2017; Vidaller *et al.*, 2021). Due to their small dimensions, glaciers in the Pyrenees have minimal impact on water resources and global albedo feedback (López-Moreno *et al.*, 2020). However, they hold scientific and touristic value while carrying strong cultural heritage (García-López *et al.*, 2021; Moreno *et al.*, 2021; Serrano Cañadas, 2023). Therefore, their melting represents a significant event, symbolising the wider consequences of climate change.

Glaciers, characterized by compact, perennial ice, experience mass gain through snow accumulation and mass loss during ablation, primarily through surface melting (van der Veen, 2013; Eis, 2020). The balance between accumulation and ablation determines a glacier mass fluctuations, with retreat occurring when ablation surpasses accumulation.

Glacier dynamics of mass balance respond to climate fluctuations on longer time scales rather than immediately (Huston *et al.*, 2021). Consequently, the advance or retreat of a glacier is not only determined by the weather of a single year but is a response to cumulative forcings from many years (Huybers and Roe, 2009). Furthermore, there are other processes that influence glacier evolution such as avalanches, being sheltered from dominant winds, debris cover thickness, slope of the ice surface, or rocky outcrops that may appear and enhance incoming long-wave radiation (López-Moreno *et al.*, 2019).

Given the urgency of climate change and glacier retreat, there is significant motivation to study glacier dynamics through a modelling approach, allowing for predictions of future volume trends given climatic and geographic inputs. Hence, this study aims to explore the performance of a glacier model and its practical implementation for the Monte Perdido glacier, one of the largest remaining glaciers in the Pyrenees (Vidaller *et al.*, 2021), with noticeable thinning observed in recent years (López-Moreno *et al.*, 2019).

2. Study area

The Monte Perdido glacier, located in the Ordesa and Monte Perdido National Park in the Central Spanish Pyrenees (42.6806°N, 0.0375°E), consisted of two ice bodies until 2021: the upper and lower glaciers (Fig. 1). Both bodies are north facing and lie beneath the Monte Perdido Peak (3355 m a.s.l.). The mean elevations of the upper and lower ice bodies are between 3110 and 2885 m a.s.l., respectively (Julián and Chueca, 2007). In 2022, the lower Monte Perdido glacier experienced a division, resulting in the formation of two separate ice bodies (Fig. 1).

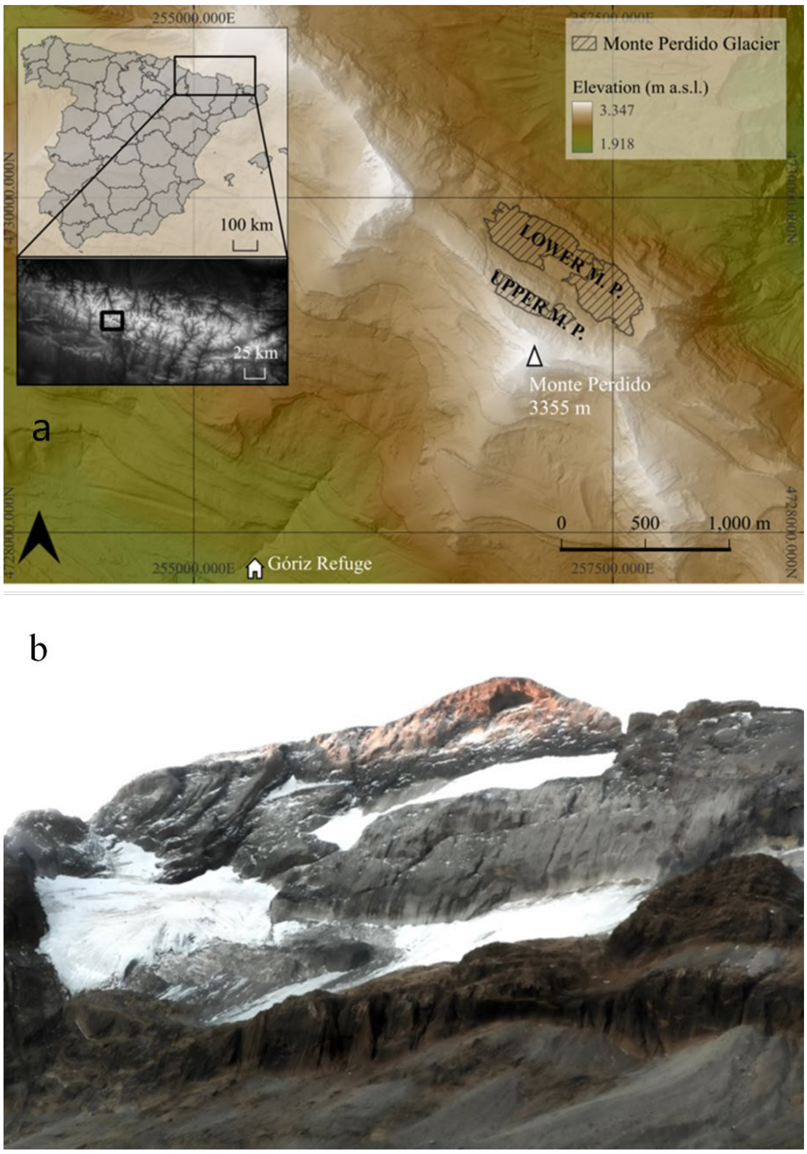

Figure 1: (a) Location and extent of the Monte Perdido glacier in 2022 (coordinates in extended UTM zone 31 T). (b) View of Monte Perdido glacier on October 5, 2022.

3. Data and methodology

3.1. Data analysis tools

To simulate and analyse the Monte Perdido glacier, we utilised the Open Global Glacier Model (OGGM), which is a Python based open-source model (Maussion *et al.*, 2019). We employed version 1.6.0 of OGGM, which was released on March 10, 2023 (Maussion *et al.*, 2023). With the glacier outlines, topographical data, and climate data at a reasonable resolution, the model can estimate the total ice volume of the glacier and simulate its dynamic evolution in response to different climate forcings (Maussion *et al.*, 2019). To compute the ice thickness, the model uses an ice thickness inversion method based on Farinotti *et al.,* (2009).

OGGM is a flowline model that simplifies the glacier geometry by representing it as lines that depict the central flow path. The flowlines are defined following the approach described by Kienholz et al., 2014. The model employs the isothermal shallow ice approximation, assuming that the ice thickness is small compared to its lateral extent, meaning that x-derivatives of stress and velocity are small compared with the z-derivatives (Paterson, 2000). It is important to note that the shallow ice approximation is primarily intended for large ice shelves and may not fully capture the complexities of small mountain glaciers like Monte Perdido. For this glacier, it would be more appropriate to use a model that solves the complete Stokes system, accounting for the three-dimensional nature of ice flow. However, for the sake of simplicity and computational efficiency, we opted to use the OGGM model for this study. Despite this limitation, the validation process supports its use for our specific objectives.

In addition, we used QGIS and CloudCompare software, both open-source platforms, to acquire the outlines of the glacier derived from TLS and compare glacier surface differences between the TLS and OGGM model.

3.2. Glacier observation dataset

The surface of the Monte Perdido glacier was derived from terrestrial laser scanning (TLS, RIEGL LPM-321), following the methodology described by López-Moreno *et al.,* (2016). This device generates a 3D point cloud by measuring the distance to thousands of points of the target area with LiDAR technology (Revuelto *et al.*, 2014). TLS observations from 2011 to 2022, allowed us to diagnose the current state of the Monte Perdido glacier and understand its recent evolution (López-Moreno *et al.*, 2019). By analysing the TLS data acquired over this period, we were able to track yearly changes in the glacier’s surface elevation, thickness, and extent, providing crucial information about its dynamic behaviour.

The high-resolution topography of the glacier’s surrounding area was obtained from the Centro Nacional de Información Geográfica (CNIG) (CNIG, 2023) (Fig. 2). Specifically, we utilised the Digital Elevation Model (DEM) with a 5 m grid resolution. This data allowed us to accurately represent the terrain and its influence on the glacier’s behaviour. The glacier outlines were derived from the 2011 TLS (first year with observations), combining this information with topographical variables (Revuelto *et al.*, 2022). Additionally, GPR measurements were obtained in 2016 to capture the ice thickness of the Monte Perdido glacier along several observation transects with an uncertainty of 5 m (López-Moreno *et al.*, 2019).

We specifically focused on analysing the lower Monte Perdido glacier due to the higher availability of TLS and GPR (ground-penetrating radar) data.

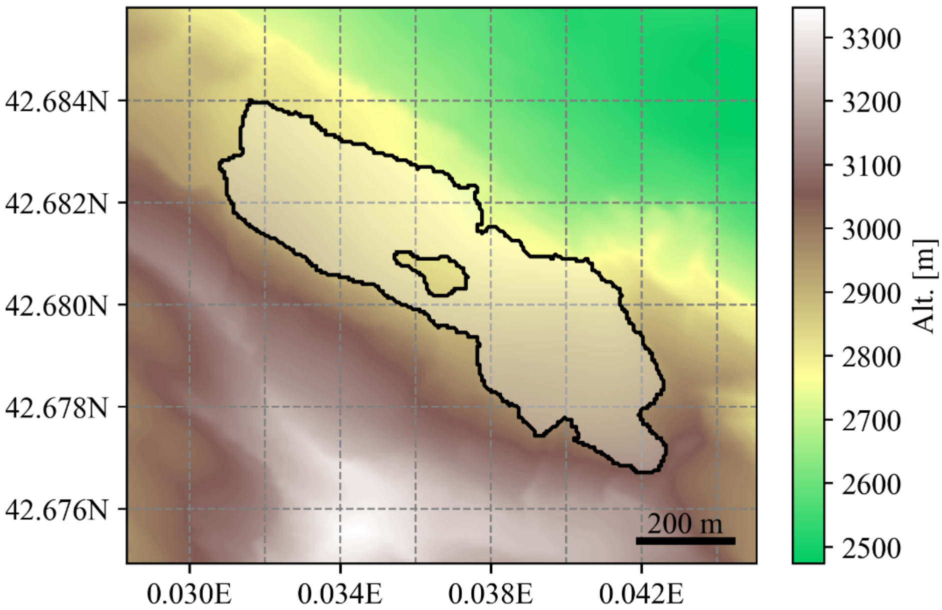

Figure 2: Outlines and DEM of glacier's surrounding area in 2011 (WGS84 coordinate system).

3.3. Climate data

We used long-term (1982-2022) monthly mean temperature and precipitation data obtained from a weather station located at the Góriz refuge (42.66335°N, 0.01501°E). This meteorological data, managed by the Spanish Meteorological Service (AEMET), was collected approximately 2.5 km from the glacier and at an elevation of 2195 m a.s.l. To adapt the data to the glacier region, we applied a lapse rate of 6.5 °C/km and a precipitation correction factor, which will be further explained in detail.

To ensure a continuous climate dataset, we addressed missing data from the weather station by utilising ERA5 reanalysis data (Hersbach *et al.*, 2023). Prior to filling the gaps, we evaluated the Góriz and ERA5 data during overlapping periods and applied the appropriate multiplication factor to precipitation and temperature. This approach was necessary to maintain data continuity for the OGGM. Furthermore, we have also used the GSWP3- W5E5 data set (Lange and Büchner, 2020), which is the default OGGM climate data. GSWP3-W5E5 dataset is a merge between the GSWP3 (Global Soil Wetness Projected phase 3) dataset (Dirmeyer *et al.*, 2006; Kim *et al.*, 2017) and the W5E5 (bias-adjusted ERA5 reanalysis) dataset (Lange, 2019; Cucchi *et al.*, 2020) at 0.5°x 0.5° spatial resolution.

For future projections, we selected a list of 10 global climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble (Taylor *et al.*, 2012) (Table 1). By considering multiple GCMs, we aimed to capture a range of potential future climate scenarios and assess their impact on the glacier.

For CMIP5, four Representative Concentration Pathways (RCPs) have been formulated that provide insights into the expected levels of radiative forcing in the year 2100 when compared to preindustrial conditions (Taylor *et al.*, 2012). These pathways serve as estimations for the impact of greenhouse gas concentrations on the Earth's energy balance. Radiative forcing represents the net change in the energy balance of the Earth system, determined at the top of the atmosphere or the tropopause, due to natural or human-induced perturbations (Myhre *et al.*, 2013). For our analysis, we focused on the RCP2.6 and RCP8.5 scenarios, as they represent the two extremes within the RCP framework. RCP8.5 stands as the "high" scenario, projecting a continuous rise in radiative forcing throughout the twenty-first century until it reaches approximately 8.5 W/m^2 by the end of the century. Conversely, the RCP2.6 scenario assumes strong mitigation efforts with a radiative forcing of 2.6 W/m^2 by 2100 (Taylor *et al.*, 2012).

Table 1. CMIP5 models used in this study.

Model name	Resolution	Originating Group(s)	References
CCSM4	0.9°×1.2°	NCAR	Gent *et al.,* 2011
CNRM-CM5	1.4°×1.4°	CNRM-CERFACS	Voldoire *et al.,* 2013
CSIRO-Mk3-6-0	1.8°×1.8°	CSIRO-QCCCE	Rotstayn *et al.,* 2009
CanESM2	2.8°×2.8°	CCCMA	Arora *et al.,* 2011
GFDL-CM3	2.5°×2.0°	NOAA, GFDL	Donner *et al*., 2011
GFDL-ESM2G	2.5°×2.0°	NOAA, GFDL	Dunne *et al*., 2012
GISS-E2-R	2.5°×2.0°	NASA, GISS	Miller *et al*., 2014
IPSL-CM5A-LR	3.7°×1.9°	IPSL	Hourdin *et al.,* 2006
MPI-ESM-LR	1.8°×1.8°	MPI-M	Zanchettin *et al*., 2013
NorESM1-M	1.8°×2.5°	NCC	Bentsen *et al.,* 2013

3.4. Model calibration

To determine the volume evolution of our glacier, it is important to know how melt in a given period relates to the climate in the same period. This relationship is established by analysing a period in which we have available both climate data and thickness change, i.e., from 2011 to 2022. Once this calibration is done, we can predict glacier evolution applying future climate forcing to our glacier, assuming that the glacier response to climate forcing remains constant in the future.

For this calibration process, several steps using OGGM were involved. Firstly, we set up the geographical input data for the glacier, such as outlines and local topography. Then the climate data was processed from a user-defined climate file, and later the glacier flowlines were determined (Maussion *et al.*, 2019). Afterwards, we proceeded with the mass balance calibration process. For this, we employed OGGM's standard mass-balance (MB) model, which utilises a temperature index approach (Maussion *et al.*, 2019; Vlug, 2021). The basic assumption of these models is that the melt is proportional to the positive temperature in a certain period of time (Braithwaite and Zhang, 2000; Hock, 2003). This calibration determines specific glacier simulation parameters: the temperature bias, the precipitation factor and the degree-day factor (Maussion *et al.*, 2019; Schuster *et al.*, 2023).

The monthly temperature index model can be calibrated on any mass balance product. The default is the geodetic MB data from Hugonnet *et al.,* 2021, which consists of comparing the glacier surface, obtained from satellite elevation datasets, over two dates (Belart, 2018). This global geodetic glacier dataset provides a mean specific glacier MB estimate between 2000 and 2019 for almost every glacier on Earth (more than 200,000) (Schuster *et al.*, 2023). However, these geodetic estimates do not capture interannual variations and its spatial resolution is moderate when compared to TLS data. Alternatively, in situ mass balance measurements can be employed to capture the year-to-year changes.

The monthly mass balance B_i at elevation z is computed as follows:

$$B_i(z) = P_f P_i^{Solid}(z) - d_f \max(T_i(z) - T_{Melt}, 0) \quad (1)$$

Where monthly solid precipitation P_i^{Solid} is multiplied by the precipitation correction factorP_f. As there is no precipitation lapse rate in the model, $P_f$can be seen as a global correction factor for orographic precipitation, avalanches, and wind-blown snow (Vlug, 2021). The precipitation is assumed as liquid above 2°C, solid below 0°C, and the fraction of solid precipitation is linearly interpolated between these two boundary values. T_i is the monthly mean air temperature at 2 m and T_{Melt} is the monthly mean air temperature above which ice melt is assumed to occur (-1°C per default according to OGGM standard due to ice pressure). The temperature lapse rate is set by default to 6.5 °C/km. The parameter d_f is the degree-day factor indicating the temperature sensitivity of the glacier (van der Laan *et al.*, 2022; Schuster *et al.*, 2023).

We conducted three simulations (each with a specific calibration of three parameters: precipitation factor, temperature bias, and degree-day factor) to analyse the behaviour of glaciers under different configurations (Fig. 3, Table 2):

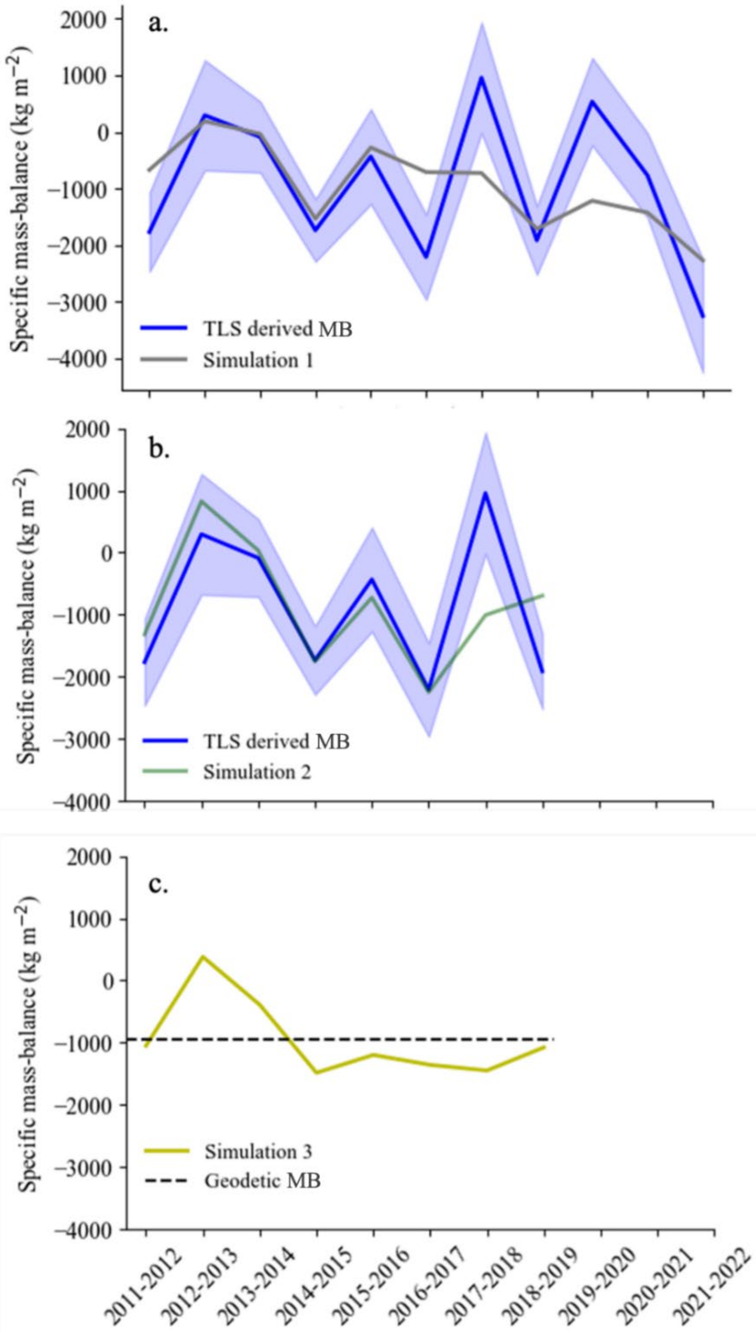

Figure 3: Comparison of TLS-derived mass balance (and its standard deviation (SD) and (a) modelled mass balance with in situ MB calibration and Góriz weather station climate data, (b) modelled mass balance with in situ MB calibration and GSWP3-W5E5 climate data, and (c) modelled mass balance with geodetic MB calibration.

Table 2. Data sources used for mass balance calibration and climate data in different simulations

	Data used for MB calibration	Climate data
Simulation 1	TLS	Góriz weather station
Simulation 2	TLS	GSWP3-W5E5
Simulation 3	Geodetic MB	GSWP3-W5E5

- Simulation 1: This simulation involved calibrating the mass balance using in situ data obtained from TLS for the years 2011 to 2022. The precipitation factor was estimated by comparing the total water equivalent of snow during the accumulation period (from October to April) at the glacier location (López-Moreno *et al.*, 2019) with the precipitation data recorded at the Góriz weather station for the same period. Analysis of specific years (2013-14, 2014-15, and 2016-17, which are the only periods with glacier surface observations during the accumulation period) revealed a maximum mean snow accumulation in late April of 3.25 m, with an average snow density of 454 kg/m^3 (López-Moreno *et al.*, 2019). This indicated a total water equivalent of 1475.5 mm for the accumulation period. Considering that the mean precipitation observed at the Góriz weather station during the same period was 1089.6 mm, a precipitation factor of 1.3 was estimated and used for the mass balance calibration. Then, the model adjusted the degree-day factor and the temperature bias to minimise the difference between the model outputs and observed data, ensuring a better fit between the simulated and the actual mass balance.
- Simulation 2: As in the first simulation, this one involved mass balance calibration using TLS data. However, instead of using weather station climate data, we used the default climate data (GSWP3-W5E5) provided by the OGGM framework. The three parameters (precipitation factor, temperature bias, and degree-day factor) were adjusted accordingly.
- Simulation 3: In this simulation, the mass balance was calibrated with the default average geodetic observations from January 2000 to January 2019 of Hugonnet *et al.,* 2021, and the default climate data (GSWP3-W5E5) provided by OGGM.

All the calibration alternatives have at least the three free parameters mentioned above (Schuster *et al.*, 2023). Without these parameters, the observed glacier MB often cannot be reproduced by the model.

Once the mass balance calibration is performed, a standard geometry evolution model, which is a depth-integrated flowline model, is responsible to compute the change in glacier geometry. Before running this simulation, stable glacier conditions are required at the beginning of the study period. To ensure this, we performed a spin-up process, where the geometry and evolution of the glaciers were initialised from a given year. We selected a fixed geometry spin-up year of 2000, approximately 10 years before the date of the outline (2011). This year (2011) represents the point at which the glacier is expected to reach equilibrium (Maussion *et al.*, 2019).

Using the flowline model, an estimate of the ice flux along each glacier grid point cross-section is computed by making assumptions about the shape of the cross-section (parabolic, rectangular or trapezoid) and relying on mass-conservation consideration (Maussion *et al.*, 2019). Using the physics of ice flow and the shallow ice approximation, the model then computes the thickness of the glacier along the flowlines and the total volume of the glacier.

After performing the historical climate run, we used the ten GCMs described in Table 1 to project future volume of the Monte Perdido glacier. We employed an ensemble of GCMs to represent the temperature and precipitation variability in climate projections. To downscale global climate data to a regional level, we obtained precipitation and temperature data for each GCM from the OGGM server hosted by the University of Bremen and we applied the precipitation and temperature biases, to the baseline local climatology, which was defined using the Góriz weather station climate dataset. The model then uses the interpolated climate data for each GCM to calculate glacier mass balance.

Using this climate data, we ran the simulation for each GCM and scenario from 2020 to 2100. To initiate this task, we inputted the GCM climate data and utilised the spun up geometry and mass balance conditions from the historical run as initial conditions within the model.

Finally, we compiled the 20 simulations generated from the ensemble of GCMs and merged them into two datasets, one for each RCP scenario. This allowed us to calculate the median values and plot the evolution of glacier volume (Fig. 7).

4. Results and discussion

4.1. Evaluation of climate data

We first evaluate the GSWP3-W5E5 dataset from the OGGM repository against the data measured at the Góriz weather stations.

Figure 4a represents the historical annual temperature data measured at the Góriz weather station, along with the GSWP3-W5E5 dataset. The data reveals long-term temperature variations in the region, and a notable temperature rise on both datasets. The 30-year rolling average highlights this increase smoothing out short-term variations. The slope of 0.04°C/year and the p-value < 0.05 on both datasets, confirm a statistically significant positive trend in temperature.

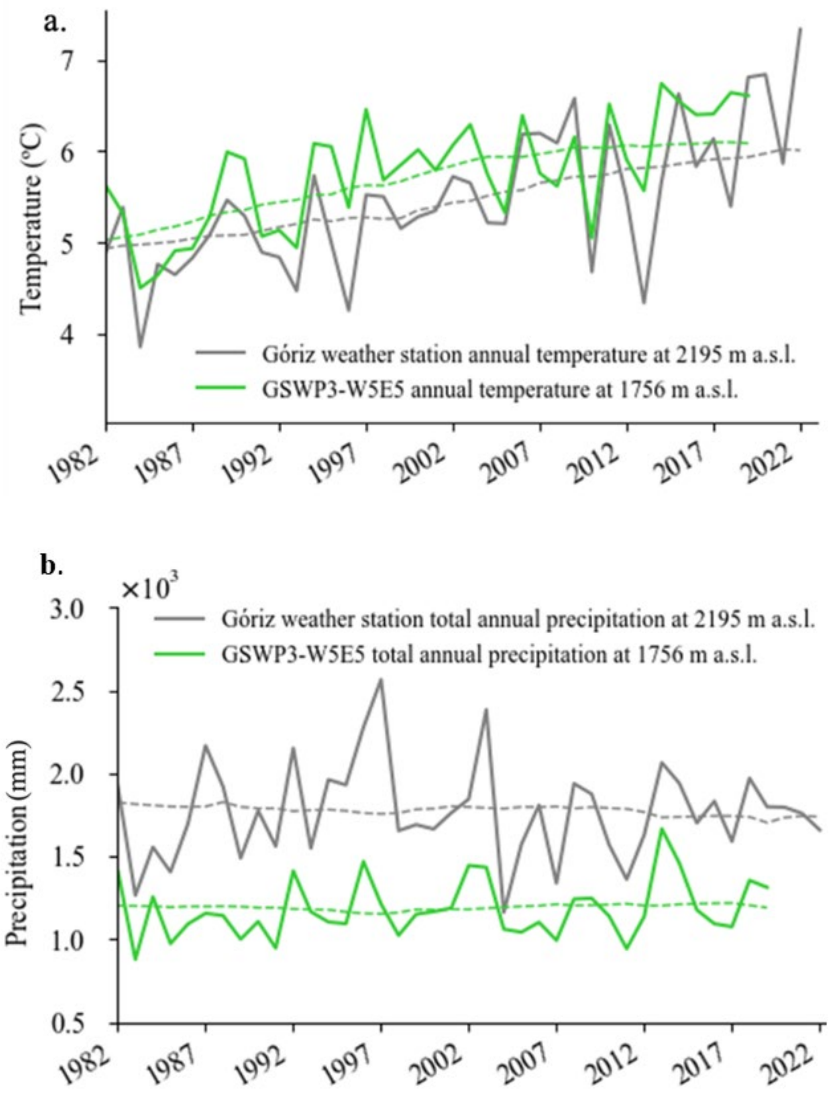

Figure 4: (a) Annual mean temperature and (b) total annual precipitation obtained from Góriz weather station (grey) and GSWP3-W5E5 dataset (green). The 30-year rolling average is depicted in dashed lines.

In addition, Figure 4b shows the historical total annual precipitation data obtained from the weather station and the GSWP3-W5E5 dataset. The data provides the interannual variability of precipitation over time. Unlike the temperature, there is no significant change in precipitation over time (p-value > 0.05). Furthermore, we observed a mean temperature difference of 0.4°C between the Góriz weather station, situated at 2195 m a.s.l., and the GSWP3-W5E5 dataset, located at 1756 m a.s.l. Additionally, the Góriz weather station records a greater total annual precipitation compared to the GSWP3-W5E5 dataset, with a difference of 590 mm.

4.2. Comparison of modelled and TLS-derived volume differences

The comparison of TLS volume evolution (surface decrease multiplied by glacier extent) and modelled volume evolution provides insights into the accuracy of the model in replicating the observed glacier volume changes (Fig. 5). The root mean square error (RMSE), correlation coefficient, and p-value were calculated to evaluate the model performance (Table 3).

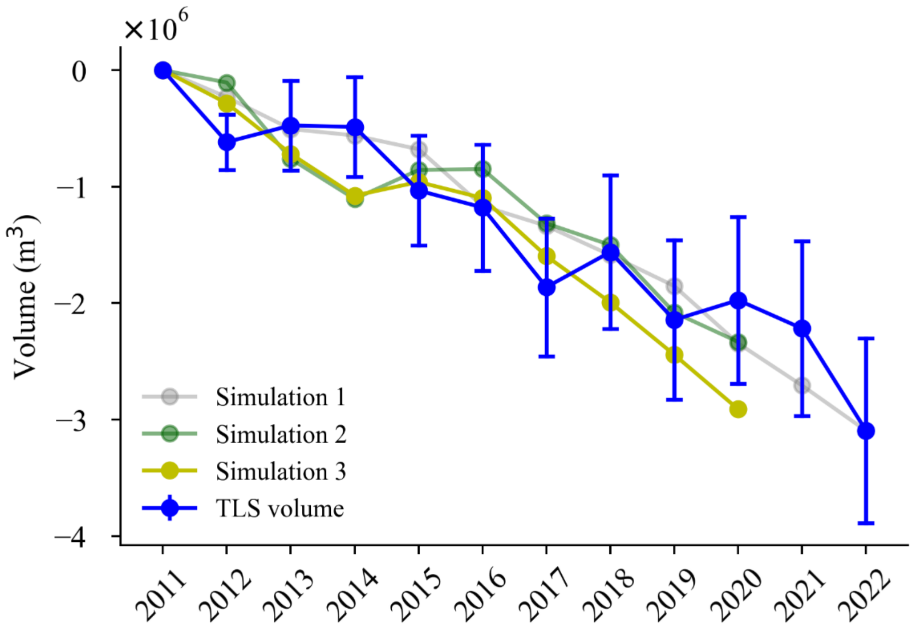

Figure 5: Monte Perdido glacier volume (and SD) since 2011 derived from TLS data compared with the three simulations.

Table 3. Comparison of TLS-Derived Volume with the three simulations from 2011 to 2020

	Corr.	p-value	RMSE (m^3)
Simulation 1	0.93	<0.01	279435.16
Simulation 2	0.92	<0.01	280778.70
Simulation 3	0.91	<0.01	418856.88

The results indicate that both simulations with in situ mass balance calibration, namely simulation 1 and 2, exhibit a higher correlation with the TLS-derived volume compared to simulation 3. This suggests that the calibration process with TLS data improves the agreement between the model and the observed data. Furthermore, simulation 1 with Góriz climate data shows slightly improved performance compared to the one with GSWP3- W5E5 climate data, as evidenced by a lower RMSE value and higher correlation coefficient (Table 3).

The incorporation of TLS data into the calibration process helps to account for the interannual variation of the glacier mass balance. This, in turn, enhances the accuracy of the model's predictions. Furthermore, Góriz climate data might provide a better representation of the local climate conditions and their influence on the glacier, resulting in a more accurate estimation of mass balance parameters.

It is important to note that simulation 3, despite exhibiting a slightly lower correlation and higher RMSE, still demonstrates a reasonable agreement with the TLS derived volume. This suggests that the calibration process, even with GSWP3-W5E5 climate data and geodetic mass balance calibration, can provide valuable insights into the glacier's behaviour. However, the differences in performance between simulation 3 and the other simulations highlight the importance of selecting appropriate climate data and calibration methods to improve the accuracy of glacier volume projections.

4.3. Comparison of modelled and GPR thickness

The GPR measurements, taken in 2016, offer a direct assessment of the glacier's ice thickness at specific locations on the Monte Perdido glacier (López-Moreno *et al.*, 2019). The comparison of modelled and GPR thickness provides additional insights into the accuracy of the model's representation of the spatial distribution of ice (Fig. 6).

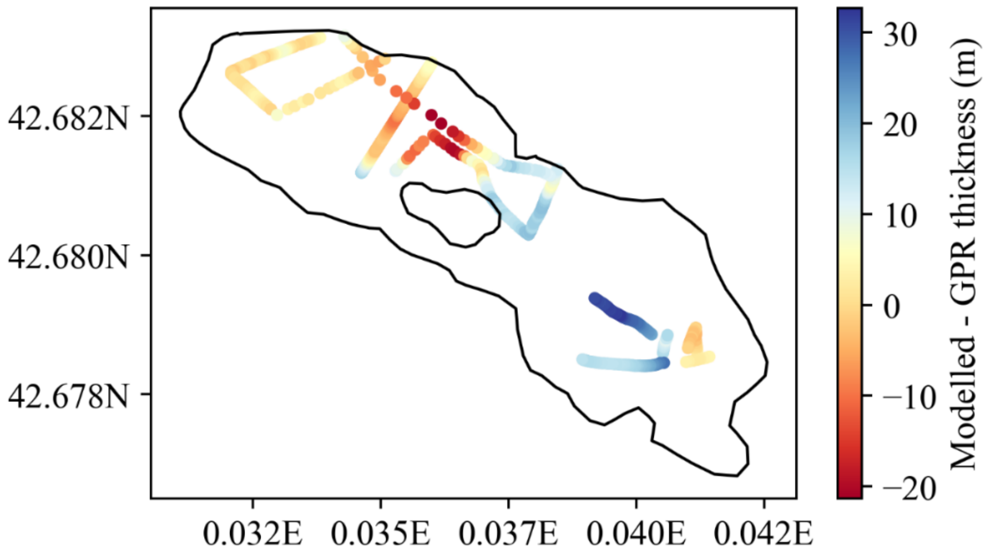

Figure 6: Difference between the modelled ice thickness and the GPR measurements taken in 2016 at specific locations of Monte Perdido glacier. WGS84 coordinate system.

It has to be noted that the GPR measurements were influenced by the presence of water, causing a very low signal to noise ratio leading to ± 5 m of uncertainty in estimations of ice thickness, which should be taken into account when interpreting the results.

The mean difference between the modelled and GPR thickness is 6.4 m, with a maximum difference of 32.7 m, indicating a certain level of variability and uncertainty in the model's ability to capture the ice thickness distribution. Furthermore, the average discrepancy between the two datasets is provided by the RMSE of 8.7 m. While there is some level of agreement between the model and the GPR data, there are still considerable differences between them.

However, it is important to note that GPR measurements provide localised information and may not fully represent the entire glacier's ice thickness distribution. Additionally, accurately modelling ice thickness is challenging without precise knowledge of the topography below the glacier.

Moreover, the weather station used for collecting meteorological data for the Monte Perdido glacier is situated about 2.5 km away from the glacier and on the south face, while the glacier itself is on the north face. This spatial difference introduces uncertainty in representing local climate conditions, despite applying temperature and precipitation correction factors. The use of a fixed lapse rate of 6.5°C/km to adjust weather station data to the glacier region simplifies temperature variations with elevation. Additionally, the estimation of the precipitation factor based on comparing data from the glacier location and a weather station may overlook variations in snowfall patterns, snow density, or liquid precipitation during the accumulation period.

4.4. Future volume projections

Across both RCP scenarios, the projected total ice volume for the Monte Perdido glacier shows a consistent decrease from 2020 to 2100. Figure 7 shows a faster decline in volume between 2020 and 2060, followed by a deceleration in the rate of decrease.

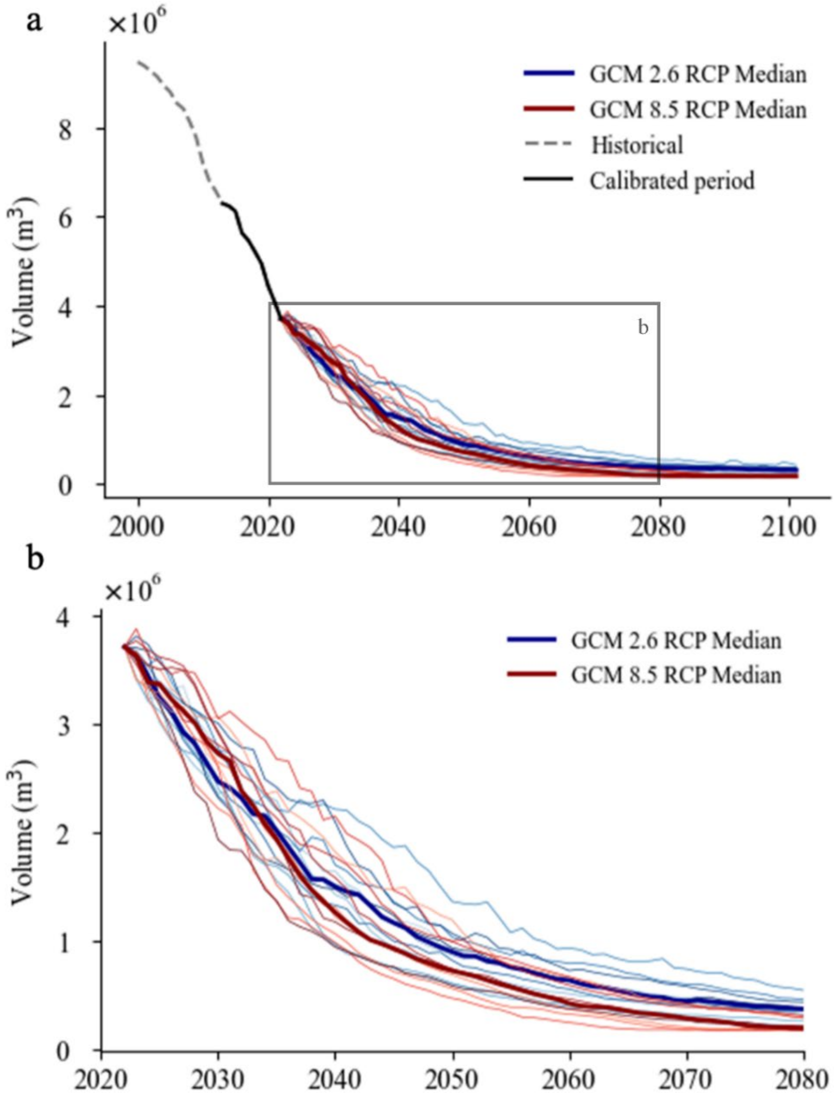

Figure 7: Multi-GCM ice volume for RCP2.6 and RCP8.5 scenarios from 2020 to 2100 with the historical simulation from 2000 to 2020 in a dashed line and the calibrated period in a solid black line. Volumes for each GCM run of RCP2.6 are plotted in blue and for RCP8.5 in red, with multi-GCM medians represented in thicker lines. Plot (a) displays the full projection, while (b) zooms the 2020 - 2080 period.

The total median volume exhibits minimal variation between the RCP scenarios. For the RCP8.5 scenario, the ice volume experiences a significant decrease of 95.2% by the year 2100, 88.6% by 2060, and 66.0% by 2040. Similarly, under the RCP2.6 scenario, there is a decrease of 91.6% by 2100, 82.8% by 2060, and 59.6% by 2040.

The observed decreasing trend in the volume of the Monte Perdido glacier is not unexpected; many studies have documented similar decreases in glacier volume worldwide (Ma *et al.*, 2010; Zekollari *et al.*, 2019; Khadka *et al.*, 2020), including in the Pyrenees (Chueca Cía *et al.*, 2005; López-Moreno *et al.*, 2016; Campos *et al.*, 2021; Vidaller *et al.*, 2021). Given that Monte Perdido is one of the largest glaciers of the Pyrenees, situated at higher altitudes and facing north, it suggests that other glaciers might experience even more pronounced losses.

5. Conclusions

We employed the Open Global Glacier Model to simulate and analyse the Monte Perdido glacier recent and future evolution. We utilised the OGGM to estimate the total ice volume of the glacier and simulate its evolution in response to different climate forcings.

The calibration process of the OGGM involved three simulations: one using in situ mass balance calibration and weather station climate data, another with in situ mass balance calibration using default climate data, and a third with uncalibrated mass balance and default climate data. Through these simulations, we evaluated the performance of the model when replicating the observed volume changes of the glacier. The simulations with in situ mass balance calibration exhibited a higher correlation with TLS-derived volume compared to the default MB geodetic calibration, indicating the importance of exploiting in-situ observations on the calibration to improve model accuracy.

Furthermore, we projected the future volume of the Monte Perdido glacier using an ensemble of ten GCMs under the RCP2.6 and RCP8.5 scenarios. The results showed a consistent decrease in total ice volume from 2020 to 2100, with a faster decline between 2020 and 2060 followed by a deceleration in the rate of decrease. The projected volume reductions were substantial, ranging from 91.6% to 95.2% by the year 2100, depending on the scenario. These findings align with the global trend of glacier volume decrease and are consistent with previous studies in the Pyrenees region.

In addition, as we look ahead, it's worth considering future directions that could further enhance our understanding of glacier behaviour and its interaction with climate. While our study primarily focused on the Monte Perdido glacier's response to climate forcing, we acknowledge the need for future investigations into the potential consequences of climate change on avalanche triggering and its subsequent impact on glacier evolution. Moreover, new approaches like ODINN.jl (Bolibar *et al.,* 2023) and MuSA (Alonso-González *et al.,* 2022) demonstrate promising paths to enhance glacier modelling by incorporating advanced data assimilation techniques.

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SUSCEPTIBILIDAD PARA INCENDIOS DE CUBIERTA VEGETAL: UNA EVALUACIÓN DESDE LOS MÉTODOS MULTICRITERIO Y RADIOFRECUENCIA (CANTÓN COTACACHI, ECUADOR)

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RESUMEN. En Ecuador, alrededor de 11688,88 hectáreas de cobertura vegetal se perdieron en el 2023 producto de los 1495 incendios de cobertura vegetal (ICV) registrados. Por ello, la presente investigación tuvo como objetivo determinar áreas susceptibles a ICV para el cantón Cotacachi en Ecuador y en sus dos zonas diferenciadas. Para evaluar la susceptibilidad a ICV en un entorno SIG se aplicaron los métodos multicriterio de Proceso de Análisis Jerárquico (AHP) y Radio Frecuencia (RF). Para ello, se establecieron 11 factores clasificados en topográficos (altitud, pendiente del terreno, orientación del terreno), climáticos (precipitación, temperatura, evapotranspiración potencial, déficit hídrico y velocidad del viento) y antrópicos (cobertura de suelo, cercanía a carreteras y cercanía a espacios agrícolas). Después, se obtuvieron los modelos espacialmente explícitos y los resultados fueron validados con la curva ROC y el área bajo la curva (AUC). Los resultados muestran que alrededor del 47% del territorio presenta peligro extremo a los ICV según el método multicriterio AHP y un 53% del cantón según el método RF, presentando una mayor concentración en la zona subtropical que en la zona andina. Los valores del rendimiento muestran que, después de comparar los modelos con información de focos de calor del sistema FIRMS-NASA del periodo 2000-2020, se obtuvo un AUC: 0,824 para el modelo AHP y un valor AUC: 0,902 para el modelo RF. Mientras que, al compararlo con los incendios históricos del periodo 2018-2020, se obtuvo un AUC: 0,748 para el modelo AHP y un valor AUC: 0,755 para el modelo RF. Finalmente, se concluye que los modelos multicriterio AHP y RF presentaron resultados y rendimientos similares con mínimas diferencias.

Susceptibility to vegetation cover fires: an evaluation using multi-criteria and radio frequency methods (Cotacachi Cantón, Ecuador)

ABSTRACT. In Ecuador, around 11688.88 hectares of vegetation cover were lost in 2023 due to 1495 registered vegetation cover fires (ICV). Therefore, this research aimed to determine areas susceptible to ICV for the Cotacachi cantón in Ecuador and its two differentiated zones. To evaluate the susceptibility to ICV in a GIS environment, the multi-criteria methods of Analytic Hierarchy Process (AHP) and Radio Frequency (RF) were applied. For this purpose, 11 factors were established classified into topographic (altitude, slope, terrain orientation), climatic (precipitation, temperature, potential evapotranspiration, water deficit and wind speed) and anthropic (land cover, proximity to roads and proximity to agricultural areas). Afterwards, spatially explicit models were obtained, and the results were validated with the ROC curve and the area under the curve (AUC). The results show that around 47% of the territory is at extreme risk of ICV according to the AHP multi-criteria method and 53% of the canton according to the RF method, with a higher concentration in the subtropical zone than in the Andean zone. The performance values show that after comparing the models with heat spot information from the

FIRMS-NASA system for the period 2000-2020, an AUC of 0.824 was obtained for the AHP model and an AUC value of 0.902 for the RF model. While, when compared with historical fires from the period 2018-2020, an AUC of 0.748 was obtained for the AHP model and an AUC value of 0.755 for the RF model. Finally, it is concluded that the AHP and RF multi-criteria models presented similar results and performances with minimal differences.

Palabras clave: Fuego, cobertura vegetal, análisis multicriterio, radiofrecuencia, Cotacachi.

Key words: Fire, vegetation cover, multi-criteria analysis, radio frequency, Cotacachi.

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1. Introducción

Los ecosistemas son dinámicos y vulnerables a perturbaciones como los incendios, los cuales, a través del tiempo han configurado su estructura, composición y distribución geográfica (del Campo Parra-Lara y Bernal-Toro, 2010; Martelo-Jiménez y Vargas Ríos, 2022). Los incendios forestales se consideran como una de las principales perturbaciones debido a la capacidad de propagarse sin control, consumir todo el material vegetal y cambiar las propiedades del suelo (Cheng *et al.,* 2023). Si bien es cierto que el efecto directo se centra en la pérdida de la cobertura vegetal por donde se propagó el fuego (Tyukavina *et al.,* 2022), existen otros efectos adicionales como cambios en la flora y fauna, alteraciones edáficas, hídricas y paisajísticas (Bargali *et al.,* 2022; Cheng *et al.,* 2023; Doerr y Shakesby, 2006; He *et al.,* 2002). Autores como del Campo Parra-Lara y Bernal-Toro (2010) definen a estos eventos como incendios de cobertura vegetal (ICV), debido a que el bosque forma parte de un conjunto heterogéneo de coberturas vegetales y no representa ninguna barrera que impida la propagación del fuego hacia otras coberturas.

Para identificar la susceptibilidad a incendios de cobertura vegetal (ICV) actualmente se integran los Sistemas de Información Geográfica (SIG) dentro de varios enfoques metodológicos: regresión logística (Rodrigues *et al.,* 2018), análisis multicriterio (Eugenio *et al.,* 2016), redes neurales (Naderpour *et al.,* 2021), radio frecuencia (De Santana *et al.,* 2021; Hong *et al.,* 2017; Jaafari y Mafi Gholami, 2017) e incluso el uso del *machine learning* (Reyes-Bueno y Loján-Córdova, 2022).

Los ICV se originan y propagan debido a factores ambientales y antrópicos (del Campo Parra-Lara y Bernal-Toro, 2010). Entre los factores ambientales destacan los topográficos como la pendiente o la altitud y los meteorológicos como la temperatura o la precipitación (Abedi Gheshlaghi, 2019; Eugenio *et al.,* 2016). En cambio, los factores antrópicos son producto de las costumbres o de la cercanía a actividades humanas (Tebbutt *et al.,* 2021; Vélez Muñoz, 2000). En Sudamérica, gracias a estudios realizados en países como Colombia, Brasil y Ecuador, se ha identificado que los factores con un papel crucial en la generación de incendios son de tipo meteorológico como la temperatura, la precipitación y la humedad. Factores como la cobertura y uso de suelo (CUS), la proximidad a carreteras, la orientación del terreno y la pendiente del terreno tienen un rol condicionante (De Santana *et al.,* 2021; Martelo-Jimenez y Vargas Ríos, 2022; Pazmiño, 2019).

Considerando que los incendios forestales causaron la pérdida de 6566,66 hectáreas de cobertura vegetal en Ecuador debido a 1.249 incidentes registrados en 2022, las investigaciones actuales son realmente insuficientes (Servicio Nacional de Gestión de Riesgos y Emergencias, 2022). Imbabura se encuentra entre las cinco provincias con mayor número de incendios en 2022 (Servicio Nacional de Gestión de Riesgos y Emergencias, 2022), y dentro de ella el cantón Cotacachi ha experimentado una importante exposición a los incendios forestales. No obstante, pese a estos antecedentes, aún no existen estudios previos sobre la susceptibilidad de este tipo de incendios en este cantón ecuatoriano.

Por ese motivo, el objetivo principal de este estudio fue desarrollar modelos espacialmente explícitos para zonificar la susceptibilidad a ICV en el cantón Cotacachi, que empleen dos enfoques metodológicos y combinen factores topográficos, climáticos y sociales en un entorno SIG. De este modo, se aplicaron y compararon dos métodos: el multicriterio para clasificar las diferentes categorías y la radiofrecuencia basada en la frecuencia de datos con la finalidad de modelar la susceptibilidad a incendios. Los objetivos específicos fueron a) evaluar el rendimiento de los modelos al compararlos con ICV históricos registrados y con los focos de calor o anomalías térmicas detectadas por satélites y procesadas por el sistema NASA FIRMS, y b) comparar el peligro de incendios entre las zonas ecológicas diferenciadas en el cantón por condiciones climáticas y topográficas.

2. Área de estudio

El cantón Cotacachi se ubica entre las coordenadas 0°18′0″ N, 78°16′0″ W y se localiza en la provincia Imbabura al norte de Ecuador (Fig. 1). Es el cantón más extenso de la provincia y el sexto con mayor extensión de la región interandina con una superficie de 1815,09 km^2. La geomorfología del cantón se caracteriza por la presencia de una zona interandina y de estribaciones de la Cordillera Oriental que se caracterizan por la presencia de relieves volcánicos, montañas, colinas, zonas deprimidas y valles (Gobierno Autónomo Descentralizado de Cotacachi, 2015). En el cantón existe un desnivel de 4439 metros. En la parte alta se encuentra el volcán Cotacachi a una altitud de 4939 m.s.n.m. y en la parte baja desde los 500 m s.n.m. están los valles subtropicales.

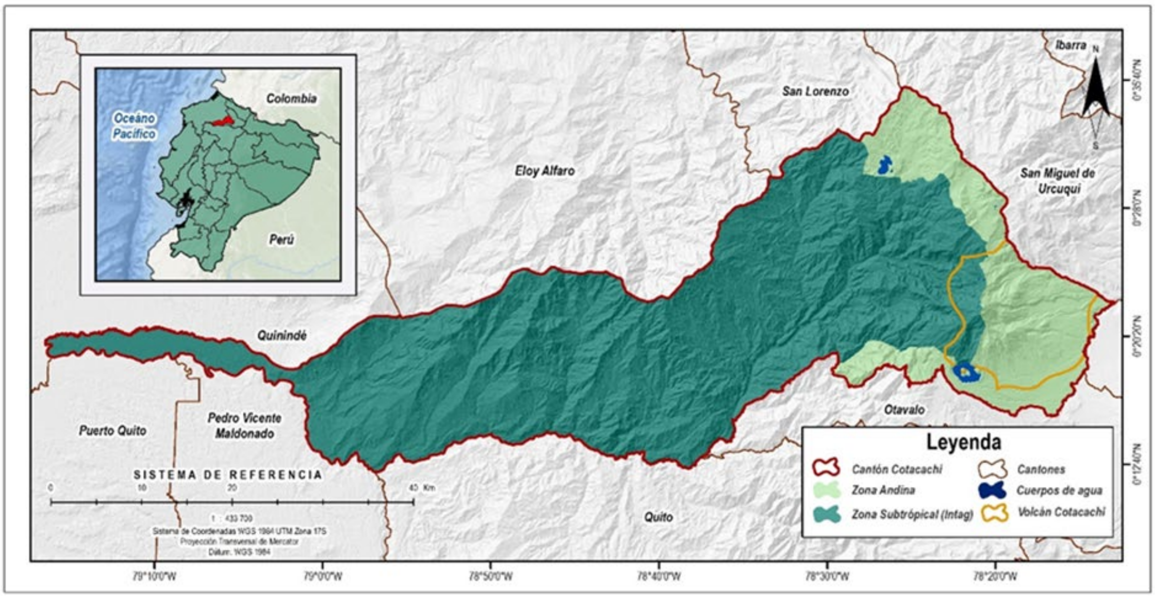

Figura 1. Ubicación del área de estudio. Cantón Cotacachi, Imbabura – Ecuador. Sistema de referencia de coordenadas WGS 1984 UTM, Zona 17 Sur.

El clima del cantón presenta una precipitación media anual de 1450 mm y una temperatura media de 16,4 °C. Sin embargo, debido a las condiciones topográficas y climáticas se diferencian dos zonas: la andina y la subtropical (Gobierno Autónomo Descentralizado de Cotacachi, 2015). El promedio de temperatura en la zona andina oscila entre los 14-22 °C y la precipitación entre 500-1000, mientras que la zona subtropical oscila entre los 16-32ºC y la precipitación entre 1200-3000 mm/año.

De acuerdo con la información del último Censo de Población y Vivienda realizado en Ecuador en el año 2022 y publicado por el Instituto Nacional de Estadísticas y Censos (2023), en el cantón conviven 53001 habitantes, de los cuales el 80% vive en el sector rural. La población rural se asienta en pequeños núcleos no consolidados alrededor de cultivos, pastos, vegetación arbustiva, bosques y hasta cerca de los páramos. Un páramo es un tipo de ecosistema andino con un clima típico tropical de alta montaña, cuya temperatura media ronda los 7 °C y su precipitación fluctúa entre 700 y 3000 mm/año con bajas intensidades de lluvia (Buytaert *et al.,* 2006). Este ecosistema en el cantón ocupa una superficie alrededor del 12% (Gobierno Autónomo Descentralizado de Cotacachi, 2015).

3. Metodología

3.1. Selección de Variables y Obtención de Datos

El registro histórico obtenido desde la plataforma del Instituto de Investigaciones Espaciales de Brasil (INPE) evidenció que para el periodo 2000-2020 se produjeron de 890 focos de calor y anomalías térmicas en el cantón Cotacachi, donde el 50,8% ocurrió en bosques nativos, 25,06% en el páramo, 11,21% en matorral, 5,03% en vegetación herbácea y el 7,67% restante en los cultivos. Esta información, junto con los datos de las condiciones particulares del cantón y la revisión de literatura, permitió identificar los factores que causan y condicionan los ICV. De este modo se clasificaron a los factores ICV en tres tipos: climáticos, topográficos y antrópicos. Los factores climáticos considerados fueron precipitación, temperatura, déficit hídrico, evapotranspiración potencial (ETP) y velocidad del viento (Eugenio *et al.,* 2016; Kane *et al.,* 2015; Pazmiño, 2019). Los factores topográficos seleccionados fueron altitud, pendiente y orientación del terreno, y los factores antrópicos fueron evaluados a través de la cobertura y uso de suelo (CUS), la cercanía a vías de comunicación y la cercanía a espacios agrícolas (Sivrikaya y Küçük, 2022). En la Tabla 1 se presenta información sobre cada uno de estos factores e incluye su descripción y la fuente de datos, mientras que en la Figura 2 se muestran las características geoespaciales de cada una de estas variables.

Tabla 1. Factores utilizados en la generación de modelos de susceptibilidad a ICV

Tipo	Factor	Descripción	Fuente
Topo gráfi	Altitud	Información de SRTM DEM con 30 m de resolución espacial.	https://opentopography.org/
	Pendiente del terreno		
	Orientación del terreno		
Climáticos	Precipitación	Datos de precipitación INAMHI periodo (1986-2015).	http://www.inamhi.gob.ec
	Temperatura	Datos de temperatura INAMHI periodo (1986-2015)	http://www.inamhi.gob.ec
	Evapotranspiración potencial	Información derivada de la temperatura	
	Déficit Hídrico	Información derivada de la precipitación y temperatura	
	Velocidad del viento	Datos de velocidad del viento INAMHI periodo (1990-2020).	http://www.inamhi.gob.ec
Antrópicos	Cobertura y uso del suelo	GeoTIFF Sentinel-2 Land Use-Land Cover (10 m de resolución).	https://livingatlas.arcgis.com/landcover/
	Proximidad a vías de comunicación	Información de vías a escala 1:50.000.	https://www.geoportaligm.gob.ec
	Proximidad a espacios agrícolas	GeoTIFF Sentinel-2 Land Use-Land Cover.	https://livingatlas.arcgis.com/landcover/

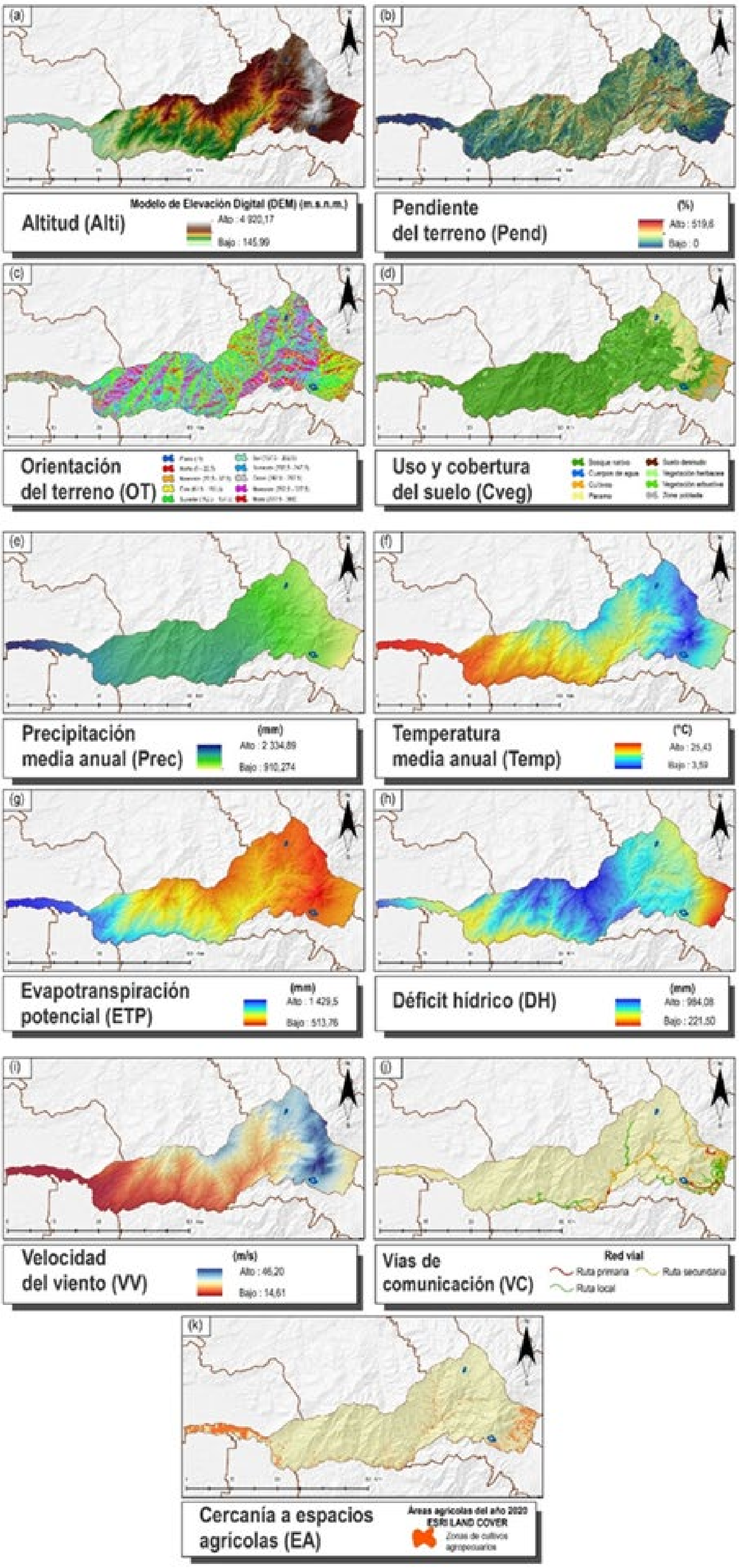

Figura 2. Factores de la susceptibilidad a ICV: (a) Altitud; (b) Pendiente del terreno; (c) Orientación del terreno; (d) Uso y cobertura del suelo; (e) Precipitación media anual; (f) Temperatura media anual; (g) Evapotranspiración potencial; (h) Déficit hídrico; (i) Velocidad del viento; (j) Vías de comunicación; y (k) Cercanía a espacios agrícolas.

3.1.1. Factores topográficos

Altitud. Al aumentar la altitud disminuye el riesgo de incendio a las coberturas vegetales (Eugenio *et al.,* 2016). En el territorio este factor se encuentra relacionado directamente con la presencia de la cordillera de los Andes que constituye una barrera topográfica que divide y aísla las masas de aire provenientes de la cordillera y genera precipitaciones de origen orográfico (Garreaud *et al.,* 2009). Para el modelo AHP se determinaron cinco intervalos utilizando la «regla práctica del intervalo». En este método se establecen cinco rangos mediante la suma y resta de la desviación estándar al valor promedio. El nivel de susceptibilidad se estableció mediante una relación inversamente proporcional entre altitud y susceptibilidad de incendio. Para el modelo RF, en cambio, el tipo de susceptibilidad se obtiene después de ejecutar un análisis estadístico bivariante mediante la comparación del registro histórico de los focos de calor FIRMS y las cinco clases de altitud del terreno obtenidas.

Pendiente del terreno. El fuego se expande más rápido cuando se incrementa la pendiente de terreno (Bonora *et al.,* 2013). Este factor se calculó en el software ArcGIS 10.8 a partir del modelo digital de elevación SRTM-DEM. Para el modelo AHP, las pendientes se clasificaron en cinco rangos, por su grado de susceptibilidad, donde: <5% susceptibilidad muy baja, 5-12% susceptibilidad baja, 12-25% susceptibilidad moderada, 25-45% susceptibilidad alta y >45% susceptibilidad muy alta. Para el modelo FR se utilizaron los mismos rangos de la pendiente, pero su nivel de susceptibilidad fue determinado utilizando el mismo proceso que fue empleado para la altitud.

Orientación del terreno. La orientación del terreno contribuye a la susceptibilidad de un terreno a ICV y a su propagación (Maingi y Henry, 2007). Por ejemplo, a diferencia de las laderas orientadas al oeste, las orientadas al este pueden recibir menos lluvia durante la estación lluviosa en algunas zonas ecuatoriales debido a los patrones de viento y precipitaciones. El resultado es que la vegetación es más propensa a ICV en las laderas orientales (Abedi Gheshlaghi, 2019). La orientación del terreno se determinó usando el SRTM-DEM en el software ArcGIS 10.8, obteniendo ocho clases de orientaciones que para el modelo AHP se clasificaron en cinco rangos, por su grado de susceptibilidad. De este modo, la orientación plana fue considerada con susceptibilidad muy baja, la orientación oeste fue considerada con susceptibilidad baja, las orientaciones sur y suroeste fueron definidas con susceptibilidad moderada, las orientaciones norte, sureste, noreste, fueron consideradas con susceptibilidad alta y para la orientación este se estableció una susceptibilidad muy alta. Para el modelo RF se usaron las ocho clases de orientaciones, pero su nivel de susceptibilidad se determinó usando el mismo proceso que fue empleado para la altitud.

3.1.2. Factores climáticos

Precipitación media anual. Este factor influye directamente en la ocurrencia de incendios, ya que el riesgo extremo se produce en zonas con escasas precipitaciones (Morante-Carballo *et al.,* 2022; Pazmiño, 2019). El mapa de precipitación se elaboró utilizando información de 11 estaciones meteorológicas para el periodo 1986-2015 proveniente del Instituto Nacional de Meteorología e Hidrología del Ecuador (INAMHI). La interpolación se realizó en el software ArcGIS 10.8 empleando el método IDW (*Inverse Distance Weight*). Este método estima valores de las celdas al calcular de manera efectiva los promedios de los valores de puntos de datos vecinos de cada celda (Johnston *et al.,* 2001). Finalmente, se establecieron cinco intervalos utilizando la «regla práctica del intervalo». El nivel de susceptibilidad para el modelo AHP se estableció con una relación inversamente proporcional entre susceptibilidad de incendio y precipitación. Para el modelo RF se ejecutó el estadístico bivariante entre las clases definidas y el registro histórico de los focos de calor FIRMS.

Temperatura media anual. A medida que se incrementa la temperatura aumenta la probabilidad de ocurrencia de un incendio en coberturas vegetales (Sivrikaya y Küçük, 2022). Esta variable se obtuvo después de aplicar el método IDW de interpolación, con los datos temperatura media mensual de 1985-

2013 de 13 estaciones meteorológicas del INAMHI. Para ello, se utilizaron las ecuaciones (1) y (2) propuestas por (Fries *et al.,* 2009).

$$T_{Det} = T_{mensual} + (r(Z_{Det} - Z_{estación})) \quad (1)$$

Donde T_{Det} es la temperatura determinada, $T_{mensual}$ es el valor de la temperatura mensual de la estación, r es el valor de (nx) de la ecuación de la recta, Z_{det} altitud referencial, $Z_{estación}$ altitud de la estación.

$$\mathrm{T_{real}} = \mathrm{T_{Det}} + (\mathrm{r}(\mathrm{Z^{DEM}} - \mathrm{Z_{Det}})) \quad (2)$$

Donde T_{Det} corresponde a la temperatura determinada, r valor de nx de la ecuación, Z^{DEM} (X, Y) es el DEM del área de estudio, Z_{Det} valor de altitud referencial.

Finalmente, se establecieron cinco intervalos utilizando la regla práctica del intervalo. El nivel de susceptibilidad para el modelo AHP se estableció con una relación directamente proporcional entre susceptibilidad de incendio y temperatura. Por otra parte, para el modelo RF se realizó el mismo proceso utilizado en la precipitación.

Evapotranspiración potencial. Un aumento de la temperatura provoca una mayor evapotranspiración, lo que se traduce en una menor humedad del suelo y una mayor vulnerabilidad de la cubierta terrestre a la ignición (Zhao *et al.,* 2021). Se calculó la evapotranspiración potencial (ETP) con las ecuaciones 3, 4, 5 y 6 las cuales provienen del método de Thornthwaite (1948). Finalmente, se establecieron cinco intervalos utilizando la regla práctica del intervalo. El nivel de susceptibilidad para el modelo AHP se determinó aplicando una relación directamente proporcional entre susceptibilidad de incendio y la ETP. Para el modelo RF se realizó el mismo proceso utilizado en la precipitación.

$$ETP_{Tho} = e * L \quad (3)$$

Donde *e* es la evapotranspiración mensual no ajustada y *L* es el factor de corrección mensual establecido según la latitud.

$$e = 16 * (10 * tm/I)^a \quad (4)$$

Donde *tm* es la temperatura media, *I* es el índice anual de calor y *a* es la variable establecida.

$$a = 0{,}000000675 * I^3 - 0{,}0000771 * I^2 + 0{,}01792 * I + 0{,}49239 \quad (5)$$

$$Ij = \left(\frac{tm}{5}\right)^{1.514} \quad (6)$$

Donde *Ij* es Índice de calor mensual y *tm* es temperatura mensual en °C.

Déficit hídrico. El déficit hídrico se puede utilizar como una variable más precisa para reflejar el impacto de la precipitación acumulada en el contenido de agua de la vegetación, y su relación con el nivel de su combustibilidad necesaria para iniciar los procesos de ignición y combustión (Eugenio *et al.,* 2016; Kane *et al.,* 2015). El déficit hídrico se calculó con la ecuación (7), propuesta por Thorhnwaite y Matter (1955) para calcular el balance hídrico. Como resultado, los valores negativos se consideran déficit y los positivos como excedente. Finalmente, se establecieron cinco intervalos utilizando la regla práctica del intervalo. El nivel de susceptibilidad para el modelo AHP se determinó aplicando la relación directamente proporcional entre susceptibilidad de incendio y el déficit hídrico. Para el modelo RF se realizó el mismo proceso utilizado en la precipitación.

$$DH = P - PET \quad (7)$$

Donde *DH*, es el déficit hídrico, *P* es igual a precipitación y *PET* hace referencia a la evapotranspiración potencial.

Velocidad del viento. La velocidad del viento influye en la intensidad de un incendio forestal al reducir el contenido de humedad de la vegetación y suministrar oxígeno para la combustión (Bradstock *et al.,* 2012). Además, el viento desempeña un papel crucial en el control de la propagación del fuego, influido por la orientación y la pendiente (Pazmiño, 2019). Esta variable se obtuvo después de interpolar, con el método IDW, un conjunto de datos de 18 estaciones meteorológicas del INAMHI para el periodo 1990-2020. Finalmente, se establecieron cinco intervalos utilizando la regla práctica del intervalo. El nivel de susceptibilidad para el modelo AHP se determinó aplicando una relación directamente proporcional entre susceptibilidad de incendio y la velocidad del viento. Para el modelo RF se realizó el mismo proceso utilizado en la precipitación.

3.1.3. Factores Antrópicos

Cobertura y uso del suelo. Las características particulares de cada cobertura vegetal definen la adaptabilidad de los ecosistemas para responder al fuego, al poder inhibirlo o propagarlo (Martelo-Jimenez y Vargas Ríos, 2022). Se utilizó la información de cobertura y uso de suelo del año 2020 desarrollado por la plataforma Esri Land Cover, a partir de imágenes Sentinel-2 con una resolución espacial de 10 m (Karra *et al.,* 2021). Así, se clasificaron ocho coberturas de suelo: bosque nativo, cuerpos de agua, cultivos, páramo, suelo desnudo, vegetación herbácea, vegetación arbustiva y zona urbana. Para la validación se usaron 385 coordenadas geográficas de las coberturas como puntos de control y se empleó el índice Kappa, el cual relaciona los acuerdos observados entre los datos de clasificación y los datos de referencia (Cohen, 1960). El resultado Kappa fue de 0,8, lo cual, según Landis y Koch, 1977) presenta una exactitud considerable. Finalmente, los cinco rangos de susceptibilidad para el modelo AHP se asignaron con referencia a estudios realizados en la provincia de Imbabura por Anrango *et al.* (2020) o Arias-Muñoz *et al.* (2020) a excepción de las coberturas de cuerpos de agua, suelo urbano y suelo desnudo, a los cuales se asignó una categoría nula. Para el modelo FR se ejecutó el estadístico bivariante entre las categorías de suelo y el registro histórico de los focos de calor FIRMS.

Proximidad a vías de comunicación. El área limítrofe a redes viales y centros poblados influyen en la ocurrencia de ICV (Zambon *et al.,* 2019). La cercanía a vías se evaluó calculando en un entorno SIG la distancia espacial a las vías de comunicación desde todos los sectores del territorio. Se establecieron cinco intervalos utilizando la «regla práctica del intervalo». El nivel de susceptibilidad para el modelo AHP se determinó aplicando una relación inversamente proporcional entre susceptibilidad de incendio y la cercanía a vías. Para el modelo RF se ejecutó el estadístico bivariante entre las clases definidas y el registro histórico de los focos de calor FIRMS.

Cercanía a espacios agrícolas. En varias regiones del mundo se ha demostrado que existe una relación entre las actividades humanas y la ocurrencia de incendios forestales (Sivrikaya y Küçük, 2022). Generalmente, los agricultores consideran al fuego como una herramienta para la eliminación de residuos agrícolas (Vélez Muñoz, 2000). Sin embargo, en países como Colombia, Ecuador y Perú, los cultivos ilícitos tienen una gran incidencia en la propagación de este tipo incendios (Tebbutt *et al.,* 2021). Por ese motivo, se delimitaron los espacios agrícolas a partir de la información del CUS. La distancia entre las áreas de producción agrícola y el resto de los sectores del cantón fueron determinados en el software ArcGIS 10.8. Para esto, se establecieron cinco categorías utilizando la regla práctica del intervalo. El nivel de susceptibilidad para el modelo AHP se determinó aplicando una relación inversamente proporcional entre susceptibilidad de incendio y la cercanía a espacios agrícolas. Para el modelo RF se realizó el mismo proceso utilizado en la variable cercanía a vías de comunicación.

3.2. Generación de Modelos Espacialmente Explícitos de Susceptibilidad a ICV

Los modelos de susceptibilidad a ICV se desarrollaron bajo dos enfoques metodológicos: a) Multicriterio de Proceso Analítico Jerárquico (AHP) y b) Radio Frecuencia (RF).

3.2.1. Método Multicriterio por Procesos Analíticos Jerárquicos (AHP)

Para obtener un modelo de susceptibilidad a ICV en el área de estudio se utilizó el Proceso Analítico Jerárquico (AHP). El AHP es uno de los métodos multicriterio más utilizados por su fácil aplicabilidad, ya que utiliza varios criterios para la construcción de matrices a partir de comparaciones con sistemas de contrapesos a fin de establecer los niveles de importancia entre los elementos (Saaty, 1980). La importancia relativa de las variables de susceptibilidad se analizó comparando dos factores simultáneamente y estableciendo jerarquías entre los factores según su influencia en la susceptibilidad. Para que los pesos ponderados se consideren válidos se debe calcular el coeficiente de coherencia (CR) de la matriz y obtener un valor de 0,10 (Eugenio *et al.,* 2016). Para ello se emplearon las ecuaciones (8), (9) y (10).

$$CR = \frac{CI}{Rci} \tag{8}$$

$$CI = \frac{\lambda max - n}{(n-1)} \tag{9}$$

$$Rci = \frac{1.98 * (n-2)}{n} \tag{10}$$

Donde λmax es el máximo auto vector de la matriz, n es el número de variables utilizadas, CI es el coeficiente de consistencia y Rci es el llamado índice de consistencia aleatoria.

El valor CR obtenido fue de -0,096, por lo que la matriz se considera consistente. A continuación, con los valores ponderados obtenidos se obtuvo la ecuación (11) que define la susceptibilidad a ICV. Con base en esta ecuación se aplicó un algebra de mapas en un entorno SIG, y así se generó el modelo espacialmente explícito de susceptibilidad a ICV. La información geoespacial se utilizó con una resolución espacial uniforme de 30 m. Los valores máximos y mínimos obtenidos tras aplicar la ecuación (11) para la susceptibilidad a los incendios forestales se han considerado para definir las categorías de susceptibilidad. Estos valores son 5 y 0, respectivamente, considerando que las masas de agua, áreas sin vegetación y las zonas urbanas tienen una susceptibilidad nula a este tipo de incendios. Finalmente, la susceptibilidad se clasificó en cinco clases divididas en intervalos iguales: muy baja, baja, moderada, alta y muy alta (Abedi Gheshlaghi *et al.,* 2020; Eugenio *et al.,* 2016).

$$\boldsymbol{Susceptibilidad\ AHP} = CUS \times 0{,}2805 + ETP \times 0{,}1151 + Pend \times 0{,}1084 + Prec \times 0{,}1058 + Temp \times 0{,}685 + OT \times 0{,}0666 + DH \times 0{,}0672 + PCV \times 0{,}0555 + EA \times 0{,}0555 + Alti \times 0{,}0458 + VV \times 0{,}0329 \tag{11}$$

Donde CUS es cobertura y uso de suelo; ETP es evapotranspiración potencial; Pend es pendiente del territorio; Prec es precipitación; Temp es temperatura media; OT es orientación del terreno; DH es déficit hídrico; PVC es proximidad a vías de comunicación; EA es cercanía a espacios agrícolas; Alti es altitud y VV es velocidad del viento.

3.2.2. Método de Radio frecuencia (RF)

El método de RF, por su parte, también es considerado de fácil comprensión, ya que emplea la frecuencia estadística para relacionar los factores causales del evento con la presencia de eventos pasados registrados (Jaafari y Mafi Gholami, 2017; Liao y Carin, 2009). Al ser un método bivariado, se asociaron los factores causales de susceptibilidad con los focos de calor o anomalías de calor (FIRMS), obtenidos desde el portal del Instituto Nacional de Investigaciones Espaciales de Brasil (INPE). El INPE tiene una base de datos de puntos de calor para América del Sur desde 1998, y para Ecuador hay datos desde 2000. Para el área de estudio, se identificaron 874 focos de calor para al periodo 2000-2020 provenientes de los satélites AQUA, GOES, NOAA, TERRA, ASTR y TRMM (Fig. 3). El proceso para obtener este modelo de susceptibilidad a ICV consistió en utilizar el 75% de los datos FIRMS para el entrenamiento del modelo y el 25% restante para la validación.

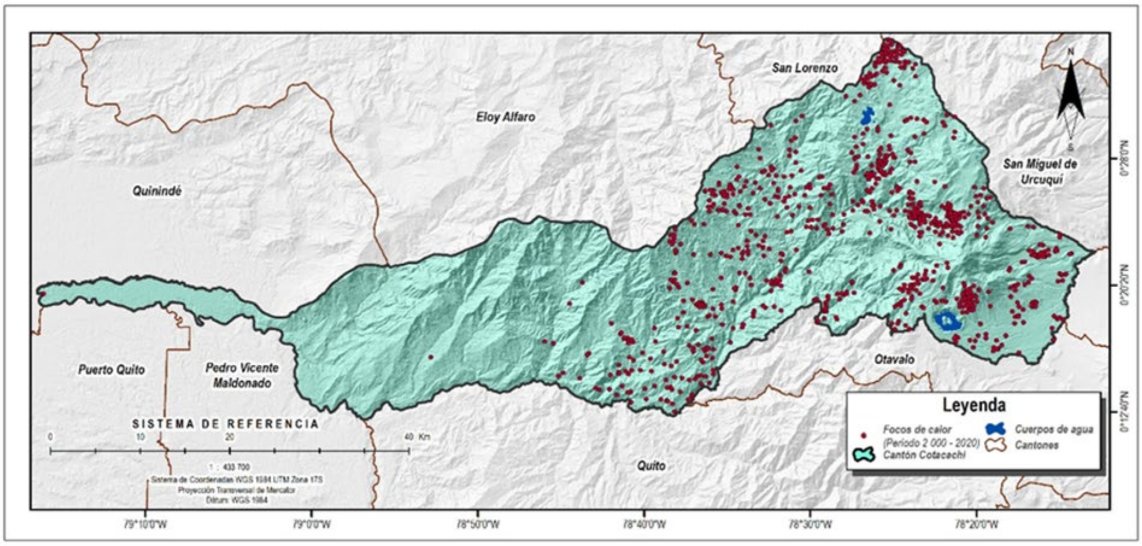

Figura 3. Focos de calor obtenido de INPE, periodo 2000–2020 para el cantón Cotacachi.

Después, su clasificación fue modificada en función del peso obtenido a partir de la frecuencia relativa y los focos de calor para generar una nueva clasificación de los factores. La jerarquización de los valores entre las ponderaciones mostró un mejor peso relativo real entre los factores que se refiere a la densidad real. De este modo, con los valores ponderados se desarrolló la ecuación (12) de susceptibilidad a ICV por método RF. Al igual que con el método AHP se empleó esta ecuación para desarrollar el modelo espacialmente explícito de susceptibilidad a ICV. En un entorno SIG se estandarizaron los datos y finalmente se clasificaron en cinco clases divididas en intervalos iguales: muy baja, baja, moderada, alta y muy alta.

$$\boldsymbol{Susceptibilidad\ RF} = CUS \times 756 + ETP \times 555 + Pend \times 100 + \text{Prec} \times 416 + \text{Temp} \times 453 + \text{OT} \times 100 + \text{DH} \times 208 + \text{PCV} \times 103 + \text{EA} \times 100 + \text{Alti} \times 542 + \text{VV} \times 100 \qquad (12)$$

Donde CUS es cobertura y uso de suelo; ETP es evapotranspiración potencial; Pend es pendiente del territorio; Prec es precipitación; Temp es temperatura media; OT es orientación del terreno; DH es déficit hídrico; PVC es proximidad a vías de comunicación; EA es cercanía a espacios agrícolas; Alti es altitud y VV es velocidad del viento.

3.3. Validación de los Modelos

El modelo fue validado utilizando el 25% de los focos de calor o anomalías térmicas registrados para el área de estudio y los incendios históricos registrados por el Servicio Nacional de Gestión de Riesgos y Desastres de Ecuador. Dicha información se cruzó espacialmente con las categorías de susceptibilidad alta y muy alta, con el fin de comprobar si el peligro extremo identificado en los modelos se acercaba a la realidad del territorio. La comprobación se realizó aplicando el área baja de la curva ROC (*Receiver Operating Characteristics*) que se utilizó para determinar la precisión de un mapa de susceptibilidad a los ICV (Anrango *et al.,* 2020; De Santana *et al.,* 2021). Este método permite analizar los valores de verdadero positivo y falso positivo en cada punto de la curva. El área bajo la curva (AUC) puede clasificarse en cinco categorías: 1 a 0,9 = excelente, 0,9 a 0,8 = muy buena, 0,8 a 0,7= buena, 0,7 a 0,6 = media, y >0,6= mala (Abedi Gheshlaghi *et al.,* 2020). Finalmente, en la Figura 4 se presenta un esquema gráfico de la metodología utilizada.

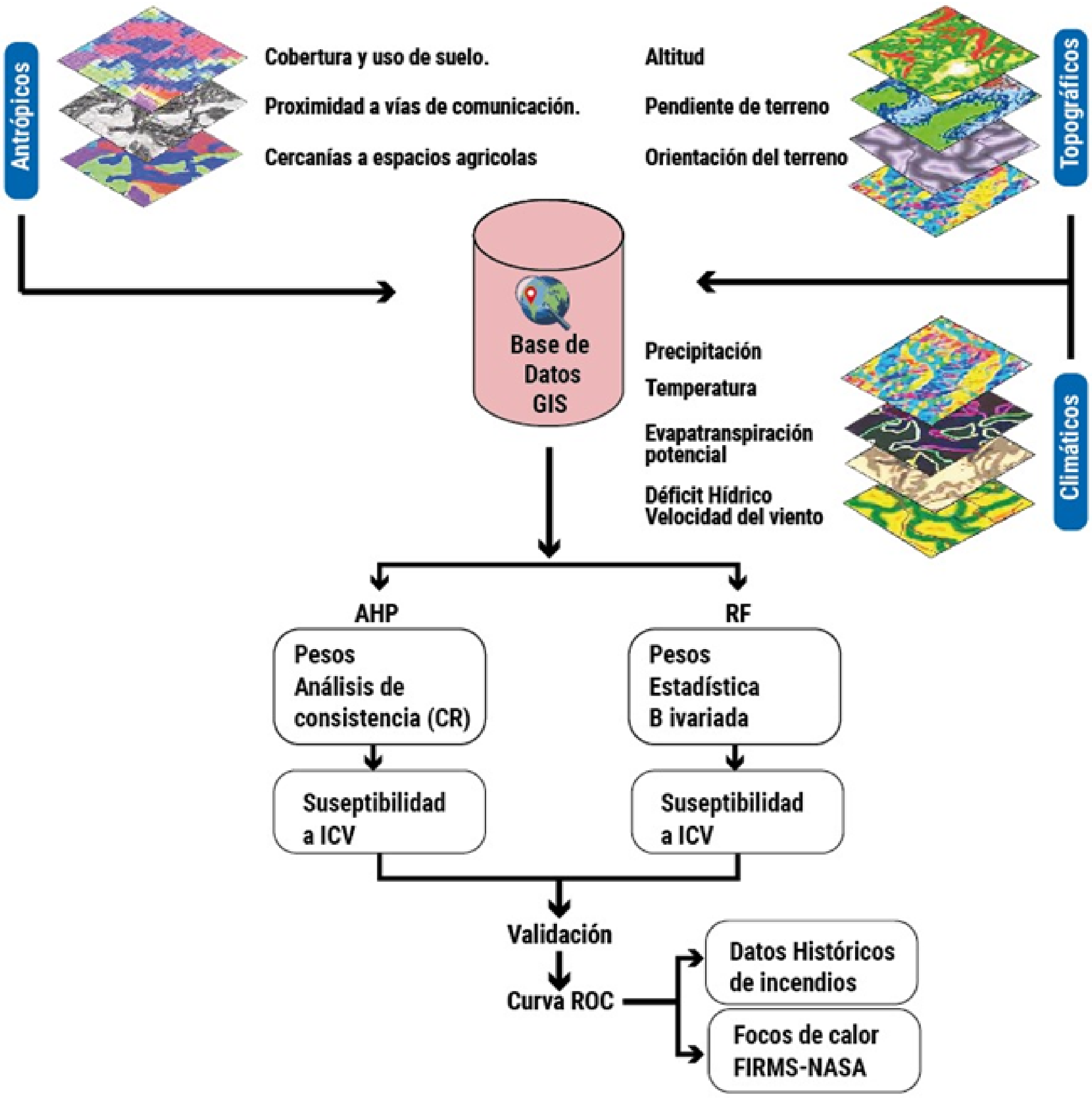

Figura 4. Esquema gráfico de la metodología.

4. Resultados

4.1. Modelo AHP de Susceptibilidad a Incendios de Cobertura Vegetal

Los resultados del modelo AHP muestran que alrededor del 51,41% del cantón presenta susceptibilidad alta y muy alta ante ICV. Estas zonas propensas a incendios se concentran en zonas pertenecientes al sector oriental del cantón y en el sector suroccidental (Fig. 5). Esta susceptibilidad se concentra en las siguientes coberturas: bosque nativo (34,85%), páramo (7,22%) y cultivos (3,50%). Por otro lado, como Cotacachi presenta dos zonas, la andina y la subtropical también se diferenciaron la variación de la susceptibilidad. La zona subtropical presenta más peligro extremo (susceptibilidad alta) porque se presenta en un 39,03% respecto al 12,39 % que presenta la zona andina (Fig. 6).

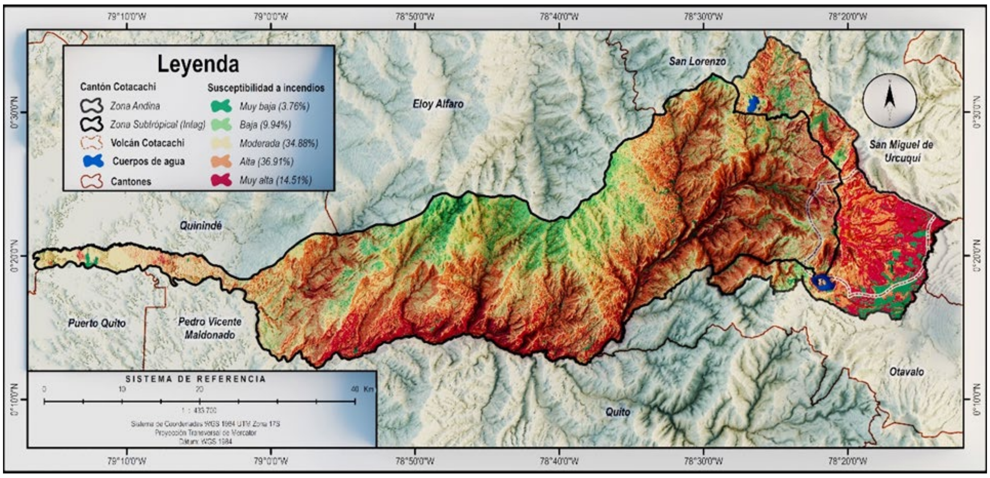

Figura 5. Susceptibilidad a incendios en el cantón Cotacachi, modelo AHP.

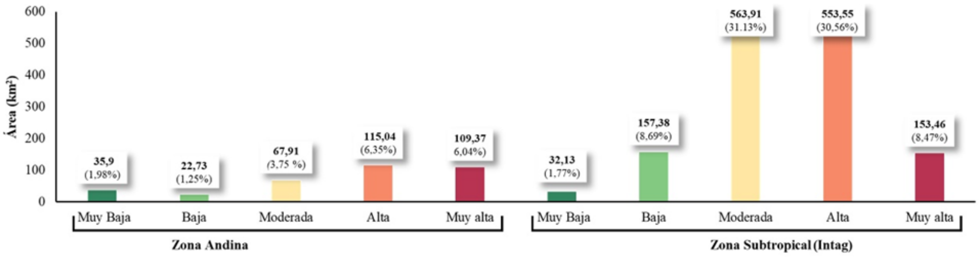

Figura 6. Niveles de susceptibilidad para la zona andina y subtropical, modelo AHP.

4.2. Modelo RF de susceptibilidad a incendios de cobertura vegetal

Los resultados del modelo RF muestran que alrededor del 47,56% del cantón presenta susceptibilidad alta y muy alta ante ICV (Fig. 7). A diferencia de lo obtenido en el modelo AHP estas zonas propensas a incendios se concentran principalmente en zonas localizadas en el sector oriental del cantón. Sin embargo, en este modelo se observa que la susceptibilidad a este tipo de incendios además de concentrarse en las coberturas: bosque nativo (25,84%), páramo (10,79%) también se presenta en la vegetación herbácea y arbustiva (7,47%). Como en el modelo AHP se observa que la zona más propensa a estos incendios es la subtropical, porque un 30,15% del territorio presenta peligro extremo (susceptibilidad alta y alta) a diferencia del 12,63 % de la región andina (Fig. 8). De ahí que, en la región andina el peligro extremo se mantiene similar en ambos modelos, sin embargo, la susceptibilidad alta se reduce respecto al modelo RF.

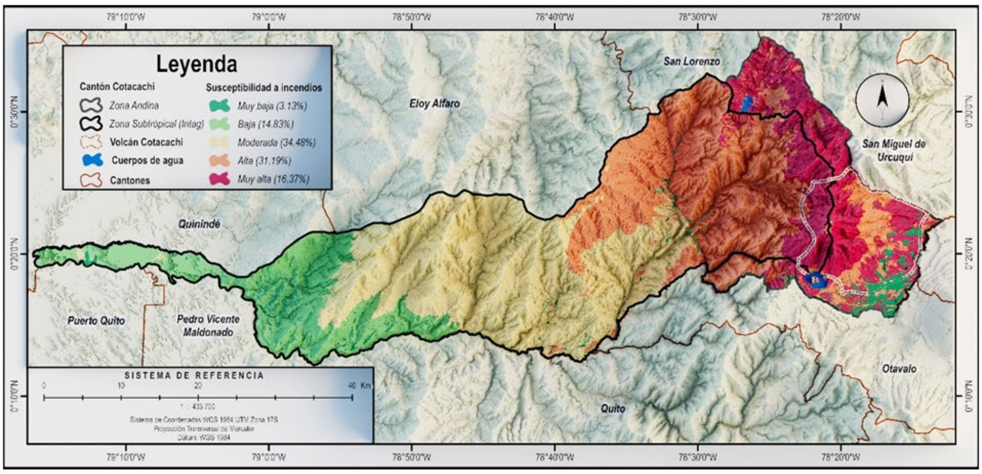

Figura 7. Susceptibilidad a incendios en el cantón Cotacachi, modelo RF.

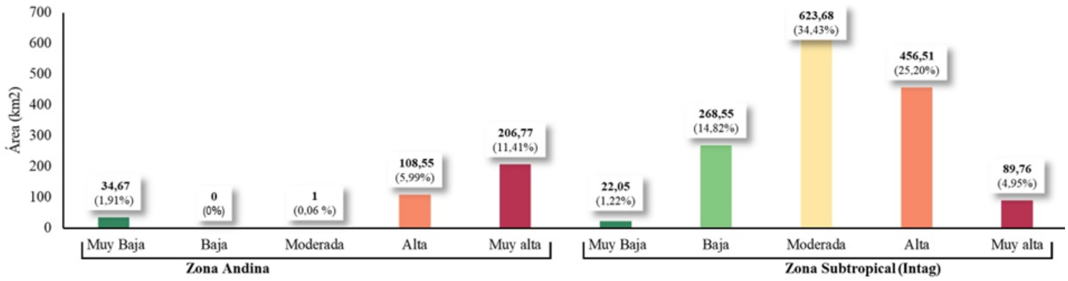

Figura 8. Niveles de susceptibilidad para la zona andina y subtropical, modelo RF.

4.3. Validación de los modelos

La curva ROC estimó la precisión los modelos AHP y RF generados (Fig. 9). La validación estadística para los focos de calor del sistema FIRMS muestra que el modelo AHP es muy bueno con un valor de AUC: 0,824 y que el modelo RF es excelente con un valor AUC: 0,902. La validación estadística para los incendios históricos muestra que el modelo AHP es bueno con un valor de AUC: 0,748 y que el modelo RF también es bueno con un valor AUC: 0,755.

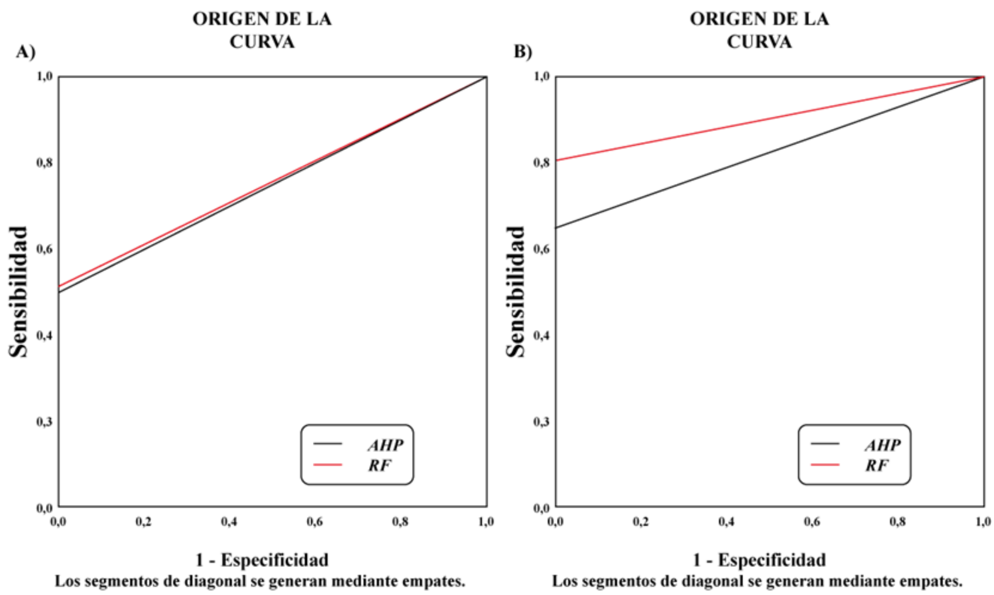

Figura 9. Curva ROC para validación estadística. A) Comparación de modelos con información de incendios de cobertura vegetal históricos. B) Comparación de modelos con focos de calor.

5. Discusión

5.1. Rendimiento de los modelos AHP y RF

Las decisiones ambientales a menudo complejas se basan en conocimientos multidisciplinarios que incorporan ciencias naturales, ciencias sociales, incluso, la política y la ética (García Leyton y Baldasano Recio, 2004; Huang *et al.,* 2011). Sin embargo, la toma de decisiones resulta cada vez más difícil por razones como: a) la nula o escasa información disponible o b) el conflicto de intereses. Ambas incrementan la incertidumbre en los datos y reduce la precisión de los resultados (Huang *et al.,* 2011). Por ello, la integración de la información técnica de tipo heterogénea e incierta requiere la opinión de expertos, lo cual se puede alcanzar con la aplicación de métodos como el multicriterio o de radio frecuencia (Linkov *et al.,* 2006).

Ambos métodos permiten incorporar variables en el análisis, pero mediante procesos estadísticos y probabilísticos se asignan ponderaciones con el fin de determinar y respetar la mayor o menor influencia en la generación de varios fenómenos (Saaty, 1980; Liao y Carin, 2009). El método de radio frecuencia es uno de los métodos más empleados porque es capaz de ejecutar análisis estadísticos bivariantes y de ponderar el efecto de cada factor en el análisis de los riesgos naturales (Tehrany *et al.,* 2015). Aunque casi todas las metodologías de análisis de decisiones comparten pasos similares de organización en la construcción de la matriz de decisión, son las metodologías multicriterio y de radio frecuencia las de más fácil comprensión para sintetizar la información y clasificar las alternativas por relevancia e influencia (Saaty, 1980; Liao y Carin, 2009).

Son varios los estudios enfocados al análisis de los riesgos naturales que llegan a ser útiles por la ventaja de combinar técnicas multicriterio o de RF con los SIG (De Santana *et al.,* 2021; Sivrikaya y Küçük, 2022). La razón es que ambos métodos permiten la identificación espacial de espacios susceptibles a riesgos naturales como es el caso de los incendios de cobertura vegetal (Arias-Muñoz *et al.,* 2020; De Santana *et al.,* 2021; Hong *et al.,* 2017).

Otra ventaja es que, a diferencia de otras alternativas como la aplicación de redes neuronales o técnicas de *machine learning,* no es necesario utilizar programas de software especializados. Sin embargo, tanto el AHP como el RF presentan una desventaja a la sensibilidad a los datos de entrada (Huang *et al.,* 2011; Linkov *et al.,* 2006). Ello es debido a que la selección de los datos de entrada y las preferencias de los expertos pueden causar variación en los resultados por la subjetividad de las opiniones, por lo que la efectividad y precisión de los resultados depende de realizar procesos de validación.

Los resultados de este estudio facilitaron una buena representación cartográfica de la susceptibilidad a ICV usando tanto el modelo AHP como el RF. Los valores del área bajo la curva (AUC) muestran que ambos modelos presentaron mejor validación comparando con los datos de los focos de calor (FIRMS) que con los incendios históricos registrados. Los valores AUC obtenidos, al utilizar la información de FIRMS, son de 0,824 y 0,902 para los modelos AHP y RF, respectivamente, mientras que los valores AUC derivados de la información de incendios históricos son de 0,748 y 0,755 para los modelos AHP y RF, respectivamente. Esto demostraría que los rendimientos de los modelos son similares, pero cambian su rendimiento según la información geoespacial con la que se valida. Por otro lado, estos valores AUC son similares a los encontrados en otros trabajos que utilizaron el RF u otros modelos de cartografía de susceptibilidad a incendios. Así, está el modelo obtenido por De Santana *et al.* (2021) con un valor AUC de 0,81 en su modelación de incendios forestales en el bosque del Corredor Central del Atlántico en Brasil; o el obtenido por Hong *et al.* (2017) en un estudio de susceptibilidad a ICV en la zona de Yihuan (China) que es de 0,81.

En Ecuador, existen pocos estudios que desarrollen la cartografía de este tipo de incendios, y que a la vez sea validada estadísticamente. A diferencia de Estacio y Narváez (2012) que, después de identificar las áreas susceptibles a incendios de cobertura vegetal en el Distrito Metropolitano de Quito (DMQ), no validaron su modelo con el empleo de la estadística, Reyes-Bueno y Loján-Córdova (2022) obtuvieron un valor AUC de 0,825 para uno de sus modelos en el estudio desarrollado en sur de Ecuador, en la provincia de Loja. También están los estudios desarrollados por Anrango *et al.* (2020) en el cantón Ibarra con un valor AUC: 0,862, o por Arias-Muñoz *et al.* (2020) en la subcuenca del río Mataquí, en la provincia de Imbabura, con un valor AUC: 0,95.

5.2. Condiciones y factores de susceptibilidad a ICV

Los resultados de la susceptibilidad a ICV muestran una tendencia similar en ambos modelos, porque mientras, en el modelo multicriterio (AHP) un 51,42% del territorio presenta peligro extremo (susceptibilidad alta y muy alta), en el modelo de radio frecuencia (FR) un 47,56% del territorio presenta este tipo de peligro. Las zonas de susceptibilidad alta y muy alta generalmente se concentran en el sector oriental del territorio, excepto en zonas urbanas y en cuerpos de agua. El patrón de susceptibilidad alta y muy alta se alinea con regiones caracterizadas por altas temperaturas, cobertura natural y pendientes pronunciadas, lo que contribuye a la propagación de los incendios.

La temperatura media en el cantón Cotacachi es de 16,4 °C aproximadamente; sin embargo, normalmente las áreas de alta susceptibilidad superan esta temperatura promedio. Esto demuestra que existe una fuerte correlación entre el aumento de la temperatura y la incidencia de ICV, similar a la correlación con la evapotranspiración potencial (Sivrikaya y Küçük, 2022). A medida que aumenta el déficit hídrico de la zona, también lo hace su susceptibilidad a los incendios. Cuando la disponibilidad de agua, en ambos modelos, cae por debajo de 605 mm dentro de la cubierta vegetal, el riesgo de incendio aumenta. Esto se debe a la correlación inversa entre la cantidad de precipitación y el riesgo de ICV (Morante-Carballo *et al.,* 2022). En Cotacachi, los valores de susceptibilidad disminuyen a medida que aumenta la precipitación. En ambos modelos, cuando la precipitación media anual es menor a 1490 mm, existe alta susceptibilidad al fuego.

En cuanto a la pendiente, se concluye que la frecuencia de incendios forestales es mayor en pendientes superiores al 35% (Eugenio *et al.,* 2016). La susceptibilidad a este tipo de incendios aumenta a medida que se incrementa el grado de la pendiente, ya que la inclinación favorece el ascenso de aire caliente y la propagación del fuego se ve afectada por la acumulación de calor (Bonora *et al.,* 2013). Además, se determinó que la distancia a las carreteras sí es un factor que influye en la ocurrencia de incendios de cobertura vegetal. Esto sugiere que la proximidad a núcleos urbanos y la cercanía a actividades antrópicas influye en la susceptibilidad (Sivrikaya y Küçük, 2022). La presencia de vías de comunicación tiende a desencadenar este tipo de incendios (Zambon *et al.,* 2019).

Las variables climáticas influyen directamente en el origen de estos fenómenos y también en el desarrollo de las actividades humanas, especialmente la agricultura. En particular, durante los meses secos de agosto y septiembre, aumenta la frecuencia de incendios forestales. Así lo corroboran datos del Servicio Nacional de Gestión de Riesgos y Desastres de Ecuador, que indican que el 59% de los incendios registrados entre el 2018 y 2020 ocurrieron durante estos meses. Por otro lado, la susceptibilidad baja a ICV se concentra en los sectores occidentales del cantón, ya que aquí predominan bosques pluviales porque la precipitación puede llegar a alcanzar hasta 2334 mm. En general, las cubiertas naturales son sensibles al fuego porque carecen de estrategias adaptativas a este fenómeno, excepto las cubiertas como el bosque pluvial que presentan más resiliencia porque se localizan en un clima con alta pluviosidad (Martelo-Jimenez y Vargas Ríos, 2022). El déficit de agua tiene un impacto directo en la alta susceptibilidad del cantón, ya que los bajos índices de humedad aumentan la combustibilidad (Casado y Gil, 2006).

Por último, en sectores de alta o muy alta susceptibilidad, muchos estudios indican la posibilidad de implementar acciones y estrategias que ayuden a reducirla o mitigarla (Úbeda y Sarricolea, 2016). De acuerdo con las particulares condiciones geográficas y socioeconómicas de los asentamientos humanos y ecosistemas subtropicales y montañosos andinos, se considera que la implementación de algunas estrategias sería compleja o inviable. En el cantón Cotacachi, donde el uso del suelo, la temperatura y la orientación de las laderas son factores claves en la propagación de los incendios, algunas estrategias viables serían los cortafuegos, las torres de observación y monitoreo meteorológico constante de las zonas con susceptibilidad alta y muy alta para mejorar la toma de decisiones en base a datos técnico-científicos (Pazmiño, 2019; Úbeda y Sarricolea, 2016).

6. Conclusiones

Los resultados de la susceptibilidad a incendios de cobertura vegetal (ICV) muestran que los modelos multicriterio (AHP) y radio frecuencia (RF) presentaron resultados y rendimientos similares, con mínimas diferencias. El modelo multicriterio AHP establece que el 51,42% del territorio presenta peligro extremo a ICV producto de la presencia de zonas con susceptibilidad alta y muy alta, el modelo

RF establece que un 47,56% del territorio presenta este tipo de peligro. Los modelos de multicriterio AHP y RF desarrollados resultaron fiables para representar la susceptibilidad a ICV en el cantón Cotacachi y no presentan diferencias significativas.

Después de validar ambos modelos con información de focos de calor recopilados entre los años 2000-2020 y con registros de incendios registrados entre los años 2018-2020, los valores AUC fluctúan entre 0,74 y 0,902. Estos valores categorizan a los modelos entre buenos y excelentes, dependiendo de los insumos utilizados para la validación. No obstante, una lectura más próxima a la realidad brindaría el proceso de validación efectuado con los incendios históricos, más que con los focos de calor (FIRMS) a pesar de que los modelos presentan un mejor rendimiento al comparar con los datos FIRMS, ya que éstos no necesariamente se traducen en incendios. Bajo este antecedente, ambos modelos presentan rendimientos similares con un AUC: 0,748 para el modelo AHP y un AUC: 0,755 para el modelo RF. La diferencia en el área bajo la curva tampoco se consideraría significativa, por lo tanto, se concluye que ambos modelos presentan rendimientos similares en el establecimiento de zonas susceptibles a ICV.

En ambos modelos el peligro extremo a ICV es mayor en la zona subtropical que en la zona andina, incluso 3 veces más. Además, la susceptibilidad alta se concentra en ecosistemas sensibles como bosques nativos y páramos. Finalmente, la implementación de medidas como líneas cortafuegos, torres de observación y monitoreo meteorológico para desarrollo de un Sistemas de Alerta Temprana (SAT) servirán para generar una gestión adecuada al riesgo de incendio, donde la prevención es el eje central.

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INFLUENCE OF CLIMATE VARIABILITY ON FIRE GENERATION: MYTHS AND FACTS IN SOUTHERN PAMPAS (ARGENTINA)

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ABSTRACT. This study evaluates the occurrence of dry and wet events and their relationship with fires in southern Pampas, Argentina. The intensity and magnitude of dry and wet events were determined based on the regional series of the Standardized Precipitation and Evapotranspiration Index (SPEI) for the 2000-2021 period. The data obtained were related to the El Niño Oceanic Index (ONI) to analyze the incidence of El Niño and La Niña events in generating them. Fires in the region were detected using remote sensing techniques, considering the number of events, their intensity, extent, and duration. The southern Pampas experiences marked rainfall variability, with 15 dry events, 11 wet years, and 2 standard years recorded for the period analyzed. Extreme dry years were, on average, more intense (SPEI = -2.14) and occurred mainly during the negative ONI phase. In contrast, extreme wet years exhibited lower intensity (SPEI = 1.98), and only the most intense ones were related to neutral ONI phases. We analyzed a representative extremely dry (ED) and an extremely wet events (EW) to interpret the relationship between climate variability and the spatiotemporal variability of fires in the region. It was observed that during the EW event (2014-2015, SPEI = 1.52, and El Niño event until 2015) the number of fires was higher compared to an ED event (2008-2009, SPEI = -2.22, and La Niña event during 2008), with 460 and 205 fires, respectively. The intensity was higher in the EW (302.6 and 31.5 MW), while the area presented considerable differences (1722 and 815.5 km^2, respectively). Finally, the duration of the fires was shorter in ED than in EW (6 and 8 months, respectively). These results were related to vegetation health (NDVI = 0.29 and 0.41 and EVI = 0.15 and 0.21 in ED and EW, respectively) and changes in land covers. This study provides a solid database for future research efforts and sustainable land management plans.

Influencia de la variabilidad climática en la generación de incendios: mitos y hechos en el sur de la Pampa (Argentina)

RESUMEN. Este estudio evalúa la ocurrencia de eventos secos y húmedos y su relación con los incendios en el sur de la Pampa, Argentina. La intensidad y magnitud de los eventos secos y húmedos se determinaron a partir de las series regionales del Índice Estandarizado de Precipitación y Evapotranspiración (SPEI) para el período 2000-2021. Los datos obtenidos se relacionaron con el Índice Oceánico El Niño (ONI) para analizar la incidencia de eventos de El Niño y La Niña. Los incendios en la región fueron detectados utilizando técnicas de teledetección, considerando el número de eventos, su intensidad, extensión y duración. El sur de la Pampa experimenta una marcada variabilidad de precipitaciones, con 15 eventos secos, 11 años húmedos y 2 años estándar registrados para el período analizado. Los años de sequía extrema fueron, en promedio, más intensos (SPEI = -2,14) y ocurrieron principalmente durante la fase ONI negativa. En contraste, los años húmedos extremos exhibieron menor intensidad (SPEI = 1,98), y solo los más intensos estuvieron relacionados con las fases ONI neutrales. Se analizó un evento representativo extremadamente seco (ED) y un evento extremadamente húmedo (EW) para interpretar la relación entre la variabilidad climática y la variabilidad espacio-temporal de los incendios en la región. Se observó que durante el evento EW (2014-2015, SPEI = 1,52 y El Niño hasta 2015) el número de incendios fue mayor en comparación con un evento ED (2008-2009, SPEI = -2,22 y La Niña durante 2008), con 460 y 205 incendios, respectivamente. La intensidad fue mayor en el EW (302,6 y 31,5 MW), mientras que el área presentó diferencias considerables (1722 y 815,5 km^2, respectivamente). Finalmente, la duración de los incendios fue más corta en ED que en EW (6 y 8 meses, respectivamente). Estos resultados se relacionaron con la salud de la vegetación (NDVI = 0,29 y 0,41 y EVI = 0,15 y 0,21 en ED y EW, respectivamente) y los cambios en la cobertura del suelo. Este estudio proporciona una base de datos sólida para futuras investigaciones y planes de gestión sostenible de la tierra.

Keywords: Climate variability, El Niño and La Niña events, fires, southern Pampas.

Palabras clave: Variabilidad climática, El Niño y La Niña, incendios, sur de la Pampa.

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1. Introduction

Climate variability results from the heat exchange between the oceans and the atmosphere (Wang *et al.*, 2004). The magnitude and persistence of climate fluctuations exhibit a scalar structure in space and time involving all climate variables. However, temperature and precipitation exhibit the most noticeable spatial manifestation (Franzke *et al.*, 2020). In South America, interannual precipitation variability is an essential modulator of synoptic and intra-seasonal variability and responds primarily to the effects of the El Niño-Southern Oscillation (ENSO) phenomenon (Grimm, 2011). ENSO influences the frequency of extreme events, resulting in a succession of dry and wet periods that affect soil moisture and vegetation health and, by extension, fires' occurrence, intensity, and magnitude (Xu *et al.*, 2020).

On the other hand, global warming results in greater atmospheric ignition power and promotes a higher frequency of fire events. Indeed, most literature documents that dry and warm conditions contribute to vegetation drying, leading to an increase in the number, intensity, and duration of fires on the global scale, regardless of the climate region (Wehner *et al.*, 2017 in the United States; Bowman *et al.*, 2020 in Australia; Zupichiatti *et al.*, 2022 in Argentina; among others).

Fires in Argentinean Pampas exhibit varying origin, intensity and extent yet high frequency and obey complex relationships between hydroclimatic variability, land cover changes, and agro-pastoral activities management (Delegido *et al.*, 2018; Ferrelli *et al.*, 2022). Most generally, the events of greater magnitude are related to long-standing drought conditions and affect mainly both natural and grazing grasslands (Bert *et al.*, 2021). From a climatic point of view, the arid and semiarid sectors in southern Pampas are exposed to greater risk, as dry events are the most intense and long-lasting in these areas (Aliaga *et al.*, 2017; Ferrelli *et al.*, 2021). However, there is evidence that fires in these sectors are mainly linked to agricultural activity and that their intensity may vary depending on the agroecosystems management (Pezzola and Winschel, 2004). In this regard, the origin of fires in southern Pampas is likely associated with hydrological conditions favouring such management practices.

This study evaluates the occurrence of dry and wet events and their relationship with fire dynamics in southern Pampas (Argentina). It seeks to determine the causal relationship between climate variability, vegetation status and health, and fire dynamics within a region where natural precipitation variability strongly intensifies arid and semiarid conditions. The analysis evaluates and combines (i) the intensity and duration of dry and wet events based on the regional series of the Standardized Precipitation and Evapotranspiration Index (SPEI), (ii) their associations to El Niño and La Niña events based on the Oceanic Niño Index (ONI), (iii) the vegetation response to such variability, and (iv) the resulting fire dynamics in terms of the number of events, intensity, extent, and duration, using remote sensing techniques. In addition to providing robust results based on the detailed analysis, two key events of contrasting hydroclimatic conditions were selected and compared to determine different scenarios. The results of this study provide a solid database to guide future research efforts and sustainable development land management plans.

2. Materials and methods

2.1. Study Area

The southern Pampas comprise the Villarino and Patagones districts, both of which belong to Buenos Aires province, Argentina (Fig. 1). Primary land uses mix both livestock and rainfed agriculture, except for a central band irrigated by the Colorado River (Iurman, 2010). The total population is 61,221 inhabitants. The 79 % of the population concentrates in urban areas, being the city of Carmen de Patagones the most populated (20,533 inhabitants). The rural population density remains below unity over 94 % of the territory (INDEC, 2010). The absence of marked topographic gradients is in contrast to a marked decreasing rainfall gradient from 600 mm in the northeast to 360 mm in the southwest (Winschel, 2017; Ferrelli *et al.*, 2020), reaching arid conditions near Río Negro (Gabella *et al.*, 2013).

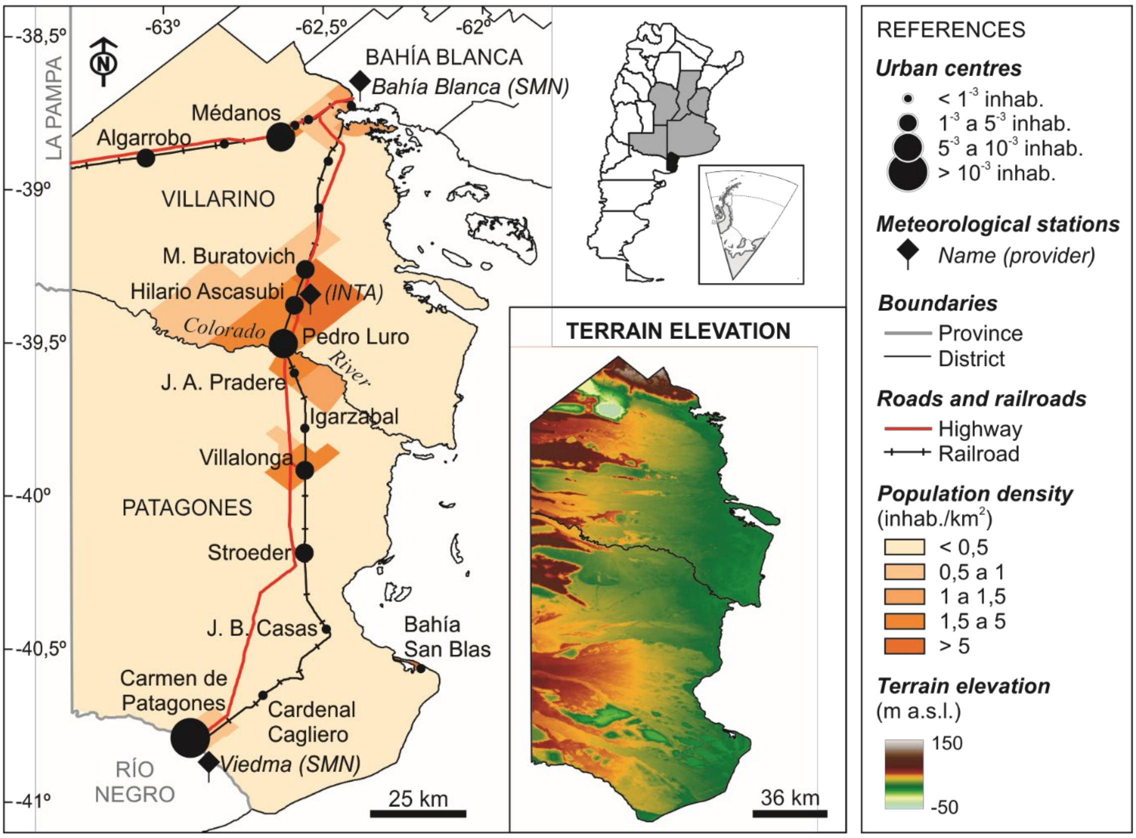

Figure 1. Location and configuration of the southern pampas (Argentina). Source: Own elaboration based on cartographic data from the National Geographic Institute (IGN, Argentina). Population data was extracted from the 2010 Census (National Institute of Statistics and Census, INDEC, Argentina). GMTED2010 Digital Elevation Model with a resolution of 7.5 arc seconds (U. S. Geological Survey).

Mean annual temperature ranges between 14 and 15 ºC, with a yearly amplitude of about 13 to 14 ºC (Campo de Ferreras *et al.*, 2004; Aliaga *et al.*, 2017). The natural vegetation integrates the Espinal and Monte ecoregions (Cabrera, 1976). The Espinal develops in the northern and eastern sectors, and exhibits low, xerophytic, dense to open forests dominated by *Prosopis caldenia* and grasslands of *Stipa sp*. in the lower strata. The Monte develops in the southwestern sector, and constitutes a shrub steppe of *Larrea sp.*, interspersed with *Geoffroea decorticans* and *Capparis sp*. in the most humid sites (Morello *et al.*, 2012). Grazing, tillage, and fires, originated by human activity, introduce profound changes in the landscape, with particularly noticeable impacts on the vegetation structure (Pezzola and Winschel, 2004).

2.2. Materials

This study combines gridded climate data series, global climate models, and environmental indices with global fire information (Table 1). The dataset is openly accessible and distributed as maps or spatially referenced data series. All data were processed to span a concurrent analysis period (2000-2021) and area of interest (southern Pampas). The geospatial information layers were projected following the national system of flat coordinates (POSGAR 07). Additionally, we used meteorological records from the National Institute of Agricultural Technology (INTA, Argentina) and the National Meteorological Service (SMN, Argentina).

Table 1. Summary of the dataset used for analysis.

Data type	**Serie**	**Resolution**		**Source**	**Reference**
		Spatial	**Temporal**		
Gridded climate series	Standardized Precipitation and Evapotranspiration Index (SPEI)	25 km	Monthly 2000-2021	Sistemas de Información sobre Sequías para el Sur de Sudamérica (SISSA)	https://sissa.crc-sas.org/
	Standardized Precipitation and Evapotranspiration Index (SPEI)	0,5°	Monthly 2000-2021	Consejo Superior de Investigaciones Científicas de España (CSIC)	Vicente Serrano *et al.* (2010)
Global climate indices	El Niño Oceanic Index (ONI)	---	Monthly 2000-2021	Climate Prediction Center (CPC), NOAA	NOAA (2022)
Global environmental indices and maps	Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI)	250 m	Monthly 2000-2021	Sistema de Análisis Temporal de Vegetación (Brazil)	https://www.satveg.cnptia.embrapa.br/satveg/login.html
	CCI Land Cover products v2.0.7	300 m	1992-2015	European Space Agency (ESA)	https://www.esa-landcover-cci.org/?q=node/164
Global information on fires	Fire Information for Resource Management Systems (FIRMS)	250 m	Daily 2000-2021	Earth Data, NASA	https://www.earthdata.nasa.gov/learn/find-data/near-real-time/firms

2.3. Methods

2.3.1. Climate analysis

The analysis of climate variability involved detecting dry and wet events based on gridded series of the Standardized Precipitation and Evapotranspiration Index (SPEI) using time scales of 3 and 12 months. Hereafter, these series are referred to as SPEI-3 and SPEI-12, respectively. Gridded SPEI series were provided by the CSIC and the SISSA (Table 1) and were used comparatively because of their global and regional relevance, respectively. Initially, SISSA and CSIC data sets were compared to inspect the degree of agreement between regional and international gridded SPEI series. In the second step, the quality of the regional SPEI series was evaluated based on *in-situ* observations. Meteorological data is available for three stations strategically located in the North (Bahía Blanca), the Centre (Hilario Ascasubi) and the South (Viedma) of the study area (Fig. 1). Irrespective of their reduced number, these stations provide a valuable set of records *in situ* to validate the accuracy of regional SPEI series. For each station, the SPEI was calculated following the equation of Vicente-Serrano *et al.* (2010) as follows:

$$SPEI = W - C0 + C1 + C2W21 + d1W + d2W2 + d3W3' \qquad (1)$$

where W = -2ln (P), P is the probability of exceeding a specific D, and D is the difference between precipitation and potential evaporation. The constants C and d are: C0 = 2.515517, C1 = 0.802853, C2 = 0.010328, d1 = 1.432788, d2 = 0.189269, and d3 = 0.001308. The quality of the gridded SPEI series was evaluated using the Pearson and Spearman correlation coefficients, the Concordance index, and the determination coefficient R^2.

The regional series of the SPEI were averaged into one series accounting for mean regional SPEI values for each time scale (3 and 12 months) over the 22-yr analysis period (2000-2021). Dry and wet events were determined based on deviations of mean regional SPEI-3 and SPEI-12 values, as shown in Table 2. The characteristics of such events (intensity, duration and magnitude) were determined using the methodology described by Aliaga *et al.* (2017). SPEI-3 series allow evaluation of the succession of seasonal dry and wet events affecting the soil moisture content. They are beneficial for inspecting for associations between climate variability and vegetation states. SPEI-12 series aggregate the effects of seasonality on an annual scale, allowing determining key events exhibiting contrasting hydroclimatic conditions. For the study, key events are selected based on extreme hydroclimatic conditions, i.e., events showing the lowest and the highest values of the SPEI-12.

The relationship between climate variability and varying phases of ENSO was analyzed based on cross-correlations between the series of the SPEI and El Niño Oceanic Index (ONI). According to the ONI, a warm ENSO event (El Niño) occurs when the index remains above 0.5 for five consecutive months or more, while a cold ENSO event (La Niña) occurs when the index remains below -0.5 for the same period. The association between SPEI-based climate events and ONI-based ENSO phases was measured using tests on contingency tables (Chi-square). The frequency of months classing as a given event under Niño, Niña and neutral conditions allowed inspecting for the ENSO influence on the regional climate variability.

Table 2. Classification criteria for dry and wet climate events according to SPEI values

Type of event	**Intensity**	**SPEI value**	**Probability of occurrence**
Dry	Extreme drought (ED)	SPEI < -1.5	0.067
	Severe drought (SD).	-1.5 < SPEI < -1	0.092
	Moderate drought (MD)	-1.0 < SPEI < -0.5	0.18
Normal	Normal (N)	-0.5 < SPEI < 0.5	0.38
Wet	Moderate wet (MW)	0.5 < SPEI < 1.0	0.18
	Severe wet (SW)	1.0 < SPEI < 1.5	0.092
	Extreme wet (EW)	SPEI > 1.5	0.067

2.3.2. Environmental analysis

We inspected for variations in two spectral indices, the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI), to determine the association between vegetation status, health, and climate variability. NDVI and EVI series were aggregated at the regional scale to ensure compatibility with SPEI gridded series. Both NDVI and EVI series were classed into five status categories based on the mean (μ) and the standard deviation (σ). Vegetation status classes range from very low (μ-2 σ) to very high (μ+2 σ). Associations between vegetation classes and SPEI-based climate events were determined based on tests on contingency tables (Chi-square). In addition, we measured variations in the surface extent of land cover types for the key events determined by climate analysis.

2.3.3. Fire analysis

The nature of fires in southern Pampas (intensity, extent, and duration) was analyzed for two key events defining extreme dry and extreme wet scenarios. Active fire products provided by MODIS and VIIRS satellites were analyzed along with thermal anomaly products to detect fire events, their extent, and their duration. We used WorldView and FIRM's websites to perform these analyses. The latter allowed for the location of fires and the study of their spatiotemporal evolution.

The fires were studied considering i) the number of fires, determined by the number of fire spots identified throughout the events, ii) their intensity, represented by the average value of the fires measured in MW, iii) their extension, measured in km^2, determining the area affected by the fires, iv) the fire season, defined from the temporal extension in months with the presence of fires, and v) the brightness temperature (°K) indicating the average energy of the fire spots. Finally, the satellite products were analyzed to identify fire spots. They were located according to their intensity using ArcGIS 10.3 software.

3. Results

The following sections present the results from the spatiotemporal evolution of fires in the southern pampas. The effects of climatic variability on vegetation health and soil cover extent are analyzed, and the quantity, intensity, and size of fires during different climatic events are identified.

Before analysis, we inspected the quality of regional gridded SPEI series (SISSA) considering their agreement relative to global data sets (SCIC) and their accuracy relative to the SPEI calculated from meteorological records *in situ*. The spatiotemporal behaviour of regional and global SPEI series exhibited an excellent correlation, with Pearson and Spearman values of 0.91 and 0.89, respectively, a Concordance of 0.88, and an R^2 of 0.89, considering the SPEI-12 scale. Regional series from SISSA also exhibited a good correlation with *in-situ* data, although the SPEI-3 series showed lower adjustment than the SPEI-12 series. Pearson and Spearman's correlations were 0.79 and 0.81 for SPEI-3 and 0.93 and 0.95 for SPEI-12, respectively. The Concordance was 0.74 for SPEI-3 and 0.91 for SPEI-12, and the R^2 was 0.88 and 0.95, respectively. Irrespective of these differences, both SPEI-3 and SPEI-12 series exhibit reasonable adjustment.

3.1. Climate variability: extreme events and their relationship to the ENSO phenomenon

The marked climate variability characteristic of the southern Pampas is evidenced by both the SPEI-3 and the SPEI-12 series (Fig. 2). Note that an *event* begins when the SPEI value for a given month classifies under a given category that is different from the previous month and ends when that category changes in the subsequent month. It is also vital to notice that climate events may be referred to as individual events, defined by the intensity of the SPEI (Table 2) or as types of events, namely wet and dry, represented by the direction of the SPEI and its persistence above or below normal conditions, respectively. In this regard, *wet events* refer to a continuous succession of months classing as MW, SW and/or EW, whilst *dry events* refer to a constant sequence of months classing as MD, SD and/or ED.

The march of the SPEI-3 along the 22 years of analysis registers 27 wet events (from which 5 were extreme), 32 dry events (from which eight were extreme), and 53 normal events (Fig. 2). On average, wet events exhibited an intensity of 0.9 for a 2.6-month duration, reaching maximum period (12 months) and extreme values (2.2) in 2014-2015. Dry events were slightly longer (2.7 months, on average) and intense (-1.0, on average), although the driest events (2009 and 2014) exhibited smaller values (-2.0) and duration (4 months). Climate events defined by the SPEI-12 series were smaller in number than for SPEI-3 but notably greater in duration (Fig. 2). The series accounts for 11 wet events that average 5.8-month duration. From these, two events were classed as extreme, although the event of 2014-2015 exhibited the greatest duration (17 months) and the highest SPEI-12 value of the series. Dry events were greater in number (15 events) and longer in duration, persisting over 7.0 months, on average. Although the series registers two extreme dry events, the most marked drought occurred in 2008-2009, persisting over 23 consecutive months and reaching up to -2.5. This event and the extreme wet event of 2014-2015 define two key events of contrasting hydroclimatic conditions on which to base fire analyses.

Correlations between SPEI-based climate events and the ONI in southern Pampas are low yet statistically significant (for $\alpha = 0.05$), with the best Pearson coefficients obtained for a lagged ONI of -2 (0.22; SPEI-3) and -7 (0.30; SPEI-12). Table 3 summarizes the proportion of months under varying climate events and varying phases of the ENSO phenomenon, determined from deviations of lagged ONI series. Most dry events occur under La Niña and neutral conditions for both time scales of the SPEI, following a similar trend to that observed for Southeastern South America. In opposition to what was expected, wet events do not exhibit clear associations with El Niño phases, as most occur under neutral ENSO phases. This indicates the influence of other large-scale atmospheric phenomena on precipitation extremes whose analysis exceeds the scope of the present study. Irrespective of these broad associations, key dry conditions (2008-09) occurred under negative ONI conditions (La Niña event), while key wet conditions (2014-15) occurred under positive ONI conditions (El Niño event).

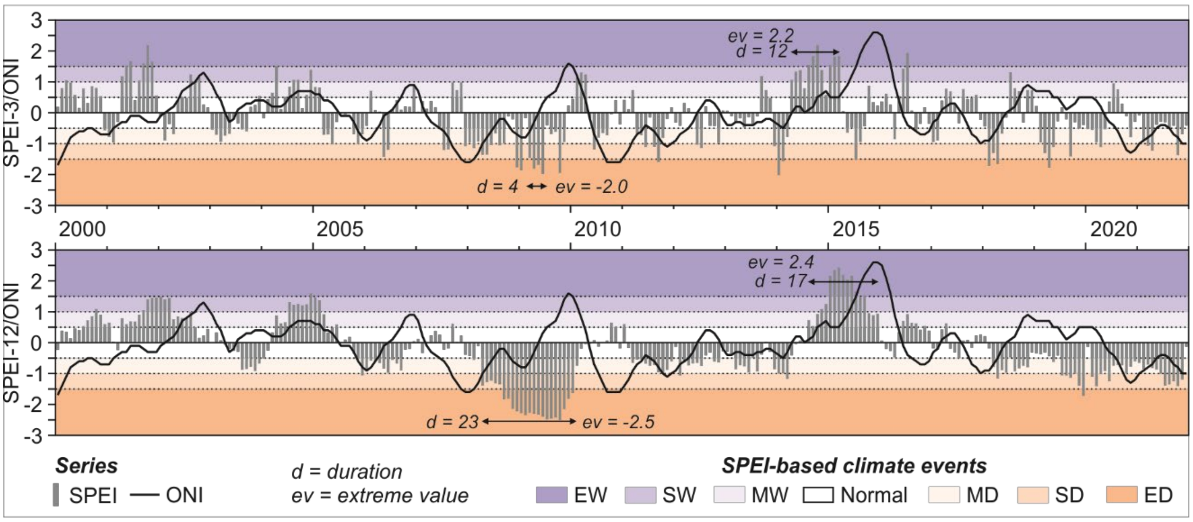

Figure 2. Distribution of the SPEI for two temporal scales (3 and 12 months) in the southern pampas and series of ONI over 2000-2021.

Table 3. Frequency of months (%) classing under varying SPEI-based climate events by ONI-BASED ENSO phases in the southern Pampas (2000-2021 period)

	ENSO phase				ENSO phase		
SPEI-3	Niña	Neutral	Niño	***SPEI-12***	Niña	Neutral	Niño
EW	0.0	**76.9**	23.1	EW	0.0	**55.6**	44.4
SW	10.5	42.1	**47.4**	SW	11.1	**77.8**	11.1
MW	31.6	**42.1**	26.3	MW	35.1	**35.1**	29.7
Normal	31.8	**48.6**	19.6	Normal	21.6	**44.3**	34.0
MD	36.2	**38.3**	25.5	MD	**49.2**	44.4	6.3
SD	**55.6**	37.0	7.4	SD	**50.0**	29.2	20.8
ED	**46.2**	30.8	23.1	ED	**56.3**	37.5	6.3

3.2. Environmental impacts

The EVI and NDVI series trend exhibits the seasonality characteristic of temperate climates. However, the intensity of the peaks is closely related to the interannual climate variability of the region (Fig. 3). Pearson correlation coefficients of EVI and NDVI series to SPEI-3 series were significant (for $\alpha = 0.05$), reaching 0.58 and 0.50, respectively. The lowest values occurred in 2008-2009 for both series, according to the most intense drought recorded along the analysis period (key dry conditions), while the highest peaks matched the maximum positive deviations of the SPEI-3 in 2014-2015 (key wet conditions).

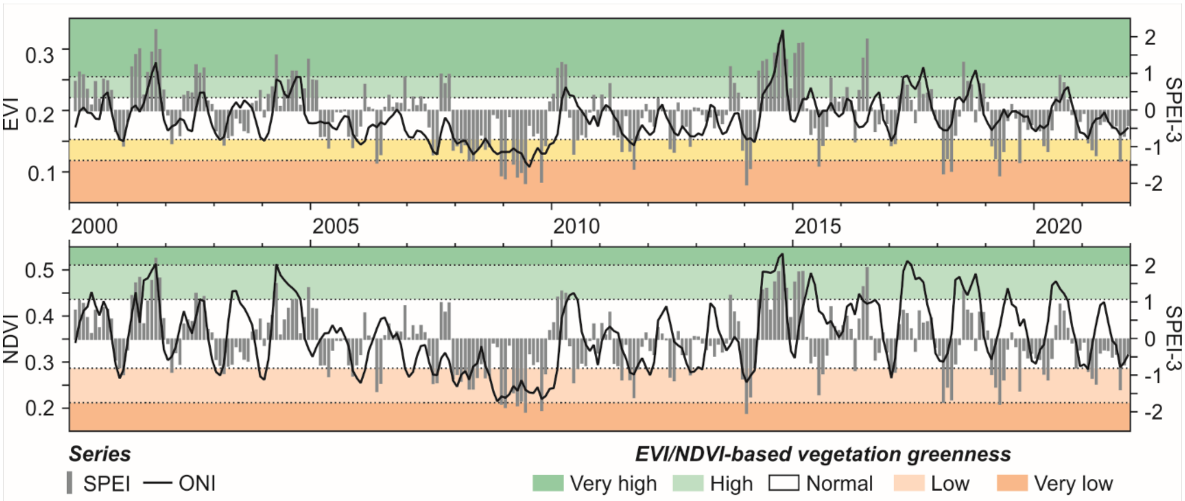

Figure 3. Distribution of NDVI and EVI for the 2000-2021 period for the southern pampas.

The behaviour of both spectral indices, EVI and NDVI, strongly correlates to the succession of wet and dry events (Table 4). For example, vegetation greenness above normal conditions matches wet climate conditions for most cases and for both indices, with the strongest associations occurring for very high greenness and extremely wet climate. On the other side of the scale, most cases where vegetation greenness is below normal conditions occur under dry climate conditions. However, vegetation-climate associations for dryness are less clear than those for wetness. Very low EVI values match extreme dry events by 50 % of cases, whilst the remaining proportion occurs under normal climate. Regarding the NDVI, the series does not account for very low values so that interpretations may be awkward.

Changes in land cover were analyzed considering the two key events defined by climate variability analysis. The most remarkable differences between extreme dry and extreme wet conditions were observed in the central and western regions, where scrublands contracted in extent against the expansion of croplands (Fig. 4). The importance of land cover areas showed remarkable differences. For example, shrublands covered a much larger size during the dry period (14,087 km²) and contracted by 11,8 % under extreme wet conditions. In opposition, cropland and mosaic cropland cover was lower under extremely dry conditions, increasing by 19,6 % under wetter climates (8,268 and 9,890 km², respectively).

Table 4. Monthly frequency (%) by the value of (a) EVI and (b) NDVI, according to climatic events based on SPEI-3 series for the southern pampas (2000-2021 period)

(a) EVI	EW	SW	MW	Normal	MD	SD	ED
Very high	**62.5**	0.0	12.5	25.0	0.0	0.0	0.0
High	5.9	26.5	**32.4**	26.5	5.9	2.9	0.0
Normal	3.3	5.4	13.6	**46.7**	17.9	9.8	3.3
Low	0.0	0.0	2.9	22.9	**34.3**	22.9	17.1
Very low	0.0	0.0	0.0	**50.0**	0.0	0.0	**50.0**

(b) NDVI	EW	SW	MW	Normal	MD	SD	ED
Very high	**66.7**	0.0	16.7	16.7	0.0	0.0	0.0
High	7.5	17.5	27.5	**35.0**	10.0	2.5	0.0
Normal	3.6	7.1	13.7	**46.4**	16.7	10.1	2.4
Low	0.0	0.0	6.1	26.5	**30.6**	18.4	18.4

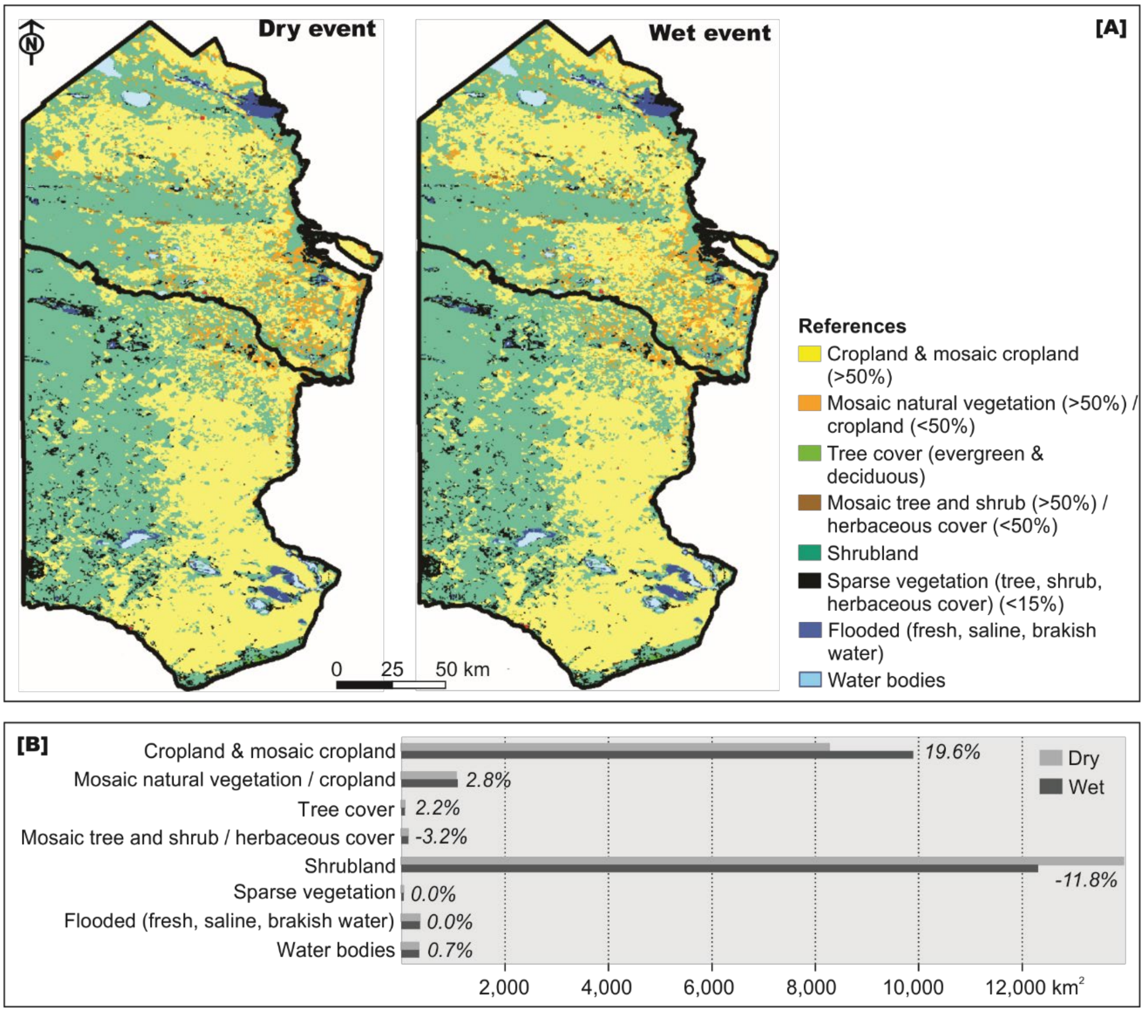

Figure 4. [A] Land cover maps for key dry and wet events, and [B] surface extent by land cover class and percent variation between events. Land cover classes were modified from those provided on the ESA/CCI.

3.3. Characterization of fires

Fire analysis was performed for the two key events defined from climate variability analysis, 2008-09 (key dry year) and 2014-2015 (key wet year). It is noticeable that climate fluctuations along with the changes in vegetation and land cover, generate different scenarios where fires have very different impacts (Table 5). During the 2014-2015 event, there were twice as many fires as in 2008-2009 (460 and 206, respectively). The intensity of the fires was ten times higher in the wet event than in the dry one, while the affected area was doubled on the surface. In addition, the fire season was two months longer under extreme wetness than under extreme dryness. All these results are related to the agricultural activities in the study area. As a semiarid and subhumid area, wet events create favourable environmental conditions for crop planting. These results suggest that the area could be affected by a complex combination of wildfires and agricultural fires, including controlled and uncontrolled burns.

Table 5. Characteristics of fires, vegetation, and rainfall events in extreme dry period (2008-2009) and extreme wet period (2014-2015). Results are the addition or the average of each period

Characteristics	2008-2009 (ED)	2014-2015 (EW)
Number of fires	205	460
Intensity (MW)	31.5	302.6
The extension (km^2)	815.5	1722
Fire season (months)	6	8
Brightness temperature (°K)	302.3	336.2
NDVI	0.29	0.41
EVI	0.15	0.21
ONI	-0.24	0.78
SPEI-12	-2.22	1.52

The frequency of fires, their location, and their relationship with the SPEI during extreme wet and dry events were analyzed. Marked differences were observed. The extreme wet event (EW) was characterized by presenting higher values of SPEI > 1.5 all over the study area. The fires were more intense and were mainly located in the west and south of the study area, coinciding with shrub cover. Similarly, the centre of the study area presented fires of great intensity. That is because the irrigated crop areas are located in that region (Fig. 5). On the other hand, in the extreme dry event (ED), the SPEI values were consistently below -1.5. The most extreme values were located in the centre of the study area, marking an event of great intensity, with areas where the SPEI was less than -2.5. In this scenario, vegetation presented minimum values of NDVI and EVI, and the environmental conditions of drought generated the occurrence of fires but of low intensity. Most of the fires had an intensity of 3.3 to 55 MW and were scattered in location. As in the EW period, the highest-intensity fires were located west and south of the study area (Fig. 5).

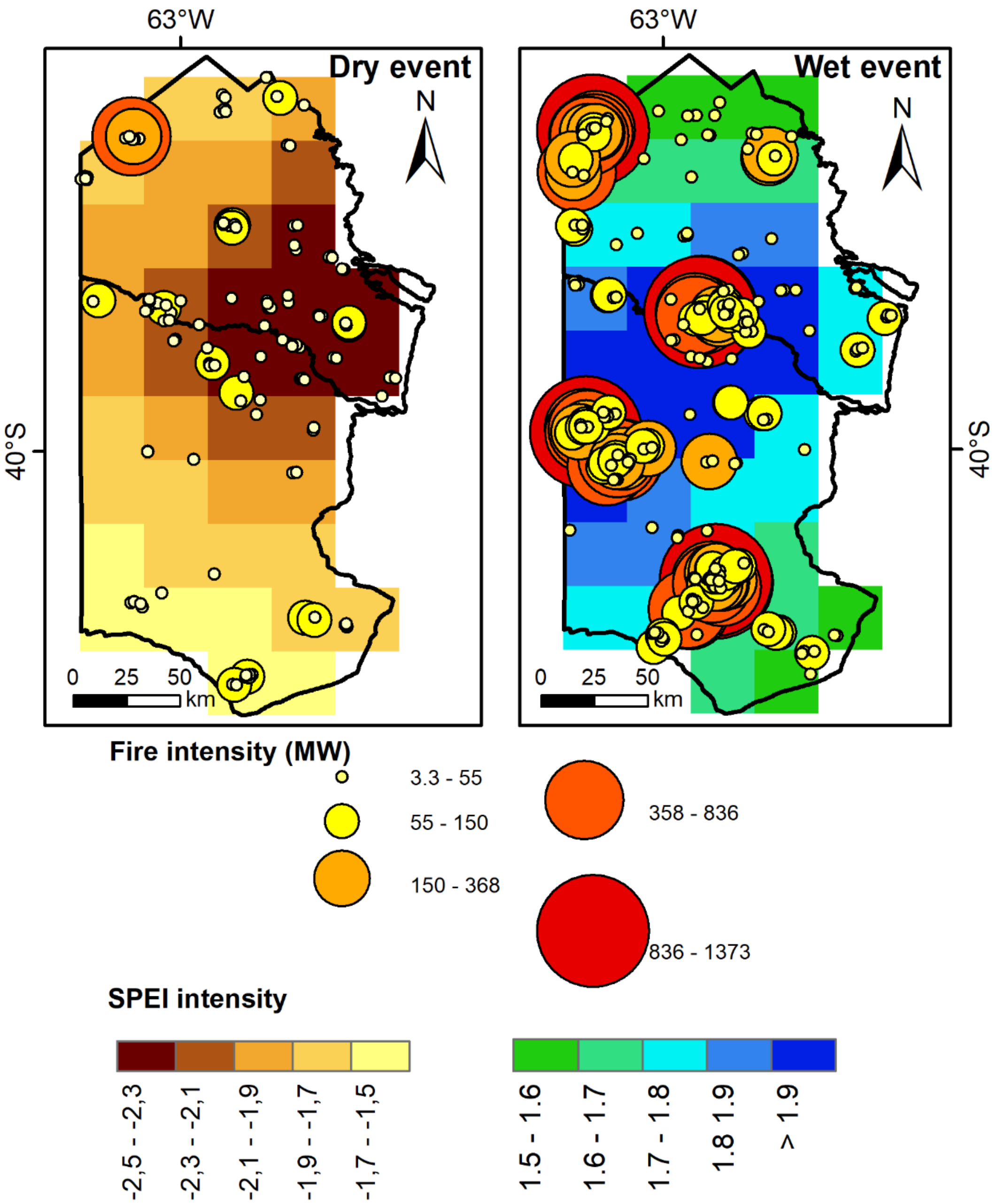

Figure 5. Fire intensity and rainfall events in the southern pampas during dry (2008-2009) and wet (2014-2015) events.

4. Discussion

4.1. Climate variability and its effects on soil, water and vegetation

This study has investigated the influence of climate variability on fire generation in southern Pampas. The area is not only in transition, but is also affected by marked climate variability, with conditions ranging from arid to humid. There may be 300 mm of rainfall in one year, while the following year could bring 1000 mm (Aliaga *et al.*, 2017; Ferrelli *et al.*, 2021). As a result, the vegetation varies between very low vigour and very high vigour. An interesting factor is the changes in land use: during wet periods, agriculture expands over natural vegetation, while during dry periods, agriculture contracts, and shrublands thrive. This creates two complex scenarios for the occurrence of fires. It is evident that during dry periods, the number of fires is lower (perhaps due to fewer controlled burns related to agriculture activities), and the intensity is also lower (possibly due to less combustible material). In wet periods, the number of fires increases (because of increased agriculture) as well as their intensity (more considerable amount of vegetation available to burn) (Pezzola and Winschel, 2004).

Results suggest that the spatial and temporal fire dynamics within this complex environment are also complex, and different from what is observed on a global, national, and regional scale. In these arid and semiarid ecosystems, fires are primarily agricultural and caused by complex interactions between climate variability, soil moisture content, vegetation cover and greenness, meteorological conditions, and crop and grazing management practices (Bran *et al.*, 2007; Delegido *et al.*, 2018). Climate variability is marked and evidenced both in space and in time. Spatial climate variability is given by the transition from humid and warm northeastern pampas to arid and cold southwestern Patagonian features (Aliaga *et al.*, 2016), with differences of up to 400 mm in mean annual rainfall and up to 1.7 ºC in mean annual temperature (Aliaga *et al.*, 2017; Ferrelli *et al.*, 2019). Time climate variability responds to the complex influence of regional and global atmospheric phenomena (Wu *et al.*, 2022), resulting in rainfall and temperature variations that occur at nested seasonal, annual, and interannual scales (Ferrelli *et al.*, 2021). Whilst vegetation cover types express regional climate and soil features, the extent and greenness of vegetation cover are an expression of climate variability affecting the soil moisture content within a season, within a year, or between seasons and years. In this point, it is interesting to highlight the difference between meteorological drought, involving rainfall shortfalls that affect the soil moisture content, and hydrological drought, involving a long-standing water deficit that affects not only the soil moisture, but also the sources of freshwater (Andrade *et al.*, 2015; Brendel *et al.*, 2019). In this regard, a meteorological drought will result in a drying of vegetation that grows under normal or wet conditions.

In contrast, a hydrological drought will prevent vegetation growth and spread. Finally, irrigation plays a fundamental role in areas affected by climate variability. It provides a vital solution to ensure a consistent water supply to crops, especially in regions with insufficient or irregular precipitation. In non-irrigated areas, adaptation to this climate variability is achieved through a combination of grazing and cultivation practices. In southern Pampas, for example, grazing becomes a primary strategy during dry periods. Animals feed on natural vegetation, making the most of any available resources. This adaptation allows for maintaining a certain level of livestock production even in adverse climatic conditions (Foucher *et al.*, 2023).

On the other hand, during wet periods, the increased water availability is utilized for cultivation. Farmers use soil fertility and favourable conditions to grow crops such as cereals, oilseeds, and forages. This helps diversify production and make the most of available resources during these periods (Scherger *et al.*, 2022). However, it is essential to note that exclusive reliance on climate variability can have limitations. Controlled and planned irrigation remains an efficient and reliable solution to ensure agricultural production in areas affected by extreme climate variability. It allows for proper water distribution, maximizes crop yields, and reduces risks associated with climate fluctuations.

4.2. Fires generation – Myths and Facts

Both wild and agricultural fires occur periodically and model the regional landscape by affecting the balance between crops, pastures, natural grasslands, and shrublands (Pezzola and Winschel, 2004; Delegido *et al.*, 2018). This study suggests, however, the coexistence of two contrasting scenarios for fire generation, intensity and extent that result from varying land cover and land use dynamics as a consequence of a variable climate. Fires are more significant in number, size and intensity under wet climate conditions, as rainfed croplands and grasslands mosaics expand over much of the natural shrublands, exhibiting their highest vigour even if reduced in extent. For example, in addition to the 460 fire events detected during the key wet period selected for this study (2014-2015), a series of thunderstorms that took place in the context of a meteorological drought resulted in a large-scale fire that affected more than 30,000 km^2 between December 2016 and January 2017 (Delegido *et al.*, 2018). The magnitude of most fire effects is related to the prior land use condition of the plot (for example, whether the land was used for grazing or for extracting firewood as fuel), the accumulation of dry matter, density and size of woody species, the proliferation of refined fuel before the fire, as well as the environmental conditions at the time of the incident (Vanzolini *et al.*, 2017). In much of the region, the high density of shrubs makes it difficult for livestock to access and consume the forage provided by the natural grassland (Kröpfl *et al.*, 2007), increasing combustible material. In opposition, the water stress caused by long-standing drought conditions prevents rainfed agricultural practices and vegetation development other than natural shrublands, which in turn lose their vigour. Consequently, fire generation under such conditions is less likely to occur because the fuel material is reduced relative to wetter periods.

In southern Pampas, legislation regarding fire prevention is based on meteorological indices that consider short-term drought conditions. However, this study has shown that initial drought conditions do not increase the number and intensity of fires. For such an increase, sustained periods of normal or wet weather conditions are required. In this scenario, vegetation can thrive, and the environmental conditions favour intensive farming and grazing activities in dryland areas.

Therefore, this study has demonstrated the importance of considering climate variability beyond just meteorological conditions and anticipating the occurrence of these periods to develop effective land management plans. Resource managers and fire experts are facing new challenges when effectively applying current climate science and fire ecology to adapt their day-to-day practices. To address these challenges, the Adaptation Strategies and Approaches for Managing Fire in a Changing Climate (Sample *et al.*, 2022) offers a comprehensive fire menu encompassing the concepts of resistance, resilience, and transition. It establishes clear connections between these concepts and actionable steps, identified as strengths by workshop participants during the workshop's reflection phase. Additionally, the group expressed a keen interest in ongoing collaboration as part of the Kaibab Climate Workgroup, ensuring continued regional discussions, scientific advancements, and management efforts related to fire and climate adaptation. This includes sharing the Fire Menu and Adaptation Workbook process with other audiences to further progress in the field (Sample *et al.*, 2022).

In Argentina, the National Forest and Rural Fires Law 26815 in the 2nd Article Scope consider the actions and operations related to prevention, pre-suppression, and firefighting of forest and rural fires that burn live or dead vegetation in native and planted forests, protected natural areas, agricultural zones, meadows, grasslands, shrublands, wetlands, and areas where building structures are intermingled with vegetation outside strictly urban or structural environments. It also covers planned fires that can burn under previously established environmental conditions, aiming to achieve management objectives for a territorial unit.

Is in this context where Fire Hazard Assessment and Early Warning Plans are crucial components of effective fire management strategies. These plans assess the potential risk and danger of fires in specific areas and provide timely warnings to minimize the impact and damage (Lestienne *et al.*, 2022). Fire Hazard Assessment involves evaluating various factors such as weather conditions, fuel availability, topography, and historical fire data to determine the likelihood and severity of fire incidents. It identifies high-risk areas and prioritises resources for prevention, preparedness, and response efforts (Ribeiro *et al.*, 2022).

Early Warning Plans are developed based on the fire hazard assessment results. They outline the procedures and protocols for detecting and monitoring fire activity and issuing timely warnings to relevant authorities, communities, and emergency responders. Early warning systems often incorporate various technologies, such as remote sensing, meteorological data, and fire behaviour modelling, to detect and predict fire incidents (Chen *et al.*, 2022).

4.3. A look beyond climate variability: fire generation and climate change

Climate change has become one of the world's most serious environmental problems (Wang *et al.*, 2013). Evidence of a progressive increase in air temperature affects mainly economic and agricultural activities, increasing negative impacts on the population's quality of life (Worku *et al.*, 2018; IPCC, 2021). In this context, it is essential to highlight that the increase in greenhouse gases released into the atmosphere due to anthropogenic activity has intensified the adverse effects related to climate change (IPCC, 2021). The temperature increase has been homogeneous worldwide. This warming is closely related to the occurrence of fires, given that the thermal expansion translates into a greater ignition power that increases the number and intensity of fires (Masson-Delmotte *et al.*, 2018). In this context, it is essential to note that the risk of fires will increase by 74 % by the end of this century (Xu *et al.*, 2020).

The study of these events is relevant because they directly impact the population's health. We highlight the affections of physical implications (burns, injuries), mental health (post-traumatic stress), and even loss of life resulting from flame exposure. Fires also require more significant planning of medical assistance services and public and private investments to repair, for example, property damage (Abatan *et al.*, 2016; Xu *et al.*, 2020). The effects on the population are also related to the generation and spread of smoke. That can affect people's health in areas far from the fires (Xu *et al.*, 2020).

In the literature, there is evidence that forest and agricultural fires are typical in Argentina. The generation of these events is directly related to prolonged droughts and the consequent succession of electrical storms that act as an ignition mechanism (Delegido *et al.*, 2018; Garay, 2020). Particularly in the Pampas region, fires are periodic and are generated due to soil conditions, changes in soil moisture, and changes in land cover (Ferrelli *et al.*, 2022). The events of greater magnitude occur during prolonged periods of drought in the grassland ecoregion (Bert *et al.*, 2021).

There is evidence that southern Pampas is subject to strong signals of global warming that will increase in future scenarios (Ferrelli *et al.*, 2021). Along with this, the change in the rainfall pattern will impact the current development of economic activities since a reduction in annual precipitation amounts and an increase in more severe and intense daily rainfall events (Ferrelli *et al.*, 2020). The fertile areas of southern Pampas are closely linked to rainfall variability. An increase in cultivated areas during wet periods has been recorded, drastically reducing pasture coverage (Ferrelli, 2017). In contrast, dry and extremely dry events have reduced crops affecting the region's economy and negatively impacting the population due to suspended dust from soil erosion processes.

5. Conclusion

Fires were studied in an area of high relevance due to their agricultural and livestock activities. Remote sensing techniques allowed us to identify and quantify fires' number, intensity, and magnitude in different rainfall periods. The SPEI proved to be a good indicator of these events because it considers precipitation and evapotranspiration. It is relevant to highlight that dry and wet events in southern Pampas are not linked with the fluctuation of the ONI index.

The land cover showed spatial and temporal variations related to different rainfall events generated in the study area. It was evident that crops occupy more in rainy periods, while shrubs cover the most extensive area during extreme droughts.

For those mentioned above, southern Pampa is an area that challenges the generalities established in the literature. In contrast to what happens in the rest of the world, this area has more fires of greater magnitude and intensity during severe rain events. They are closely related to increased agricultural and livestock activities and are generated by replacing grasslands with crop cover. In contrast, during drought events, shrubs occupy a more significant amount of surface area. However, the lack of combustible material, together with vegetation characteristics in Argentina's semiarid regions, means that fires are not as intense as those observed elsewhere in the world.

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BURYING THE CARBON TO DIG UP THE FUTURE: REVIEWING THE ROLE OF GEOGRAPHY IN VALUING SOIL CARBON ECOSYSTEM SERVICES

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ABSTRACT. Soil carbon sequestration presents a pathway towards climate change mitigation and adaptation while also fostering sustainable socio-economic development. The emergence of soil carbon markets, which monetize carbon capture and land management practices, has given new impetus to this area of study. However, the intersection of environmental, social, and economic systems inherent to soil carbon markets introduces significant complexities. To understand the research landscape and the prevailing themes within the field, we conducted a systematic literature review, sourcing articles from the Web of Science and SCOPUS databases that focused on soil carbon markets, published between January 2017 and august 2023. Our analysis revealed three primary research themes emerged: 1) Soil Ecosystem Services (61%), closely associated with the agricultural and environmental sciences; 2) Environmental Economics (21%) show the growing focus on economic valuation of ecosystem services since the Paris Agreement; and 3) Exploratory Analyses (18%) highlight recent efforts in dealing with the complex network of environmental, social, economic, political and cultural factors. However, these areas of research are often treated separately, reflecting a broader disconnect between natural and social sciences: Geography, uniquely positioned at the intersection of natural and social sciences, could bridge this divide. Through a geographical lens, one can better comprehend drivers behind land management and land-use changes and how they relate to environmental indicators and soil carbon markets. In the social sciences, cultural aspects that shape soil management practices, farmers' relationships with land and markets, and their engagement with soil carbon markets could be examined to predict actions towards improving environmental performance indicators. These settings are highly local, influenced by factors like land tenure rights, landscape ecology, political settings, and power dynamics. Geography's role extends beyond merely understanding these local factors. It also involves studying 'space' and 'place', concepts that are crucial in the context of soil carbon markets. Within the framework of complexity theory and spatial agent-based modelling for socio-ecological systems, Geography can provide valuable insights into how different entities within soil carbon markets interact and influence each other. In the context of climate change, soil ecosystem services, and by extension soil carbon markets, can influence social and economic vulnerabilities. An integrated study of land use, management practices, and their impact on soil ecosystem services, using both quantitative and qualitative approaches, can provide insights into social behaviour and ecosystem responses over time.

Enterrando el carbono para desenterrar el futuro: Revisando el papel de la geografía en la valoración de los servicios ecosistémicos de carbono del suelo

RESUMEN. El secuestro de carbono en el suelo puede ser un camino hacia la adaptación y mitigación del cambio climático, al mismo tiempo que puede fomentar el desarrollo socioeconómico sostenible. La aparición de los mercados de carbono del suelo, que monetizan la captura del carbono y las prácticas de gestión de la tierra, ha dado un nuevo impulso a esta área de estudio. Sin embargo, la intersección de los sistemas ambientales, sociales y económicos inherentes a los mercados de carbono del suelo introduce complejidades significativas. Para comprender el estado de la investigación y los temas predominantes en este campo, se realizó una revisión sistemática de la literatura científica, obteniendo artículos de la Web of Science y de las bases de datos de SCOPUS centrados en los mercados de carbono del suelo, publicados entre enero de 2017 y agosto de 2023. Nuestro análisis reveló tres ámbitos principales de investigación: 1) Servicios ecosistémicos del suelo (61%), estrechamente relacionados con las ciencias agrícolas y ambientales; 2) Economía ambiental (21%) que muestra el creciente enfoque en la valoración económica de los servicios de los ecosistemas desde el Acuerdo de París; y 3) Análisis exploratorios (18%) que resaltan los esfuerzos recientes en el tratamiento de la compleja red de factores ambientales, sociales, económicos, políticos y culturales. Sin embargo, estas áreas de investigación a menudo se tratan por separado, lo que refleja una desconexión más amplia entre las ciencias naturales y sociales: la Geografía, posicionada de manera única en la intersección de las ciencias naturales y sociales, podría salvar esta brecha. A través de una visión geográfica, se puede comprender mejor los impulsores que están detrás de la gestión de la tierra y de los cambios en el uso del suelo y cómo se relacionan con los indicadores ambientales y los mercados del carbono del suelo. En las ciencias sociales, los aspectos culturales que configuran las prácticas de gestión del suelo, las relaciones de los agricultores con la tierra y los mercados, y su compromiso con los mercados del carbono del suelo pueden ser examinados para predecir las acciones de mejora de los indicadores de comportamiento ambiental. Estos parámetros son altamente locales, influenciados por factores como los derechos de tenencia de la tierra, la ecología del paisaje, los entornos políticos y las dinámicas de poder. El papel de la Geografía va más allá de la mera comprensión de estos factores locales. También implica estudiar el espacio y el lugar, conceptos que son cruciales en el contexto de los mercados de carbono del suelo. En el marco de la teoría de la complejidad y la modelización espacial basada en agentes para sistemas socioecológicos, la Geografía puede proporcionar información valiosa sobre cómo interactúan e influyen entre sí diferentes entidades dentro de los mercados de carbono del suelo. En el contexto del cambio climático, los servicios de los ecosistemas del suelo y, por extensión, los mercados de carbono del suelo pueden influir en las vulnerabilidades sociales y económicas. Un estudio integrado del uso de la tierra, las prácticas de ordenación y su impacto en los servicios de los ecosistemas del suelo, utilizando enfoques cuantitativos y cualitativos, puede proporcionar información sobre el comportamiento social y las respuestas de los ecosistemas a lo largo del tiempo.

Keywords: Soil carbon sequestration, soil carbon markets, environmental Geography, climate change mitigation, land management practices.

Palabras clave: Secuestro de carbono del suelo, mercados de carbono del suelo, Geografía ambiental, mitigación del cambio climático, prácticas de gestión de la tierra.

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1. Introduction

The global discourse surrounding Climate Change Mitigation and Adaptation has been gaining momentum since the early 1990s. This increased attention is primarily fuelled by the collective understanding of a changing climate that is predicted to become warmer and drier. Consequently, the scientific community's focus has gravitated towards strategies to mitigate climate change's causes and adapt to its inevitable effects (Lobell *et al.,* 2013; Smith *et al.,* 2020; Tubiello, 2012). In response to these pressing concerns, according to the International Panel to Combat Climate Change (IPCC), mitigation strategies are typically classified into two distinct categories. The first pertains to efforts to reduce emissions of greenhouse gases, and the second involves the removal of a proportion of the existing atmospheric greenhouse gases. In contrast, adaptation to climate change involves comprehending the potential responses of natural ecosystems to climate forcings and designing strategies to navigate these changes.

The Agriculture, Forestry and Other Land Use (AFOLU) sector is at the forefront of climate change mitigation options. This sector accounts for over 24% of global greenhouse gas emissions, second only to the Energy sector (IPCC, 2014), and directly impacts the three fundamental components of the global carbon cycle, namely soil, biomass, and the atmosphere. The carbon storage capacity of soils surpasses the combined total of atmospheric and biomass pools (Lal, 2010; Scharlemann *et al.,* 2014). This capacity is maintained for extended periods, thereby making soil an essential tool in carbon sequestration (Lal and Ussiri, 2017).

Historical land use changes, including the transition from natural vegetation to agricultural and urban areas, have led to increased carbon emissions (Arneth *et al.,* 2017). These changes have driven biomass burning and soil erosion, thereby reducing carbon from these vital pools and subsequently releasing it into the atmosphere (Bristow *et al.,* 2016; Drews *et al.,* 2020). Population growth in recent decades has added further pressure on natural ecosystems. The increasing demand for food production often extends to marginal lands, accelerating desertification and leading to productivity and income loss (Kirkby, 2021; Shukla *et al.,* 2019). Consequently, the cycle of intensification and the search for new arable lands continue.

Early research suggested the potential of poor and degraded lands worldwide to capture and store half to two-thirds of historical GHG emissions (Lal, 2004). While contemporary studies challenge the magnitude of this potential and the complexity of soils as adaptive systems introduces uncertainties, there is consensus about the pivotal role of soil carbon sequestration in climate change mitigation (Salvati *et al.,* 2015). The political landscape is gradually aligning with these perspectives, as demonstrated by the "Soil Carbon 4perMille Initiative" of the Paris Agreement (Lal, 2020; Rumpel *et al.,* 2020; Zomer *et al.,* 2017).

The mechanism of carbon trading, originating from the Cap-and-Trade emission reduction schemes of the Kyoto Protocol, has evolved over the years. The growing environmental concerns have paved the way for Voluntary Carbon markets where individuals or corporations can buy carbon offsets for their emissions. However, issues surrounding the additionality, permanence, monitoring, and validation of sequestered carbon have given rise to greenwashing concerns (Fleischman *et al.,* 2020). Despite its reduced presence in voluntary markets, agricultural land remains a potential platform for emission reductions and net atmospheric removal of CO_2, albeit questions about its dimensional relevance and complexity issues arising from working complex adaptive systems with non-linear response to both natural and human forcings (Fearnehough *et al.,* 2020; IATP, 2020; Michaelowa *et al.,* 2019; Venmans *et al.,* 2020).

Although efficacy and relevance concerns surround carbon offset schemes in agricultural land, the potential benefits of land restoration, climate change adaptation, and the redistribution of income from pollutant urban areas to low-density rural regions cannot be overlooked. This is especially true for regions with arid, semiarid, and dry subhumid climates. Areas of the globe that demonstrate environmental sensitivity to climate change and desertification often coincide with low-income developing countries, where the potential benefits of ecosystem services and food security amplify the necessity for soil carbon sequestration approaches.

The complexity of Soil Carbon Sequestration for Climate Change Mitigation and Adaptation requires interdisciplinary understanding, as it intersects environmental, social, economic, and political issues. Navigating this complexity can benefit greatly from the field of Geography, which excels in addressing complex relations within time and space (Cerqueira, 2021). This review explores recent scientific literature on soil carbon capture and storage, its relation to ecosystem services valuation, and carbon markets, as interpreted by the Social Sciences. The objective is to illuminate the potential contributions of Geography and geographical thought.

2. Methods

This study implemented a structured literature review adhering to the PRISMA Guidelines to screen and analyse results from a Web of Science (WoS) Social Science Citation Index (SSCI) and SCOPUS search query that focused on publications from January 2017 to August 2023. Both data sets were processed using an R script to exclude duplicates and organize the articles in alphabetical order of the first author, as well as creating a screening document with the following details: Author(s), Year, Title, Abstract, DOI.

We initiated the first systematic search in December 2021 and updated the final list on August, 2023, ensuring that we captured any additional relevant studies that were published during this period. The exact queries used in the SCOPUS and WoS searches are provided below:

SCOPUS (81 results):	**WoS (97 results):**
Title-Abs	Social Sciences Citation Index (SSCI),
(Soil AND Carbon AND Market*)	From 2017 to 2023.
AND (PubYear > 2016)	(((TI=(soil AND carbon AND market*))
AND (Limit-to(SUBJAREA, "Soci")	OR AB=(soil AND carbon AND market*)))

In addition to this, a secondary search was executed on the SCOPUS database to estimate the volume of scientific work exploring the valuation of soil carbon as an ecosystem service within the Social Sciences discipline. We conducted three different queries on the title and abstract content: "Soil AND Carbon", "Carbon AND Market*", and "Soil AND Carbon AND Markets". The rationale behind this was to assess the thematic variability of the subject, thereby enabling more accurate and informed future queries that can potentially eliminate field biases in the literature search.

3. Results

Our results showed that the interplay between the three keywords indeed allowed different approaches to be taken towards problems of a similar nature. The results and the analysis over the last five years are depicted in Tables 1 and 2, and Figure 1, providing a comprehensive overview of the search findings.

Table 1. Percentage of works associated with each research field in three different queries. at = All Time; 2017-p = 2017 to present day; 2020-p = 2020 to present day.

	Agriculture and Biology				Environment				Earth and Planetary			
	at	2017-p	2020-p	trend	at	2017-p	2020-p	trend	at	2017-p	2020-p	trend
Soil AND Carbon	**54%**	**52%**	**51%**		**45%**	**49%**	**49%**		18%	18%	17%	
Carbon AND Market*	10%	9%	8%		**33%**	**37%**	**37%**		6%	6%	6%	
Soil AND Carbon AND Market*	**48%**	**45%**	**42%**		**49%**	**52%**	**53%**		10%	13%	13%	

	Engineering				Energy				Social			
	at	2017-p	2020-p	trend	at	2017-p	2020-p	trend	at	2017-p	2020-p	trend
Soil AND Carbon	6%	7%	7%		4%	5%	5%		3%	5%	5%	
Carbon AND Market*	31%	32%	33%		**32%**	**36%**	**37%**		14%	15%	15%	
Soil AND Carbon AND Market*	13%	12%	12%		11%	17%	19%		**13%**	**15%**	**15%**	

Table 2. Percent distribution of published work between January 2017 and August 2023.

	2017	2018	2019	2020	2021	2022	2023	trend
Soil AND Carbon	11%	12%	13%	15%	17%	18%	13%	
Carbon AND Market*	9%	9%	11%	13%	17%	24%	17%	
Soil AND Carbon AND Market*	10%	10%	11%	17%	18%	17%	17%	

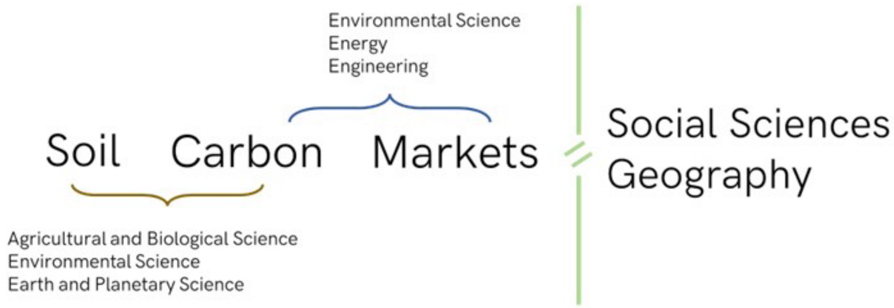

Figure 1. A comprehensive overview of the search findings.

It was observed that issues bridging the environmental and social realms were anticipated to spread research topics across different fields. As depicted in Table 1, "Soil Carbon" was predominantly associated with Agricultural and Biological Sciences, Environment, and, to a lesser extent, Earth, and Planetary Sciences. "Carbon Market*", on the other hand, was associated largely with Environmental Sciences, but also significantly with the Energy and Engineering fields.

When all three keywords were combined in the query, there was a concentration of results within Agricultural and Biological, and Environmental fields, with Social Sciences emerging as a more relevant field. Although the relative importance of Social Sciences was still minimal (13 to 15%), the introduction of the term "Soil" in the query drastically decreased the significance of the Energy and Engineering fields.

We then screened the articles by their titles and abstracts to gauge their relevance to this study, discarding articles that met the following criteria: 1) that were out of scope of the goals of these research but managed to be included in the search by having simultaneously the terms "soil", "carbon" and "markets" in the title or abstract (for example energy papers on biomass fuel such as wood pellets or agronomy papers on animal husbandry production); 2) that did not focus on soil carbon sequestration directly or indirectly as an ecosystem service (for example pure agronomic studies of crop performance); 3) focused on soil carbon emissions (either by land use change or other sources such as rice paddy emissions and erosion). This resulted in 56 documents being discarded (Table 3), leaving 77 for further analysis. These 77 documents were classified into three categories: 1) Soil Ecosystem Services (in agricultural land, integrated systems, forests, and coastal environments), 2) Environmental Economics (including topics like carbon pricing and trading mechanisms), and 3) Exploratory Analyses. The sections that follow will delve into the results of the review following the above classification, and the relevant articles can be found in a table at the end of each respective category.

Table 3. Screening and Analysis Results.

Articles (n = 133)		**Soil Ecosystem Services (n = 47)**				**Environmental Economics (n = 16)**		**Exploratory Analyses (n = 14)**
Discarded	*56*	*Agricultural Land*	*Integrated Systems*	*Forests*	*Coastal Environments*	*Carbon Pricing*	*Trading Mechanisms*	
Relevant	**77**	19	7	17	4	8	8	14

3.1. Soil Ecosystem Services

Soil resources play a critical role in the fast turnover domain of the carbon cycle, serving as the most significant carbon pool (Lal and Ussiri, 2017). However, these same resources are also responsible for the majority of carbon emissions in the Agriculture, Forest, and Other Land Use (AFOLU) sectors, primarily due to changes in land use. Furthermore, the intensity of land use and the resulting degradation creates both an opportunity and a necessity to refine management practices, with a view to bolstering carbon stocks in biomass and soils alike.

The sequestration of carbon has an intrinsic value within the context of ecosystem services, due to its beneficial impact across the board. Provision services are improved as a result of increased agricultural productivity; regulation of climate and surface temperature becomes feasible due to the net removal of atmospheric carbon and alterations in surface albedo; biodiversity and pedogenesis are promoted, thereby providing additional support; and cultural values are enriched through the preservation and propagation of local species, which are often tied to educational, aesthetic, and spiritual or religious activities. Furthermore, this also enables the production of local goods (such as specific honey varieties) and the development of tertiary activities, including tourism and sports.

The process of Soil Carbon Sequestration induces a shift in the carbon cycle, allowing terrestrial ecosystems to absorb more carbon from the atmosphere than what they lose through respiration, oxidation, or erosion. Such a shift can be achieved through the application of recommended management practices, such as enhanced tillage, the use of cover crops and green manure, or prolonged fallows. Extensive reviews on soil and land management practices have already been conducted (Aguilera *et al.,* 2013; Cerqueira, 2021, Chapter 4; Sanz-Cobena *et al.,* 2017).

Articles focusing on Soil Carbon Dynamics and Sequestration explore management practices and changes in land use, with the aim of optimizing and augmenting carbon sinks, boosting carbon pools, and addressing questions concerning the capture of carbon and the volume that can be stored. It should be noted that the methods employed for soil carbon sequestration vary according to land use type, particularly between forest and agricultural land. In the context of forests, carbon can be stored more effectively through improved management practices, regenerated through reforestation efforts, or 'saved' via the conservation of natural capital and its valuation against changes in land use and economic applications.

3.1.1. Agricultural Land

Changing land use from natural vegetation to arable land is a significant source of greenhouse gas emissions within the Agriculture, Forestry, and Other Land Use (AFOLU) sectors. This transition results in carbon loss from both soils and biomass, due to clearance and exposure to erosion processes. Mitigation measures for climate change in this sector encompass soil carbon sequestration in arable lands – often referred as 'carbon farming' (Marks, 2020; Sharma *et al.,* 2021) – facilitated by management practices that help restore some of the carbon stocks lost during conversion. These practices work by augmenting cover protection (through cover crops and straw deposition), increasing organic and nitrogen inputs (via compost and green manure), and reducing soil erodibility (through improved tillage).

The use of organic amendments such as biochar (a specific type of coal produced by emission-controlled pyrolysis) can augment soil carbon stocks while minimizing CO_2 emissions from the burning of excess biomass and N_2O from mineral fertilization (Liu *et al.,* 2020). Anticipated adaptation benefits include enhanced water retention capacity and yield (Otte and Vik, 2017). Nonetheless, the economic viability of biochar is hampered by a lack of scale, and production CO_2 emissions may outweigh the ecological advantages (Rodrigues and Horan, 2018). This could be mitigated by more efficient straw pyrolysis (Liu *et al.,* 2020). Other organic farming procedures also show benefits compared to conventional farming, providing ecosystem services of carbon and cycling, biodiversity, soil health and erosion control, especially when associated with other practices than enhance soil protection (Persiani *et al.,* 2023). However, some setbacks include high adoption costs (Auerbach, 2018) even though there is the possibility of added profitability (Beni *et al.*, 2021).

Land clearance and land use change significantly contribute to GHG emissions, however, some transition patterns are associated with carbon sequestration and increased income (Roy *et al.,* 2022). In Southeast Asia, oil palm cultivation is a primary driver, but using fruit bunches as a mulch can counterbalance some of these emissions by increasing carbon sequestration and reducing carbon emissions (Rudolf *et al.,* 2021). However, employing organic amendments for carbon sequestration may create competition between ecosystem services. As an example, a study found that using crop residue for soil carbon sequestration (regulatory service) diminishes its potential for bioenergy (provisioning service). Therefore, to harmonize climate change mitigation with other sustainability objectives, crop residue management needs to be designed in an integrated, site-specific manner (Mouratiadou *et al.,* 2019). Recent trends in land use change in some western countries include farmland and agroforestry abandonment, due to a complex network of changes in socioeconomic, environmental, political, and cultural factors, inducing soil and biomass carbon sequestration and other ecosystem services (Carlos Alias *et al.,* 2022; Yang *et al.,* 2020)

Recommended management practices also include improved tillage (null, reduced, or shallow) to reduce runoff erosion and organic matter loss; green manure to increase soil nitrogen and decrease the application of mineral fertilization and N_2O emissions; and compost to enhance soil organic matter and water retention capacity *(Bhattacharyya et al.,* 2021; Chopin and Sierra, 2021; De Leijster *et al.,* 2020). The effectiveness, scalability, and profitability of implementing these management practices could be improved through a socio-organizational framework that combines people, infrastructure, technology, culture, and knowledge (Johansson *et al.,* 2022). This approach could have a positive effect on Net Present Value and the willingness to adopt these measures, which are further enhanced by input from local stakeholders and land managers (De Leijster *et al.,* 2020; Feliciano, 2022; O'Sullivan *et al.,* 2018; Otte and Vik, 2017). Improved governance mechanisms such as a standardized framework for sustainable biomass, more efficient assessment of land management best practices, and better scaling opportunities may ensure the enhancement of co-benefits and coupling of negative emissions with 'net-neutral' practices (for instance, biomass management for biofuel that concurrently stores carbon in the soil) (Torvanger, 2019).

Table 4. Relevant articles within Soil Ecosystem Services - Agricultural Land.

Author	Year	Short Summary
Auerbach	2018	Compares conventional and organic farming effects on small-scale farmers, highlighting organic's benefits for soil health and biodiversity
Beni *et al.*	2021	Mediterranean organic farms turn to natural agriculture for environmental benefits and better profitability, contrasting soil erosion and enhancing soil health.
Bhattacharya *et al.*	2011	Examining global soil carbon sequestration practices in developing countries, the study highlights agroforestry's promise and policy implications.
Carlos Alias *et al.*	2022	Global market pressures lead to unprofitable agroforestry abandonment, increasing forests and transforming soil into carbon sinks.
Chopin and Sierra	2021	Feasibility of 4‰ increase in soil organic carbon assessed for Caribbean agricultural soils, limited by soil types and practices.
De Leijster *et al.*	2020	Agroecological practices enhance almond orchard sustainability, yet economic incentives and policies are crucial for wider adoption.
Feliciano	2022	UK horticultural farmers respond to rising demand by adopting sustainable practices for environmental and economic benefits.
Johansson *et al.*	2022	Transforming Swedish farms into carbon sinks requires agroecological practices, fostering biodiversity, soil health, and sustainable food systems.
Liu *et al.*	2020	Straw biochar application improves crop yield and reduces N_2O emissions but faces economic challenges.
Mouratiadou *et al.*	2019	Maximizing bioenergy from crop residues while mitigating soil carbon decline requires integrated, site-specific management strategies.
O'Sullivan *et al.*	2018	Functional Land Management (FLM) integrates soil functions for sustainability. Catchment challenges engage stakeholders and bridge science-policy gaps.
Otte and Vik	2017	Biochar enhances soil fertility, crop yield, and carbon capture. Challenges remain in implementing functional biochar systems, requiring socio-technical strategies for sustainable adoption.
Persiani *et al.*	2023	Identifying cost-effective measures to reduce agricultural emissions in France, emphasizing efficiency and investments.
Rodrigues and Horan	2018	Biochar emerges as a sustainable solution for agriculture, carbon sequestration, and climate change mitigation, with varying global economic viability.
Roy *et al.*	2022	Various land-use systems (LUSs) were assessed for CO_2 sequestration, C stocks, and income potential. Forest-based LUS showed highest benefits.
Rudolf *et al.*	2021	Empty fruit bunch (EFB) mulching in oil palm plantations enhances yields and soil organic carbon, benefiting sustainability.
Sharma *et al.*	2021	Carbon farming enhances sustainability by diversifying natural farming methods, sequestering carbon, and integrating agroforestry for soil health.
Torvanger	2019	Biomass energy with Carbon Capture and Storage (BECCS) is vital for achieving climate targets but requires careful governance.
Yang *et al.*	2020	Abandoned farmlands globally hold potential for carbon capture and storage and can be facilitated by biodiversity management and biochar application.

3.1.2. Integrated Systems

Apart from traditional and conventional agricultural practices, some authors refer to integrated systems as a win-win approach regarding environmental protection, and social and economic development, which are the three pillars of sustainability. These systems include complex patterns of agriculture and forestry (agroforestry), agriculture, forestry, and pasture (agrosilvopasture) and forestry and pasture (silvopasture). These measures tend to be associated with poorer and more degraded and marginal lands since they are reportedly effective in reducing land use change and intensity-related soil erosion and mitigating losses in organic matter and carbon emissions.

Integrated systems such as agroforestry and agrosilvopasture are especially promising on their potential role of increasing soil organic carbon, reduce greenhouse gas emissions, increasing yield and fostering biodiversity (Aba *et al.,* 2017), all while reducing labour costs and providing marketing advantages to farmers, providing climate change mitigation, adaptation, food security, and provision of cultural and recreational benefits (Partey *et al.,* 2017; Ryschawy *et al.,* 2021; Sollen-Norrlin *et al.,* 2020). The introduction of tree crops in agricultural production, even though yielding positive environmental results, often requires financial incentives to drive change (Englund *et al.,* 2020), as it may interfere with traditional cropping practices (Felton *et al.,* 2023).

Apart from the more traditional integrated systems, some studies also show a positive feedback from integrating feedstock crops in marginal agricultural lands in Europe to provide biofuel and other ecosystem services such as erosion control and carbon sequestration (Von Cossel *et al.,* 2020). The value of the adoption of these mechanisms increases when they target more marginal lands, where the primary agricultural activity creates a degradation gradient that is mitigated by the protective and organic properties of perennial cropping systems. In these approaches, the integration of feedstock crops not only addresses biofuel production needs but also contributes to the restoration and enhancement of ecosystem services, making significant strides towards sustainable land management practices.

Table 5. Relevant articles within Soil Ecosystem Services - Integrated Systems.

Author	**Year**	**Short Summary**
Aba *et al.*	2017	Planting trees mitigates climate change by capturing carbon and conserving nature.
Englund *et al.*	2020	Multifunctional perennial production systems can balance biomass demand with environmental benefits, needing proper compensation mechanisms.
Felton *et al.*	2023	Agroforestry offers benefits like carbon storage, soil health, and additional income, but barriers hinder its adoption.
Partey *et al.*	2017	Improved fallows in Africa enhance food security, soil fertility, carbon sequestration, and livelihoods but require policy support.
Ryschawy et al.	2021	Agroecological integrated sheep-vineyard systems show promise for reducing inputs, improving soil quality, and enhancing sustainability.
Sollen-Norrlin *et al.*	2020	Agroforestry systems offer benefits like productivity and carbon sequestration, but adoption faces challenges like costs and awareness.
Von Cossel *et al.*	2020	Cultivating perennial biomass crops like Miscanthus can enhance carbon neutrality and environmental services, requiring subsidies to bridge the gap with biofuel economics.

3.1.3. Forests

The adoption of the suggested management practices mentioned earlier enables market valuation of various soil ecosystem services. This includes the provision service, which involves boosting yield, the regulation service for climate change mitigation, and the support service that aids climate change adaptation (Chen *et al.,* 2022). However, achieving an optimized carbon cycle through these practices presupposes that a prior transition from natural vegetation to agricultural land has occurred. As a result, these endorsed agricultural practices serve as ways of estimating the value of strategies that mitigate the impacts of land use changes, essentially aiming to repair previous degradation.

Nonetheless, it's crucial to note that natural ecosystems such as forests, grasslands, and shrublands offer ecosystem services that could be valued without triggering the detrimental effects of land use change. These services include climate regulation, support for biodiversity, and cultural values. We can estimate the value of conserving and maintaining the dynamics of natural ecosystem services either through direct conservation efforts or by valuing these services at a rate comparable to, or higher than, those achievable via land use and land cover changes. The studies categorized under this topic aim to address questions on how to assign a value to carbon in natural ecosystems, making the capital in these natural areas a preferred option over triggering degradation.

Valuing forest conservation starts with assessing the baseline scenario to comprehend the carbon stocks and balances in soils and biomass. This step is essential to gauge the emissions avoided by preserving natural vegetation instead of converting it into arable land (Santini *et al.,* 2020). The same consideration applies to certain less profitable tree crops like the carob-tree (Ceratonia siliqua L.), which may be replaced by more profitable but environmentally harmful crops/practices if ecosystem service valuation is not implemented (Correia and Pestana, 2018). When carbon farming via reforestation efforts, there are cost-effectiveness differences between plantation, restored and second-growth forests as carbon accumulation rates and implementation costs vary with the degree of human intervention, even though soil carbon contents appear to remain comparable (Brancalion *et al.,* 2021).

Forest conservation, restoration, and enhancement of land management practices could potentially mitigate up to 21% of the United States' annual emissions (Fargione *et al.,* 2018), and regional cost-share programs allow for compensating landowners for the provision of market and non-market ecosystem services (Chizmar *et al.,* 2021). These practices can concurrently achieve positive effects on biodiversity (Dybala *et al.,* 2019), water retention, soil erosion (Jafarzadeh *et al.,* 2021; Kitaibekova *et al.,* 2023; Wu *et al*., 2022) as well as providing recreational services related to landscape tourism, sometimes exceeding the economic value of wood harvesting (Lopes and Amaral, 2021). In the Amazon, restoration projects are expected to yield various socioeconomic impacts, including the protection of water resources, reduction of soil erosion, income from carbon programs, and sales of timber and non-timber products. However, a conflict exists between reforestation and the demand for land clearance for agriculture and cattle ranching. This tension is amplified by the lack of market volume for commercial products from restored areas (non-timber, non-cattle, non-agriculture) (Nunes *et al.,* 2020). When evaluating the three dimensions of sustainability in forest product production, i.e., environmental measures, economic development, and social impacts, integrated assessment modelling techniques can help forecast soil carbon sequestration, greenhouse gas emission savings, financial profits, and job creation over a specific temporal and spatial scale (Jin and Sutherland, 2018). However, there are challenges and limitations to this approach, including model validation, complexity, and non-linearity of land use change.

In parallel, technological advancements, including increasingly available precision farming solutions and artificial intelligence, equip researchers, farmers, polluters, and decision-makers with superior data, information, and knowledge about soil management practices and their implications for nutrition and human health (Camarena, 2021; Costantini *et al.,* 2020; Lal, 2020). Moreover, the improving quality of environmental assessment tools like soil sampling, soil organic carbon mapping, and remote sensing applications make comprehensive benchmarking analyses possible, leading to better decision and policymaking. These tools also empower landowners by assisting them in assigning value to their ecosystem services (Baumber *et al.,* 2019).

Table 6. Relevant articles within Soil Ecosystem Services – Forests.

Author	Year	Short Summary
Baumber *et al*.	2019	Carbon farming in Australia potentially offers co-benefits like biodiversity conservation, improved soil and water quality, increased productivity, and cultural services.
Brancalion *et al.*	2021	evaluates carbon accumulation cost-effectiveness in Brazilian forests, revealing plantations' higher initial storage but lower cost-effectiveness compared to second-growth forests for carbon farming.
Camarena	2021	AI impacts food systems, offering sustainability benefits, but also raises concerns like carbon footprint and inequalities.
Chen *et al.*	2022	Valuing Pudacuo National Park's Forest ecosystem services informs conservation efforts and ecological compensation criteria.
Chizmar *et al.*	2021	US Southern Forest cost-share programs compensate landowners for timber and ecosystem services, facing funding challenges and evolving objectives.
Correia and Pestana	2018	Extreme climatic events limit agriculture in Southern Portugal. Carob trees provide alternative income and carbon sequestration potential.
Costantini *et al*.	2020	Operational Groups in the EU promote tailored strategies for increasing and maintaining soil organic carbon in arable farming.
Dybala *et al.*	2019	Reforestation for carbon storage and biodiversity can have synergies and trade-offs, requiring optimized design and management.
Fargione *et al.*	2018	Natural climate solutions (NCS) in the US can mitigate 21% of emissions through carbon storage and land management improvements, yielding multiple benefits.
Jafarzadeh *et al.*	2021	Assessing land-use allocation in western Iran, focusing on ecosystem services, trade-offs, and optimization.
Jin and Sutherland	2018	Co-firing Forest residues in US bioenergy contributes to renewables, ISM model assesses economic, environmental, and social outcomes.
Kitaibekova *et al.*	2023	Examining forest ecosystem services in Kazakhstan's Burabay National Park, emphasizing their economic value and conservation importance.
Lal	2020	Industry adoption and global initiatives are crucial for accelerating soil carbon sequestration and NET's but require market incentives, innovative soil sampling, and a "Healthy Soil Act."
Lopes and Amaral	2021	Azores forest recreational ecosystem services assessed using travel cost model, with a value exceeding wood production.
Nunes *et al.*	2020	Large-scale forest restoration in the Amazon can mitigate biodiversity loss, enhance ecosystem services, and promote sustainability through native species reforestation.
Santini *et al.*	2020	Montane ecosystems in Mexico provide vital services, including carbon and water storage, but face threats from deforestation.
Wu *et al.*	2022	Liquidambar plantations offer valuable ecosystem services including wood, carbon fixation, and biodiversity, with significant economic impact.

3.1.4. Coastal Environments

Beyond agricultural and forest lands, the valuation of soil carbon is also a pertinent topic in other natural habitats, including coastal environments such as salt marshes and tidal flats. These areas house substantial quantities of carbon within their deep organic soils. However, due to anthropogenic pressures and land use changes, these regions have experienced degradation and substantial loss of their stored carbon. Moreover, they continue to face risks from sea level rise induced by climate change.

To counteract this, conservation strategies like transplanting vegetation and planning with future sea level changes in mind can both restore some of the lost carbon and guard against future losses. Given their impressive potential for carbon sequestration, these coastal environments have gained popularity in carbon valuation schemes. This is particularly notable in voluntary markets where 'blue carbon' projects, which focus on carbon captured by coastal and marine ecosystems, are becoming increasingly prevalent.

As with forest ecosystems, establishing baseline scenarios and ensuring data availability are crucial for understanding carbon stocks and fluxes. These insights can guide the creation of policies and management practices. Understanding the relationships and dynamics among different types of coastal ecosystems, such as mangroves, salt marshes, and wetlands, and their carbon sequestration and emissions in both soil and biomass is fundamental for designing and implementing blue carbon projects (Hutchison *et al.,* 2018). However, the return on investment for the mitigation potential of both soil and biomass carbon sequestration programs is uncertain, due the complex relation between implementation costs and carbon sequestration rates in both soils and biomass (Duncan *et al.,* 2022), and there are political challenges that can be overcome by institutional frameworks that prioritize ecosystem management (Odote, 2019).

Bridging the gap between our knowledge of these ecosystems' environmental performance and the carbon market prices and environmental policies could be instrumental for the socio-economic development of the protected areas. For instance, in the Western Bay of Bengal (India), the value of carbon stored in mangrove ecosystems has been estimated to be $192,442 at a relatively low valuation of $10.90 per ton (Banerjee *et al.,* 2021). This highlights the potential of these ecosystems to contribute to climate change mitigation while also providing substantial economic benefits.

Table 7. Relevant articles within Soil Ecosystem Services - Coastal Environments.

Author	**Year**	**Short Summary**
Banerjee *et al.*	2021	Carbon storage and cycling in Indian mangroves, analysing five dominant species' carbon capacity, soil, water parameters, and carbon emission impact, aiming to inform sustainable marine resource management and carbon trading.
Duncan *et al.*	2022	Enhancing blue carbon sequestration in abandoned aquaculture ponds can boost climate change mitigation and adaptation, but ROI remains uncertain.
Hutchison *et al.*	2018	Operationalizing blue carbon in Gulf Coast wetlands by addressing knowledge gaps for effective management.
Odote	2019	Kenya's legal framework for coastal wetland management aims to adopt an ecosystem approach for sustainability.

3.2. Environmental Economics

The notion of valuing soil carbon as a driver of ecosystem services has taken cues from the early models of cap-and-trade and compliance emission reduction schemes. The premise is to trade carbon capture and storage against a defined volume of emissions, denoted in financial terms, in a similar vein to trading investments in cleaner energy sources. Despite its many criticisms, the complexity and nuance of this approach will be further explored later in this discussion. For this review, the articles grouped under the environmental economics category primarily concentrated on two key aspects: 1) Carbon Pricing; and 2) Trading Mechanisms. These studies provide insights on 'what' to do with the captured carbon.

These two aspects help to elucidate the relationship between soil and land management aimed at enhancing intangible goods and services, and their commodification into marketable terms at regional, national, and international scales. Essentially, it allows for pricing both the value of gaining carbon and the cost of losing it, so that, on one hand, recommended management practices are favoured over conventional or business-as-usual practices, and on the other, the conservation of natural ecosystems remains as profitable, or even more so, than land use changes.

Moreover, it helps understand how these new 'goods' can be integrated into the market for trading between landowners and polluters alike, using both compliance mechanisms and voluntary markets. Finally, understanding the spatial, social, and economic constraints of market placement, product availability, and policy design can benefit from spatial modelling of complex systems centered around the three pillars of sustainability. These modelling approaches provide a means to predict and mitigate potential hurdles in the deployment and optimization of carbon trading schemes.

3.2.1. Carbon Pricing

Assigning a monetary value to carbon in soils and biomass is a multifaceted task. It encompasses an evaluation of the investment required to capture and store carbon through the adoption of specific management practices, and the potential cost of carbon loss due to diminished environmental performance such as yield, biodiversity, and regulation. A study examining the effects of changes in agricultural practices on the natural resource base and livelihoods of farmers estimated that the opportunity cost of soil mismanagement under soil carbon valuation fluctuates between 95 and 168 USD per ton of CO_2 equivalents (Berazneva *et al.,* 2019).

Typically, soil carbon valuation refers to soil organic carbon. However, an important facet of the carbon cycle is the presence of inorganic carbon. This form of carbon takes longer to stabilize and is also susceptible to loss due to mismanagement and erosion, thereby resulting in negative externalities. Some researchers argue for the recognition of the ecosystem services of climate regulation provided by soil inorganic carbon, which currently remains unaccounted for in existing market pricing mechanisms *(Groshans et al.,* 2018).

However, the implementation of these management practices must account for the farmers' willingness to accept the necessary investment and change. A survey of farmers in Indiana, US, revealed that those who had not yet adopted recommended tillage practices would require a net revenue increase of $40 per acre to change their practices. They expressed a preference for government payments, which are typically less subject to price volatility, over other carbon financing solutions such as voluntary markets (Gramig and Widmar, 2018). Given that current carbon prices significantly exceed $40 per ton of CO_2 equivalents, and that effective management practices can sequester over 3 tons of CO_2 equivalents per hectare per year, these values are achievable if trading mechanisms ensure fair valuation among project managers, farmers, and carbon brokers. In France, a study found that 10% of agricultural emissions could be mitigated at a cost under €25 t CO_2eq (Pellerin *et al.,* 2017). Conversely, a separate study with German farmers discovered a high motivation for promoting soil carbon sequestration, regardless of whether the compensation originates from a government subsidy or a market certificate approach (Hermann *et al.,* 2017). On the other hand, the demand side also has been found to have a willingness to pay for land management changes that would provide ecosystem services regarding biodiversity, soil conservation and carbon storage, and aesthetics, which is was found to be around €18-93 per household in a study conducted in Brazil (Parron *et al.,* 2022).

A study centered on the economic performance of marketable (e.g., biomass, provision) and non-marketable (e.g., groundwater, nutrient, carbon) ecosystem services compared agroforestry to conventional agriculture across 11 European countries. Agroforestry demonstrated reduced externalities in terms of pollution, nutrient, and soil loss, along with added benefits of carbon capture, which makes it profitable. By adopting a market approach such as penalties for disservices and compensation for services, the services provided by agroforestry can be commodified, thereby enhancing their appeal and profitability (Kay *et al.,* 2019). The land's capacity to provide soil and water ecosystem services can be used to estimate the economic value of farmland (Priori *et al.,* 2019).

Table 8. Relevant articles within Environmental Economics - Carbon Pricing.

Author	Year	Short Summary
Berazneva *et al.*	2019	Examining soil carbon management's impact on rural livelihoods, a model reveals the opportunity cost of mismanagement.
Gramig and Widmar	2018	Economic viability crucial for carbon sequestration in soils; Indiana study shows farmers' preference for government payments over carbon markets.
Groshans *et al.*	2018	Soil databases assess soil inorganic carbon value for ecosystem services, estimating replacement cost and regional values.
Hermann *et al.*	2017	Subsidies and certificates encourage farmers to sequester soil carbon for climate protection and sustainability.
Kay *et al.*	2019	evaluating economic benefits of agroforestry through marketable and non-marketable ecosystem services, highlighting multifunctional advantages.
Parron *et al.*	2022	Growing international demand for sustainable agriculture in Brazil, valuing ecosystem services, highlights consumers' preferences for improved biodiversity, soil, and carbon management.
Pellerin *et al.*	2017	Agricultural GHG emissions in France can be reduced by cost-effective measures, focusing on efficiency and carbon storage.
Priori *et al.*	2019	An approach for economically evaluating irrigated croplands by considering soil functions and spatial variability.

3.2.2. Trading Mechanism

Carbon markets and their associated trading mechanisms have been a critical focus area in climate change mitigation policies. These markets currently operate in two distinct modalities: regulated markets and voluntary markets. Regulated markets require certain sectors to offset emissions exceeding a designated threshold. This offset can be achieved through investments in emission reductions of other companies or in carbon capture and storage projects. Voluntary markets, on the other hand, allow individuals to invest in emission reduction or carbon capture and storage projects to offset their own emissions, such as those resulting from air travel or other consumption habits. These voluntary schemes are bound by marketing strategies and storytelling to create a more successful product (Brill, 2021), even though there are questions of additionality, permanence, validation and monitoring that create conceptual and legal challenges (Davis, 2023).

However, as we inch closer to climate tipping points, driven by thresholds of atmospheric carbon concentrations, the existing emission reduction trading schemes are becoming obsolete. Current climate scenarios underscore the need for negative emission solutions –capturing more carbon than we emit– so that atmospheric greenhouse gas concentrations can be reduced before tipping points are reached. Some researchers argue that nature-based solutions are currently the only scalable solutions available, suggesting that soil carbon could play a pivotal role due to its association with multiple ecosystem service provisions. This perspective anticipates a potential growth of the global carbon market. However, trading mechanisms need to ensure the longevity of carbon storage, fair valuation, rewards for additionality, permanence, co-benefits, monitoring, and transparency across different standards and financing mechanisms (Keenor *et al.,* 2021).

Several studies have explored market design to support landowners in managing their properties for optimal carbon fluxes and balances. They have examined trading systems, land management consultancy, and soil data measurements. Concepts like "Soil Value Exchange" (Blackburn *et al.,* 2018), "Ecosystem Service Market Consortium" *(Biggs et al.,* 2021), and various "Carbon Farming" strategies have been proposed to promote environmental practices, drive sales and investments, and diversify the land sector through the development of an ecosystem service economy (Black *et al.,* 2022; Marks, 2020; Russell-Smith and Sangha, 2018).

Table 9. Relevant articles within Environmental Economics - Trading Mechanism.

Author	Year	Short Summary
Biggs *et al.*	2021	Examining California rangeland soil carbon governance, study assesses impact of corporate-led ecosystem services initiative.
Black *et al.*	2022	Analyses approaches, methods, and governance in emerging soil carbon markets for climate mitigation.
Blackburn *et al.*	2018	Nature-based solutions can store significant amounts of carbon, with the Soil Value Exchange aiming to support soil carbon trading for landowners' benefit.
Brill	2021	Carbon offsets' market challenges are addressed through storytelling, creating links between origin, customer, and value.
Davis	2023	Voluntary carbon market faces legal challenges due to uncertainty in measuring agricultural carbon sequestration.
Keenor *et al.*	2021	Current carbon pricing insufficient for Net Zero. Soil re-carbonization with economic incentives needed for climate goals and soil health.
Marks	2020	Addressing urgent climate challenges through Carbon Farming Certification, integrating carbon sequestration with agriculture.
Russell-Smith and Sangha	2018	Australia's northern savanna offers opportunities for sustainable land use, focusing on ecosystem services markets for economic and environmental benefits.

3.3. Exploratory analyses

Understanding the economic response to environmental and social factors under global climate change involves analysis across various sectors such as agriculture, forestry, and other land uses. The nature of both soil systems, carbon markets and their social, economic, political, and cultural constraints is non-deterministic and non-linear, making predictions challenging for simplistic models. Recently, researchers have started paying more attention to ways of predicting the ecosystem service response to these different variables, as well as modelling their economic performance and reflecting on the social, cultural and political meaning behind these approaches.

Some studies offer diverse perspectives on how exploratory analyses can contribute to a deeper understanding of environmental responses, helping guide future policies and practices in mitigating climate change and conserving ecosystems. One study focused on the balance between sustainable agriculture and carbon sequestration, finding that climate-smart actions like no-till and cover crops can help offset potential yield income losses through carbon credit income (Contasti *et al.,* 2023), while strategic landscape management can offer environmental and socioeconomic benefits, including increased biodiversity and carbon sequestration (Parish *et al.,* 2023). On the other hand, the reliance on negative emissions technologies (NETs) in long-term climate strategies poses a risk that promises of future NETs might inadvertently create a "spiral of delay" in taking current action (Jacobs *et al.,* 2023).

Recent studies have explored innovative approaches to modelling and predicting carbon stocks and prices. For instance, a novel artificial intelligence model for estimating mangrove soil organic carbon (SOC) showed that the use of multisensor earth observation data can significantly improve SOC estimation, providing valuable insights for sustainable mangrove conservation (Le *et al.,* 2021). Another study proposed a hybrid model using ensemble empirical mode decomposition (EEMD), a linearly decreasing weight particle swarm optimization (LDWPSO), and a wavelet least square support vector machine (wLSSVM). This model accurately predicted carbon prices across three different Chinese markets, outperforming 12 other model combinations (Sun and Xu, 2021). Another study found that, within China's cap and trade mechanism, economic costs for grassland mitigation measures could be achieved between USD -6.52 to 3.78 t CO_2eq (with negative values indicating another valuable positive effects aside carbon sequestration) and could be traded at market values between USD 12.7 and 30.90 t CO_2eq (Wilkes *et al.,* 2021).

There's also been progress in developing tools to analyse the economic impacts of various greenhouse gas mitigation practices. For instance, a Field Scale Economic Analysis Software is capable of estimating the net benefit under different mitigation practices (Li *et al.*, 2021). This tool allows researchers to evaluate whether climate change mitigation practices are economically beneficial, or whether they require government subsidies to make them preferable to business-as-usual practices that may contribute to land degradation. Similar approaches have been applied to forest land, incorporating global change scenarios into the adaptive market price of timber and its relation to the co-production of ecosystem services. Examples include a model that assesses the Net Production Value of woodlands considering carbon storage in the forest and harvested timber, carbon substitution, windthrow risk, biodiversity, water quality, and cultural values (Lundholm *et al.,* 2020).

Table 10. Relevant articles within Exploratory Analyses.

Author	**Year**	**Short Summary**
Balume Kayani *et al.*	2021	Examines soil fertility variation among smallholder farms, emphasizing factors like "market distance," "farm typology," and "site," suggesting tailored fertility management.
Contasti *et al.*	2023	Climate-smart practices like no-till and cover crops balance soil carbon storage and yield income trade-offs.
Franceschinis *et al.*	2022	Evaluating soil functions' economic value is crucial for Soil Security concept, influenced by personal and social norms.
Geng and Liang	2021	GEP theory assessed forest ecosystem service and natural resource values in Jiaokou County, China, revealing valuation complexities.
Jacobs *et al.*	2023	Countries' long-term climate strategies include future negative emissions technologies (NETs), possibly delaying immediate mitigation efforts.
Kallio and LaFleur	2023	Regenerative agriculture empowers farmers to combat climate change through soil-centered practices, challenging traditional knowledge.
Le *et al.*	2021	Developed CBR-PSO model estimates mangrove soil organic carbon using remote sensing data, enhancing accuracy for conservation.
Li *et al.*	2021	Software estimates economic viability of greenhouse gas mitigation practices for crops, suggests subsidies to incentivize adoption.
Lundholm *et al.*	2020	Study integrates ecosystem service indicators into Forest Management Decision Support System, accounting for climate change and timber markets.
Moran-Rodas *et al.*	2022	Urbanization and farming practices impact soil organic carbon; farm and household conditions crucial for positive change.
Parish *et al.*	2023	Transitioning to cellulosic bioenergy feedstocks improves carbon management and biofuel production, benefiting economics, environment, and ecology.
Santos *et al.*	2022	This study assesses and values ecosystem services of pasture-based beef farms in Alentejo, highlighting their positive environmental impacts.
Sun and Xu	2021	A hybrid model that improves carbon price prediction accuracy.
Wilkes *et al.*	2021	Improving Asian grassland management benefits livelihoods and carbon sequestration, requiring suitable financial instruments and policies.

Apart from these approaches, there are other economic indicators worth considering when assessing the economic performance of soil carbon. For example, Gross Ecosystem Product theory could be used to evaluate the total value of various final material products and services provided by ecosystems (Geng and Liang, 2021), which, in the case of the *montado/dehesa* systems in Portugal and Spain can account for between 146-176€ ha^{-1} y^{-1}, especially from soil protection (Santos *et al.,* 2022). Also, market distance, farm typology, and site characteristics can serve as proxy measurements for soil fertility in smallholder farming environments (Balume Kayani *et al.,* 2021).

The interplay between income, social and economic aspects of farming sites, as well as environmental characteristics in forest land demonstrates the complexity of these systems. This emphasizes the importance of a holistic approach to understand the intricate relationships within. Recent studies have highlighted the how social norms and personal preferences influence people's values towards soil functions (Franceschinis *et al.,* 2022), as well as the link between farm and household conditions and soil carbon management decisions (Moran-Rodas *et al.,* 2022). Lastly, and focusing on the novel concept of regenerative agriculture, another study challenged conventional ways of understanding agriculture through soil-and-carbon centered knowledge practices. Using ethnographic fieldwork in farms across Finland, Norway, and Italy, they examined the relationships between farmers and landscapes, and showed how farmers engage with their landscapes through complex dynamics of control, care, and rhythm (Kallio and LaFleur, 2023).

4. Discussion: on the role of Geography and Geographical Thought

Carbon sequestration in soil interconnects a myriad of factors that transcends the boundaries of environmental, social, economic, cultural, technological, and political dimensions. It calls for an interdisciplinary approach to decipher this intricate web, as this phenomenon sits at the intersection of various scientific disciplines.

The application of this process in addressing climate change implies a substantial degree of human involvement, therefore, engagement with social sciences is imperative. This includes deciphering cultural nuances that underpin soil management practices, the relationship of farmers to their land and markets, and the socio-cultural dynamics that may influence an individual's willingness to act (Salvati *et al.,* 2015).

These conditions are usually deeply local and intricately tied to factors such as land tenure rights, landscape ecology, political structures, and power dynamics (Santos and Roxo, 2017). A simplistic interpretation that diminishes the importance of soil and climate could result in a misleading narrative.

Geography, being an integrative discipline, stands at a unique crossroad in this discourse. It assimilates a range of scientific and epistemological perspectives, thus lending a holistic understanding of the soil carbon ecosystem services. This involves engaging with the concepts of 'space' and 'place', which embody the meanings and perceptions formed through human interactions (Tuan, 1977).

In the context of climate change, the role of soil ecosystem services takes on a heightened significance. The associated social and economic vulnerabilities might hinge upon land use and management practices. Thus, in-depth analysis and modelling of these changes could provide insights into social behaviour and ecosystem responses (An *et al.,* 2021).

The disciplinary involvement of geography in agent-based models for socio-ecological systems could be particularly beneficial. By combining social and environmental systems in a relational approach, researchers could explore how perceptions and willingness to act might differ under varying climate, policy, and development scenarios (Gomes *et al.,* 2019; Molajou *et al.,* 2021).

The intricacy of soil management extends beyond mere human-centric approaches and requires a holistic understanding of the relationships within farming and soil ecosystems. These include not only the interplay between income, social norms, and personal preferences but also the ecological aspects of land. The emergence of regenerative agriculture further underscores the connection between farmers and their landscapes, highlighting the multifaceted dynamics of control, care, and rhythm. This more-than-human perspective shifts the focus towards recognizing the complex web of relations that shape agriculture, encompassing environmental, social, and cultural dimensions. By acknowledging these rich interconnections, a pathway is forged to better integrate and value ecological livelihoods within the broader context of climate change mitigation and adaptation.

Overall, the assessment of soil ecosystem services for climate change mitigation and adaptation necessitates an integrated approach, blending the wisdom of 'human' and 'physical' geographers. It requires the balanced usage of the epistemological and methodological frameworks that often separate these sub-disciplines. By bridging these divides, we could enable more effective cooperation and devise comprehensive strategies to harness soil carbon sequestration in combating climate change (Gotts et al., 2019).

5. Conclusions

Soil carbon sequestration offers a valuable solution to reducing excess carbon in the atmosphere, promoting climate change adaptation, and combating desertification. The recent scientific literature regarding soil carbon markets has focused on three main lines of research: 1) Soil Ecosystem Services, which is a topic of research closely associated with agricultural and environmental sciences and focuses on ways to promote and maintain the uptake and storage of excess atmospheric carbon and its storage in soils and biomass; 2) Environmental Economics, a topic that has been growing since the 2015 Paris Agreement and the introduction of voluntary carbon markets, which had an initial period of reflection on how to associate an economic valuation to soil carbon and, more recently, to the complex task of implementing trading mechanisms that overcome the challenges of additionality, permanence, monitorization and validation; and 3) Exploratory Analyses, where the most recent works have focused on ways of integrating the complex non-linear nature of environmental, economic, social, political and cultural factors that influence both carbon sequestration and the valuation of its associated ecosystem services. The complex, nonlinear relationship between ecosystem response and human action underscores the need for an interdisciplinary approach that integrates various ecological and socio-economic frameworks. Social sciences play a pivotal role in understanding the cultural, political, and economic contexts surrounding soil carbon markets, land tenure rights, and farmer relationships. Meanwhile, geography provides an integrative platform for diverse scientific perspectives, offering tools like spatial agent-based models to probe deeper into socio-ecological systems and human-environment interactions. Combined qualitative and quantitative methodologies allow us to appreciate and effectively value soil ecosystem services for climate change mitigation and adaptation, paving the way for sustainable land use and management practices. To bridge the gap between human and physical geography, we must embrace a balanced use of epistemological and methodological frameworks. Looking forward, it is imperative to intensify our research efforts and refine our practices to harness the full potential of soil carbon sequestration in our fight against climate change.

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ASSESSING THE SECURITY STATUS AND FUTURE SCENARIOS OF THE MEDITERRANEAN REGION THROUGH THE WATER-ENERGY-FOOD NEXUS: A CLUSTER ANALYSIS APPROACH

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ABSTRACT. Over the past decades, the Mediterranean region has faced significant challenges due to the impacts of climate change and ongoing conflicts. This study proposes an assessment of the region's security status and potential future scenarios through the lens of the water-energy-food nexus, utilising indicators that align with the Sustainable Development Goals (SDGs). These indicators include agricultural yields, value-added, and land variations, water and sanitation services, income and inequality, use of renewable energy, carbon footprints, and political stability. To evaluate the situation, this analysis applies Ward's hierarchical clustering algorithm to group countries based on these indicators, examining the average terms and the years 2006 and 2015 for comparative analysis. Additionally, an exponential smoothing algorithm forecasts future trends and generates clusters for the years 2030 and 2050. By computing an index of convergence for each cluster and indicator, this contribution identifies areas of particular interest from a security perspective. The findings of this analysis reveal a growing polarisation within the Mediterranean region, with European countries and Israel forming one distinct group, and African and Eastern countries (excluding Israel) forming another. Notably, recurring disparities exist in variables such as agricultural land, political stability, violence, income per capita, and agricultural value added. Conversely, certain variables, including the Gini coefficient, prevalence of overweight population, and access to drinking water services, show signs of convergence. These results shed light on potential areas of both conflict and cooperation in the Mediterranean region, highlighting the importance of addressing the challenges posed by climate change. By understanding the geopolitical dynamics and identifying key areas of concern, policymakers can develop informed strategies to promote stability and sustainable development in the region.

Evaluación del estado de seguridad y escenarios futuros de la región mediterránea a través del nexo agua-energía-alimentos: un enfoque a partir del análisis cluster

RESUMEN. En las últimas décadas, la región del Mediterráneo se ha enfrentado a importantes desafíos debido a los efectos del cambio climático y a los conflictos en curso. Este estudio propone una evaluación del estado de seguridad de la región y posibles escenarios futuros a través de la conexión agua-energía-alimentos, utilizando indicadores que se alinean con los Objetivos de Desarrollo Sostenible (ODS). Estos indicadores incluyen los rendimientos agrícolas, el valor añadido y las variaciones de la tierra, los servicios de agua y saneamiento, los ingresos y la desigualdad, el uso de energías renovables, las huellas de carbono y la estabilidad política. Para evaluar la situación, este análisis aplica el algoritmo de agrupación jerárquica de Ward para agrupar países en base a estos indicadores, examinando los términos promedio y los años 2006 y 2015 para un análisis comparativo. Además, un algoritmo de suavizado exponencial pronostica tendencias futuras y genera clusters para los años 2030 y 2050. Al calcular un índice de convergencia para cada grupo e indicador, esta contribución identifica áreas de interés particular desde una perspectiva de seguridad. Los resultados de este análisis revelan una creciente polarización dentro de la región mediterránea, con países europeos e Israel formando un grupo específico y países africanos y orientales (excluyendo Israel) configurando otro. Cabe destacar que existen disparidades recurrentes en variables como el suelo agrícola, la estabilidad política, la violencia, el ingreso per cápita y el valor agregado agrícola. Por el contrario, ciertas variables, como el coeficiente de Gini, la prevalencia de la población con sobrepeso y el acceso a los servicios de agua potable, muestran signos de convergencia. Estos resultados arrojan luz sobre las posibles esferas de conflicto y cooperación en la región del Mediterráneo y ponen de relieve la importancia de abordar los desafíos que plantea el cambio climático. Al comprender la dinámica geopolítica y determinar las principales esferas de preocupación, los encargados de formular políticas pueden elaborar estrategias bien fundamentadas para promover la estabilidad y el desarrollo sostenible en la región.

Keywords: Regional analysis, geopolitics, sustainability, conflict, convergence.

Palabras clave: Análisis regional, geopolíticas, sostenibilidad, conflicto, convergencia.

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1. Introduction

The Mediterranean region plays a crucial role in socioeconomic and environmental transformations, as it faces many challenges interconnected and driven by the force of climate change. Effective management of energy resources, environmental preservation, population growth, scarcity, and existing tensions are among the pressing issues confronting the Mediterranean region (Scheffran, 2020). As a result, this region is projected to be highly vulnerable to the impacts of climate change.

The Mediterranean region is expected to experience a decline in rainfall and rising temperatures, exacerbating environmental stress, and causing water scarcity, heatwaves, and wildfires. These challenges will be further compounded by population growth and rapid urbanisation, particularly in the Southern and Eastern areas, where social conflicts and political instability are more prevalent.

Paradoxically, despite the abundance of renewable energy sources available in the Mediterranean, countries within the region continue to rely heavily on fossil fuels, leading to an ongoing energy crisis. The European Union, which has seen a decline in its influence over the Mediterranean since the 1990s (Anoushivaran *et al.,* 2017), is particularly vulnerable to this crisis.

The energy challenges faced by the European Mediterranean countries are multi-faceted and complex. These challenges include ensuring energy security, diversifying energy sources, promoting renewable energy, and mitigating the environmental impact of energy production. By working together in a bilateral framework, the EU and the Mediterranean countries can pool their resources, knowledge, and expertise to address these challenges more effectively (Tagliapietra and Zachmann, 2016), particularly considering the current energy scenario shaped by the COVID pandemic (Bianchi, 2020) and the conflict in Eastern Europe.

The COVID-19 pandemic has significantly impacted the energy sector. Lockdown measures and economic slowdowns have caused fluctuations in energy demand and prices. The pandemic has highlighted the importance of energy resilience and the need to build more sustainable and resilient energy systems. Collaborative efforts between the EU and the Mediterranean countries can help to mitigate the negative effects of the pandemic on the energy sector and promote a more resilient recovery.

Furthermore, the security scenario in Eastern Europe implies factual and potential disruptions in energy supplies and transit routes. Cooperation can help diversify energy sources and routes, reducing dependency on a single supplier or route and enhancing energy security for all parties involved.

In these circumstances, cooperative security (Wohlfeld, 2020) emphasises the importance of building trust, dialogue, and support among nations to address common security challenges. Applying this concept to the energy sector, cooperative security can provide a framework for Mediterranean countries to collaborate on energy-related initiatives, exchange best practices, and coordinate policies. By viewing energy security as a shared interest, countries can work together to enhance their collective resilience and stability.

Network diplomacy (Prontera, 2020) can guide the creation of networks and partnerships among various stakeholders to achieve common goals. In the context of energy cooperation between the EU and the Mediterranean countries, network diplomacy can facilitate the exchange of knowledge, technology, and investments. It can bring together governments, international organisations, private sector entities, and civil society to mobilise resources and support common interest projects, such as the development of renewable energy infrastructure or the establishment of interconnection projects for electricity and gas transmission.

The gas potential of countries like Israel, Egypt, and Cyprus (Giuli, 2021; Prontera and Ruszel, 2017; Tsakiris, 2018) is seen as an opportunity for the European Mediterranean countries to diversify their energy sources and reduce reliance on traditional fossil fuel suppliers. Developing gas reserves in these countries can contribute to regional energy security and provide economic opportunities for both producers and consumers. However, it is essential to ensure that the development and extraction of these resources are done in an environmentally sustainable manner, considering the potential impact on ecosystems and local communities.

Against this backdrop, this paper aims to analyse the current situation and potential future scenarios of the Mediterranean region through the lens of the water-energy-food nexus. By exploring the interrelationships between water, energy, and food, this approach can help identify security threats and suggest strategies to address them. Section 2 provides a context for the current situation, highlighting the relevance of the water-energy-food nexus and proposing a selection of indicators to assess it. Section 3 presents the finalised selection of indicators, describes the composition of the sample, and outlines the techniques used to process the data. Section 4 presents the results, and Section 5 summarises the key findings.

By employing a cluster analysis approach, this study seeks to shed light on the security challenges facing the Mediterranean region and provide insights into potential internal behaviours that can effectively address these challenges. Ultimately, this research aims to contribute to the development of sustainable and resilient strategies for the future of the Mediterranean region.

2. Contextualisation

The Mediterranean region is currently facing and is expected to continue experiencing a range of environmental and societal challenges (Scheffran and Brauch, 2014). One of the key factors shaping the region is the increasing temperatures. It is projected that the southern parts of the Mediterranean will experience a rise of 2-3 ºC (Schilling *et al.*, 2020), leading to shorter and milder winters, intensified droughts, and increased water shortages and evaporation rates during summers. This vulnerability is particularly significant in the Southern and Eastern zones, which have lower adaptation capacities.

Another pressing issue is the declining precipitation in the region. With a temperature increase of 2 ºC, it is estimated that precipitation will decrease by 5-10%, and sea levels will rise by 6-12 cm (IPCC, 2013). These changes can have adverse effects on ecosystems and densely populated coastal areas, thereby potentially resulting in social and economic impacts.

Furthermore, the Mediterranean region faces various forms of environmental stress due to its high biological and geographical diversity, as well as demographic changes, socio-political transitions, and conflicts (Lange, 2019). The environmental changes expected in the region are likely to compound these challenges, potentially leading to unequal social impacts across different areas.

Water scarcity, heat waves, polluting particles, and wildfires are additional factors that pose threats to human and animal health (Cramer *et al.,* 2018) and can exacerbate existing geopolitical conflicts in resource-rich areas and important trade routes (Scheffran, 2020). Water scarcity has the potential to fuel conflicts in the region (Messerschmidt, 2012).

Population growth and increasing urbanisation are noteworthy factors, especially in the most vulnerable areas such as North Africa and the Eastern zone. Environmental changes can trigger distributive conflicts and migrations, potentially leading to population traps (Geddes, 2015).

Food security is a significant concern in the Mediterranean region (Scheffran, 2020). Climate change could negatively impact soil productivity and agriculture, resulting in food shortages and higher prices, disproportionately affecting the most vulnerable populations. This vulnerability is expected to be more pronounced in the Northern and Western areas, where agriculture is more intensive.

The energy patterns in the Mediterranean region are complex, characterised by a dependence on fossil fuels, a need to increase the use of renewable resources, and the potential for the utilisation of nuclear energy for defence purposes.

In summary, the Mediterranean region is facing substantial environmental and societal challenges in the coming years. These challenges are expected to worsen existing vulnerabilities, and their impacts may be unevenly distributed across the region. As a result, there has been a growing recognition of the water-energy-food security nexus in the region in recent years (Stockholm Environment Institute, 2011). The interconnectedness of these sectors highlights the need for integrated approaches and proactive measures to address the challenges and promote sustainable development in the Mediterranean region.

The water-energy-food security nexus is a concept that recognises the interdependencies and linkages between water, energy, and food systems. It highlights the complex relationships and trade-offs among these sectors and emphasises the need for an integrated and holistic approach to ensure sustainable development and security in each area.

Water, energy, and food are essential for economic development and are interconnected in various ways:

Energy production requires water, particularly for cooling power plants and extracting and refining fuels. At the same time, water supply and treatment require energy. Changes in water availability or energy generation can have significant impacts on each other.

Agriculture accounts for a significant portion of water usage, as crops and livestock need water for irrigation, hydration, and processing. Water availability and quality directly affect agricultural productivity and food production.

Modern food production, processing, and distribution systems heavily rely on energy inputs, including fossil fuels. Energy costs and availability can influence agricultural practices, food processing, and transportation, thereby impacting food security.

These interdependencies create a nexus where actions and decisions in one sector can have ripple effects on others. For example, if water resources become scarce due to drought or overuse, it can limit agricultural production, which may lead to food shortages. Similarly, energy shortages or high energy costs can affect irrigation systems, food processing, and transportation, leading to food insecurity.

Addressing the water-energy-food security nexus requires a coordinated and integrated approach that considers the interactions and trade-offs between these sectors. It involves promoting sustainable practices that ensure efficient water use in agriculture, adopting renewable energy sources and improving energy efficiency, and implementing policies that enhance food security while minimising environmental impacts.

By recognising and managing the interdependencies among water, energy, and food systems, policymakers, researchers, and stakeholders can work towards achieving Sustainable Development Goals and enhancing the resilience of communities and ecosystems in the face of challenges such as population growth, climate change, and resource scarcity.

By analysing a set of indicators based on the Sustainable Development Goals (SDGs), we can gain insights into the current and potential security concerns related to these interconnected systems (Saladini *et al.,* 2018). Building upon the insights presented by Saladini *et al*. (2018), this analysis not only endorses their proposal but also seeks to further enhance and expand upon their findings.

One of the indicators highlighted is the Multidimensional Poverty Index (MPI). This indicator measures deprivations in living standards, health, and education, providing a broader understanding of poverty beyond income measures. In the context of the water-energy-food nexus, the MPI helps assess the impact of inadequate access to water, energy, and food on human well-being.

The prevalence of overweight in the adult population is another significant indicator in this framework. It sheds light on the health implications of the nexus, as it reflects the share of the population that is considered overweight based on the Body Mass Index. This indicator suggests that imbalances in the availability and accessibility of nutritious food can lead to health issues such as obesity.

The variation of the share of agricultural land over the total land area is a key indicator that helps understand the evolution of agricultural activities. By monitoring changes in agricultural land annually, including arable land, permanent crops, and pastures, we can assess the sustainability and efficiency of land use practices, which are vital for food production and the preservation of ecosystems.

Greenhouse gas (GHG) emissions, both total and AFOLU (agriculture, forestry, and other land uses), provide insights into a country's behaviour regarding climate change and its relationship with land use. These indicators become particularly relevant when cross-checked with the variation of land uses, indicating the environmental impact of agriculture and energy systems on the water-food-energy nexus.

Cereal yield, measured in kilograms per hectare, is an indicator that reflects the efficiency of cereal production, as well as the efficient use of water and fertilisers. This indicator is valuable for evaluating agricultural productivity and resource management, highlighting the potential for improving water and nutrient use efficiency in food production.

Agricultural value added, calculated in constant USD per worker, captures the difference between the sector's output in agriculture and the value of its intermediate inputs in monetary terms. This indicator helps assess the economic contribution of the agricultural sector and its productivity in generating income and employment opportunities.

Fertiliser consumption per hectare of arable land is an important indicator that reflects the amount of plant nutrients used in agriculture per unit of arable land. Monitoring this indicator helps evaluate the efficiency of fertiliser use, which is crucial for sustainable agricultural practices and minimising environmental impacts.

Crop water productivity, measured in kilograms per cubic meter, highlights the value added by agriculture concerning the freshwater used for irrigation. This indicator provides insights into the efficiency of water use in agriculture, emphasising the importance of optimising water resources to meet food production demands.

The annual freshwater withdrawal for agriculture, measured as a percentage, indicates the relative scale of freshwater withdrawals used in agriculture and livestock for irrigation, excluding evapotranspiration losses. Monitoring this indicator helps understand the level of water resource allocation to agriculture and its potential impacts on water availability for other sectors and ecosystems.

Indicators related to access to safe drinking water and sanitation services are crucial for assessing the water component of the nexus. The population using safely managed drinking water services and safely managed sanitation services indicators measure the share of the population that can access protected water sources and sanitation facilities. These indicators reflect the importance of ensuring access to clean water and adequate sanitation, which are essential for human health, well-being, and food safety.

Lastly, the indicator of agricultural residues used for energy purposes quantifies the waste generated by the agricultural and food industry, as well as the potential for energy production from these residues. This indicator provides insights into the food-energy nexus, particularly in less developed contexts, where innovative approaches to utilising agricultural waste can contribute to energy security and sustainable resource management (Saladini *et al.,* 2016).

In conclusion, the water-energy-food security nexus, analysed through a series of indicators, offers a comprehensive framework for understanding and addressing the interconnected challenges and opportunities related to water, energy, and food systems. These indicators provide valuable insights into the social, economic, and environmental dimensions of the nexus, supporting evidence-based decision-making and policy development to achieve the SDGs.

3. Methodology and data

Constructing a comprehensive database grounded on the proposed indicators necessitates the collection of empirical data. However, data availability poses challenges for this analytical study, as some indicators are either unobtainable or outdated:

- The Multidimensional Poverty Index (MPI) is not calculated for all Mediterranean countries, requiring an estimation based on previous works as done by Saladini *et al.* (2018).
- For most less developed countries in the region, the original sources do not provide data on GHG emissions (total and AFOLU, t CO_2). Moreover, emissions are measured solely at the national level, overlooking the global impact of a country's environmental degradation.
- Although agricultural residues' use for energy purposes is relevant in representing the food-energy nexus in less developed contexts, it has not been computed at this level.
- The data on crop water productivity is outdated, with the latest available figures dating back to 2007.

To address the challenge of unavailable data, this study proposes the inclusion of additional indicators that are more readily available and can provide a more comprehensive picture of the situation in the Mediterranean region. These indicators include:

- Gini coefficient (0-100): This measure indicates the extent of income inequality in a country and can be used to assess the level of social inequality.
- Adjusted net national income per capita (constant 2015 USD): This indicator deducts the consumption of fixed capital and the depletion of natural resources from gross national income and references the result to the total population of the country. It is especially relevant for resource-rich, low-income countries. By using 2015 as the base year, the effect of price variation is removed, allowing for a more accurate assessment of the evolution of income.
- Carbon footprint, consumption-based accounting (t CO_2 per capita): This measure provides a more complete picture of a country's environmental impact by accounting for both national

emissions and those associated with international activities such as trade (Eora MRIO, 2023; Moran *et al.,* 2020).

- Renewable energy share in total final energy consumption (%): This indicator, which corresponds with SDG indicator 7.2.1, reflects the proportion of a country's total final energy consumption that is covered by renewable energy. It can provide insights into a country's efforts to transition to more sustainable energy sources (United Nations, 2023).

In addition, to enhance the assessment of security threats, this study suggests introducing an Index of Political Stability and Absence of Violence/Terrorism. This index measures the perceived risk of political instability or violence motivated by political factors, including terrorism. By standardising the scores to a normal distribution, the index typically ranges from -2.5 to 2.5 (World Bank, 2023b).

By incorporating these indicators, this study aims to provide a more comprehensive and nuanced assessment of the situation in the Mediterranean region. The final selection, units, codes, and data sources are disclosed in Table 1.

Table 1. Data sources

Variable – Abbreviation: Description, Unit (Database code)	Source
Pop Over: Adult population overweight, % (NCD_BMI_25C)	The Global Health Observatory (World Health Organization, 2023)
Var Agri Land: Variation of the share of agricultural land over the total land area, % (AG.LND.AGRI.ZS)	World Development Indicators (World Bank, 2023a)
Cer Yield: Cereal yield, kg/ha (AG.YLD.CREL.KG)	
Agri VA: Agricultural value added, constant USD 2015/worker (NV.AGR.EMPL.KD)	
Fert Consump: Fertilisers consumption, kg/ha arable land (AG.CON.FERT.ZS)	
Freshw Withd: Annual freshwater withdrawal for agriculture, % (ER.H2O.FWAG.ZS)	
Drink Wat Serv: Population using safely managed drinking water services, % (SH.H2O.SMDW.ZS)	
Sanit Serv: Population using safely managed sanitation services, % (SH.STA.SMSS.ZS)	
Gini: Gini coefficient, 0-100 (SI.POV.GINI)	
Adj NNI: Adjusted net national income per capita, constant 2015 USD (NY.ADJ.NNTY.PC.KD)	
Ren Energ: Renewable energy share in the total final energy consumption, % (SDG indicator 7.2.1)	UNSDG (United Nations, 2023)
Pol Stab: Index of Political Stability and Absence of Violence/Terrorism, standard normal distribution	Worldwide Governance Indicators (World Bank, 2023b)
C Footprint: Carbon footprint, t CO2/person	The Eora Global Supply Chain Database: Carbon Footprints of Nations (Eora MRIO, 2023; Moran *et al.,* 2020)

To enhance the comprehensiveness and precision of the analysis, this paper recommends focusing on countries that share a direct border with the Mediterranean Sea. Consequently, the selected territories include Spain, France, Italy, Malta, Slovenia, Croatia, Bosnia and Herzegovina, Montenegro, Albania, Greece, Türkiye, Cyprus, Syria, Lebanon, Israel, Egypt, Libya, Tunisia, Algeria, and Morocco.

An essential consideration in selecting indicators is data availability. To address this issue, this paper has developed a three-dimensional database, encompassing retrieved datasets for the chosen indicators and countries. While certain indicators have data available as early as 1960, it is important to note that data collection has not been continuous, resulting in variations in data availability across different years. Figure 1 illustrates the percentage of available data for each selected indicator and country.

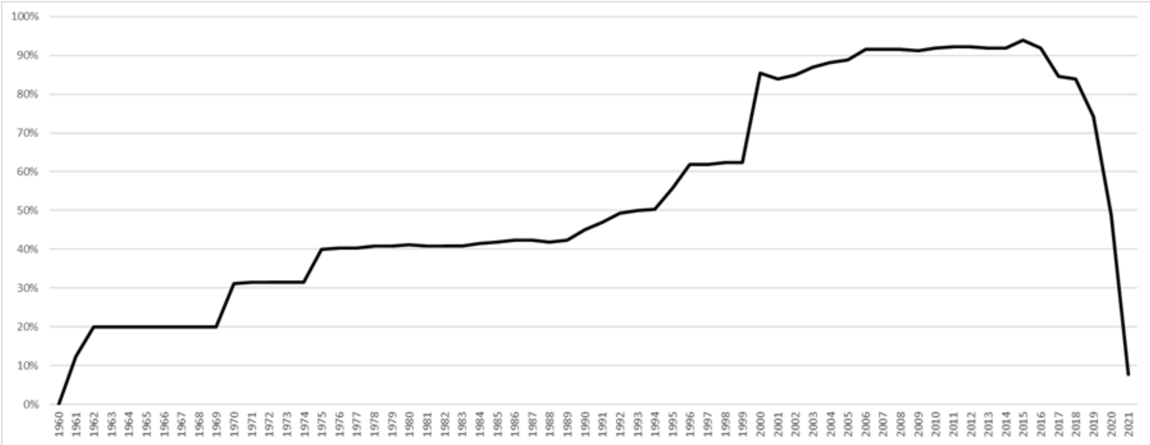

Figure 1. Share of data availability, 1960-2021. Source: Own elaboration based on the data in Table 1.

To ensure the most robust analysis, this paper strongly advises prioritising the years with the highest availability of data. This approach will allow for a more accurate representation of the trends and patterns within the Mediterranean region, enabling a deeper and more insightful examination of the chosen indicators' impact and significance.

Figure 1 illustrates the data availability over time, reaching its peak in 2015 with 94% of the database available. To ensure a suitable time gap from 2015, it is recommendable to select the year 2006, which boasts availability of 92%. Consequently, the analysis focuses on two years in the sample: 2006 and 2015. To estimate unavailable data, this proposal adopts two strategies.

The first strategy entails replacing missing indicators for a given year with the closest available value. If multiple values are equidistant from the missing year, the strategy prioritises the value from the previous year. On the other hand, the second strategy replaces completely missing indicators for a particular country with the mean value of the same indicator for the entire Mediterranean region for that specific year.

For the 2006 dataset, Strategy 1 is applied to compute the Gini coefficient for Croatia (2009), Bosnia and Herzegovina (2007), Montenegro (2012), Albania (2005), Syria (2003), Lebanon (2011), Egypt (2004), Tunisia (2005), and Algeria (2011). Additionally, the adjusted net national income per capita is estimated for Türkiye (2015), Syria (2015), and Libya (2015) using the same strategy. On the other hand, Strategy 2 is employed to determine the agricultural value added in Syria and Libya, freshwater withdrawals in Bosnia and Herzegovina, drinking water services in Türkiye, Syria, Egypt, and Libya, sanitation services in Syria, the Gini coefficient in Libya, and the adjusted net national income per capita in Malta.

Moving on to the 2015 dataset, Strategy 1 helps complete the data for drinking water services in Croatia (2007), the Gini coefficient in Bosnia and Herzegovina (2011), Syria (2003), Lebanon (2011), Algeria (2011), and Morocco (2013). As before, Strategy 2 is applied in the same instances as in the previous dataset.

Finally, an additional dataset is generated to compute the average values for each country and indicator. Here, the only missing values are those referenced in Strategy 2, specifically indicators that are fully unavailable for a country throughout the entire period.

Regarding procedures, this paper presents a comprehensive methodological sequence to analyse geopolitical actors, areas of cooperation and conflict, as well as convergences and divergences in the Mediterranean region. The proposed approach incorporates clustering techniques, forecasting, and convergence indexes to gain valuable insights into the region's future development.

The first methodological step involves using Ward's hierarchical clustering method to calculate clusters within the sample. This technique helps identify internally homogenous groups that play a crucial role in shaping the Mediterranean reality. To determine the optimal number of clusters, this proposal utilises the Thorndike criterion, which reduces distances between resultant groups (Thorndike, 1953). The clustering algorithm is performed for selected years (2006 and 2015) as well as average values across the sample.

One potential concern might be the influence of missing values on clustering results. However, the implemented analysis inherently lowers the degree of conditioning caused by these missing values. This is because clustering relies on various indicators that sufficiently reflect the national situation, making the absence of a few indicators unlikely to significantly affect the overall results since available variables serve as an anchor point.

In the second step, this method forecasts indicator values for each country up to 2030 and 2050 to repeat the clustering process with future projections. For simplicity, the forecasting technique is a non-seasonal exponential smoothing algorithm, applicable to data without seasonality and clear trends, like the dataset under study. These forecasts consider the entire time series, with more weight assigned to recent values as present events have more impact on subsequent happenings than past events. In cases where forecasting is not possible due to missing values or the unavailability of certain indicators, Strategy 2 is applied.

After implementing the clustering process with both present and future data, the resultant clusters are labelled based on the average values of each indicator within the group. This approach allows the identification and understanding of the characteristics of each cluster more effectively.

The third step involves computing convergence indexes for all past and future years considered. The index of convergence (IC) is calculated as the ratio between the value of an indicator (I) for a country and the average value of that indicator ($\bar{I}$) for the Mediterranean region (Med) in a particular year (t).

$$\mathrm{IC}_{\mathrm{c,Med,t}} = \frac{\mathrm{I}_{\mathrm{c,t}}}{\bar{\mathrm{I}}_{\mathrm{Med,t}}}$$

An IC value greater than 1 indicates that the cluster performs above the regional average, while values below 1 suggest the cluster performs below the average. The larger the deviation from 1, the greater the divergence between the cluster and the region. Analysing the convergence or divergence of each cluster helps provide valuable insights into potential future developments beyond a business-as-usual (BAU) projection.

This understanding of convergence and divergence assists in identifying areas of potential conflict and cooperation, allowing for a more realistic approach to future evolutions. Instead of solely relying on a BAU projection, our methodology considers the possible impact of various geopolitical actors and their interactions, providing a more nuanced understanding of the region's future dynamics. By incorporating clustering, forecasting, and convergence indexes, this paper offers a framework to analyse the complexities of the Mediterranean region and facilitate informed conclusions.

4. Results

In this section, the results of the previous methodology are presented in three subsections. Subsection 4.1 introduces the clusters obtained using factual data in average terms, 2006, and 2015. Subsection 4.2 presents the clusters forecasted for 2030 and 2050. Finally, Subsection 4.3 evaluates the degree of convergence or divergence for all the computed clusters.

4.1. Factual clusters

By utilising the mean values of each indicator and applying the criterion of optimality, the clustering algorithm successfully identifies two optimal clusters. This clustering approach results in a substantial coefficient reduction of 88.175 units in the agglomeration schedule, which is visually represented in Figure 2.

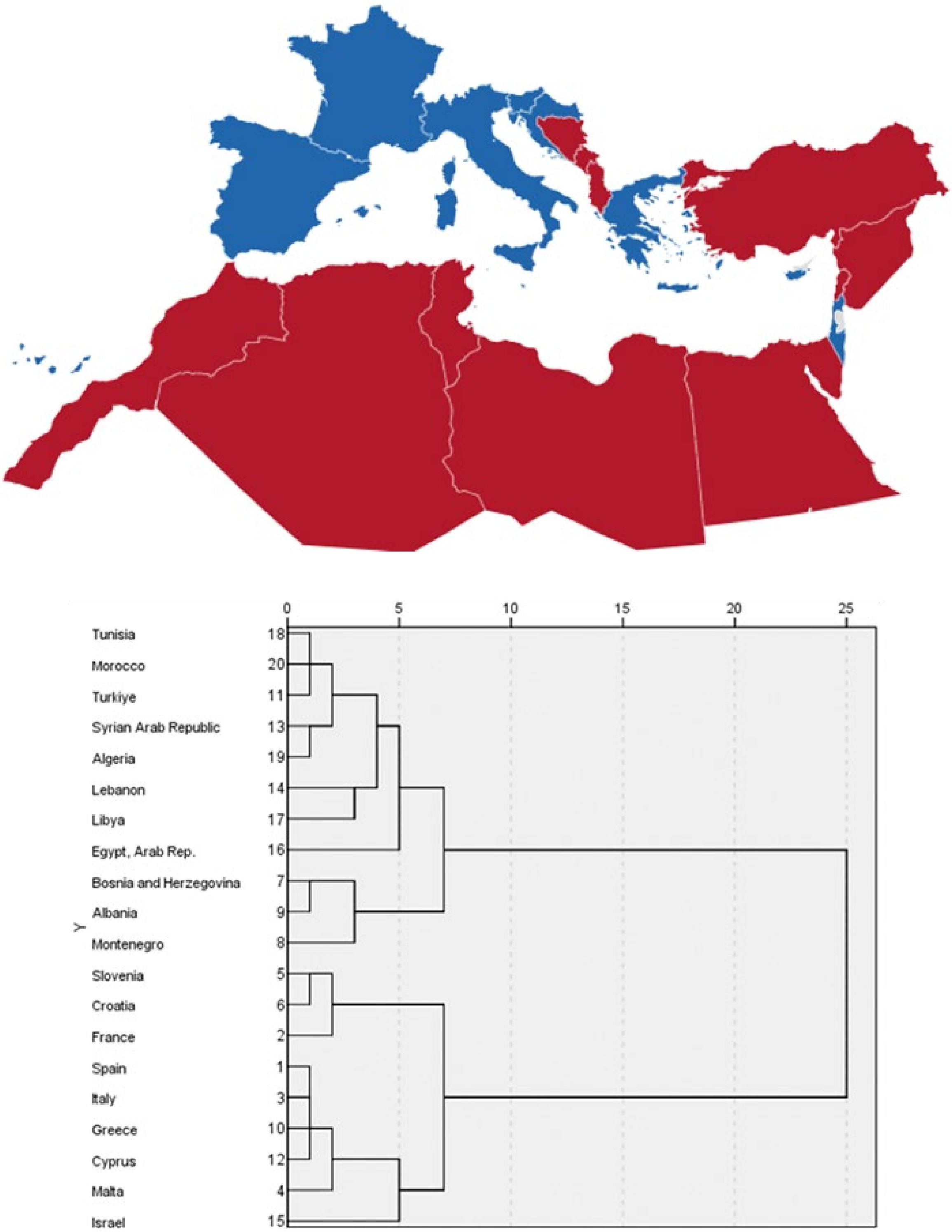

Figure 2. Dendrogram of average values. Source: Own elaboration based on the data in Table 1.

In terms of averages, the Mediterranean region can be categorised into two distinct clusters. Cluster 1 comprises Southern and Eastern countries, excluding Israel, along with European countries with relatively lower adaptation capacity. The countries included in Cluster 1 are Tunisia, Morocco, Türkiye, Syria, Algeria, Lebanon, Libya, Egypt, Bosnia and Herzegovina, Albania, and Montenegro. On the other hand, Cluster 2 consists of European countries with higher adaptation capacity, namely Slovenia, Croatia, France, Spain, Italy, Greece, Cyprus, Malta, and Israel. The values for each of the indicators considered to characterise these two clusters are presented in Table 2.

Table 2. Profiles of the clusters based on average values

	Cluster 1	Cluster 2
Countries	Tunisia, Morocco, Türkiye, Syria, Algeria, Lebanon, Libya, Egypt, Bosnia and Herzegovina, Albania, and Montenegro	Slovenia, Croatia, France, Spain, Italy, Greece, Cyprus, Malta, and Israel
Pop Over	45.94	53.21
Var Agri Land	0.0012	-0.0048
Cer Yield	2215.04	3741.62
Agri VA	9726.64	30920.21
Fert Consump	98.39	188.67
Freshw Withd	68.07	43.59
Drink Wat Serv	75.91	95.73
Sanit Serv	41.28	81.50
Gini	35.43	32.64
Adj NNI	3549.01	17541.51
Ren Energ	14.56	12.27
Pol Stab	-0.72	0.38
C Footprint	5305707.60	10394019.37

Table 2 reveals significant differences between Cluster 1 and Cluster 2 across various indicators. Cluster 2 stands out with higher values in several key metrics, including the prevalence of overweight population, cereal yield, agricultural value added, consumption of fertilisers, access to drinking water services, sanitation services, equality, adjusted national income, political stability, and carbon footprints. On the other hand, Cluster 1 experiences a positive annual variation of agricultural land, whereas Cluster 2 exhibits a negative trend in this regard. Moreover, freshwater withdrawals are higher in Cluster 1, along with a greater reliance on renewable energy sources.

However, it is essential to recognise that these average groupings are subject to annual fluctuations, as highlighted by the comparison of two selected moments: 2006 and 2015 (Fig. 3). This temporal analysis shows that the characteristics of both clusters may change over time, underlining the dynamic nature of the indicators and the need for ongoing monitoring and evaluation.

In 2006, the clustering algorithm identified 7 optimal clusters with a coefficient reduction of 76.846 units (Fig. 3 A). In contrast, in 2015, the algorithm revealed 5 clusters with a coefficient reduction of 64.768 units (Fig. 3 B). Notably, the composition of these clusters exhibited three prominent differences.

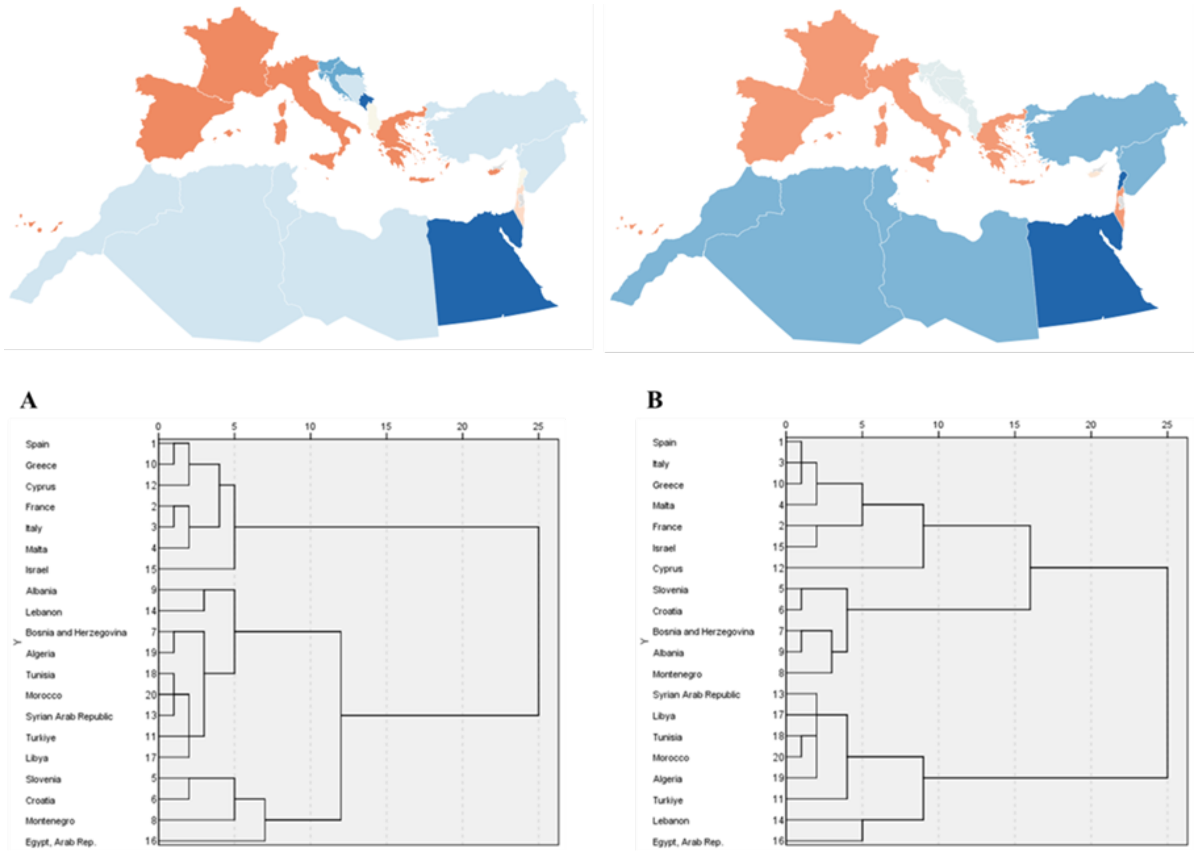

Figure 3. Dendrogram in 2006 (A) and 2015 (B). Source: Own elaboration based on the data in Table 1.

Firstly, there was a significant change in the proximity of Cyprus and Israel to European countries. In 2006, Cyprus was closer to the European cluster, while Israel stood as a unique one-case cluster, highlighting its distinctiveness. However, by 2015, the roles had reversed, and Cyprus became an individual case, while Israel joined the European cluster.

Secondly, Slovenia and Croatia remained in the same cluster in both years, but in 2015, they were joined by Bosnia and Herzegovina, Albania, and Montenegro, forming a larger cluster. Back in 2006, Bosnia and Herzegovina had been clustered with the Southern and Eastern countries, Albania had formed a cluster with Lebanon, and Montenegro had stood alone as an individual case. These shifts indicated a notable movement towards the European side of the sample and away from the African and Eastern regions.

Thirdly, in 2015, Egypt was no longer a single-case cluster, as it was joined by Lebanon.

These observations suggest significant changes in the clustering patterns over time, reflecting shifts in regional affiliations and highlighting the evolving dynamics within the dataset.

In Table 3, a detailed description of each cluster identified in 2006 is provided:

Cluster 1 is characterised by a higher prevalence of overweight population, a high share of drinking water and sanitation services, a high national income, and an elevated carbon footprint.

Cluster 2, represented by the individual case of Israel, shares some similarities with Cluster 1, but it has a lower cereal yield, higher agricultural value added and consumption of fertilisers, higher inequality, and lower political stability.

Cluster 3 is defined by a higher positive variation of agricultural land, poor agricultural value added, access to drinking water and sanitation services, as well as low carbon footprints.

Cluster 4 is determined by the low prevalence of overweight individuals, poor cereal yield, low fertiliser consumption, low sanitation services, higher inequality, lower national income, as well as low carbon footprints.

Cluster 5 is delimited by low freshwater withdrawals, higher equality, elevated national income, energy renewability, and political stability.

Cluster 6, which consists of the individual case of Montenegro, stands out for showing poor consumption of fertilisers and freshwater withdrawals, low sanitation services, and high inequalities, combined with high energy renewability and political stability.

Finally, Cluster 7, which consists of the individual case of Egypt, stands out for the low prevalence of overweight population, the lowest agricultural value added and national income, low renewability and carbon footprints, and high cereal yield, consumption of fertilisers, and freshwater withdrawals.

These clusters collectively offer valuable insights into the diverse socioeconomic and environmental characteristics observed during the 2006 study.

Table 3. Profiles of the clusters in 2006

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7
Countries	Spain, Greece, Cyprus, France, Italy, and Malta	Israel	Albania and Lebanon	Bosnia and Herzegovina, Algeria, Tunisia, Morocco, Syria, Türkiye, Libya	Slovenia and Croatia	Montenegro	Egypt
Pop Over	60.08	61.10	56.10	52.50	56.40	56.50	54.20
Var Agri Land	-0.0225	-0.0111	0.0399	-0.0025	-0.0098	0.0000	0.0028
Cer Yield	4052.62	2398.50	3143.70	1998.50	5268.10	2971.20	7500.20
Agri VA	30800.30	80343.90	4717.28	9677.25	8934.48	18421.84	4214.75
Fert Consump	144.44	304.95	99.66	52.63	351.40	18.70	586.56
Freshw Withd	52.25	56.84	48.66	75.55	0.76	5.42	86.08
Drink Wat Serv	98.05	99.86	49.90	78.03	83.56	83.87	83.43
Sanit Serv	86.31	84.36	26.75	40.31	57.97	28.14	56.23
Gini	31.85	41.60	31.20	35.71	28.50	41.20	31.80
Adj NNI	22387.49	24545.23	3917.64	3380.07	12901.46	4336.55	2397.43
Ren Energ	6.12	6.86	19.33	9.98	21.44	44.83	6.22
Pol Stab	0.30	-1.63	-0.80	-0.42	0.77	0.82	-0.61
C Footprint	13669131.67	13035500.00	4416144.50	4145240.29	10238664.00	9050883.00	3314026.00

Table 4 presents an analysis of the Mediterranean region in 2015, revealing distinctive characteristics and trends within five identified clusters.

Cluster 1 stands out for its high prevalence of overweight population, cereal yield, agricultural value added, access to drinking water and sanitation services, national income, and carbon footprints. This cluster represents countries with strong agricultural and economic performance, coupled with relatively healthy living conditions.

Cyprus (Cluster 2) shares similarities with Cluster 1 in various aspects. However, it differs with lower cereal yield and higher freshwater withdrawals, as well as facing challenges with political stability.

Cluster 3 is characterised by a lower prevalence of overweight population, agricultural value added, and freshwater withdrawals. Notably, it shows a positive aspect of higher equality and energy renewability.

On the other hand, Cluster 4 is defined by poor cereal yield, high consumption of fertilisers, low national income, limited energy renewability, and political instability. Additionally, this cluster experiences significant inequality issues, reflecting socio-economic challenges.

Cluster 5 exhibits a mixed profile, with a high prevalence of overweight population and cereal yield, but also poor agricultural value added, limited access to drinking water and sanitation services, low national income, and renewable energy usage. Moreover, this cluster faces difficulties in achieving a low carbon footprint.

Globally, the clustering patterns suggest an evolution towards a bipolar Mediterranean region. While less adaptable European countries were previously clustered with African and Eastern countries in 2006, by 2015, they gravitated towards a distinct European sphere, leaving African and Eastern countries in their respective geographically specific groups. Consequently, the clusters in 2015 are less geographically diverse than in 2006. The observed trends indicate that the conditions of the nexus no longer vary country by country, but rather from one geographical context to another, creating a clear bipolar trend within the region.

Table 4. Profiles of the clusters in 2015.

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
Countries	Spain, Italy, Greece, Malta, France, and Israel	Cyprus	Slovenia, Croatia, Bosnia and Herzegovina, Albania, and Montenegro	Syria, Libya, Tunisia, Morocco, Algeria, and Türkiye	Lebanon and Egypt
Pop Over	65.62	60.30	49.90	61.20	63.60
Var Agri Land	-0.0040	0.1624	0.0058	0.0011	0.0123
Cer Yield	5038.82	2683.00	3968.55	1649.02	5193.00
Agri VA	48227.13	18079.58	9023.20	14424.08	5997.44
Fert Consump	151.69	158.00	157.86	45.04	417.51
Freshw Withd	50.71	66.33	22.89	81.72	61.21
Drink Wat Serv	98.92	99.17	70.37	81.13	67.01
Sanit Serv	90.14	76.83	43.01	48.16	38.89
Gini	34.90	34.00	26.88	35.75	31.80
Adj NNI	22333.57	20097.61	6498.41	3890.27	4690.78
Ren Energ	12.24	10.51	26.86	6.80	4.81
Pol Stab	0.20	0.49	0.29	-1.43	-1.40
C Footprint	10133597.00	11524140.00	6279532.83	4100844.33	3998917.00

4.2. Forecasted clusters

After applying the clustering algorithm to the forecasted values, the data reveals two distinct clusters for the year 2030, showcasing a notable coefficient reduction of 72.643 units (Fig. 4 A). In 2050, the algorithm identifies six clusters, resulting in a significant coefficient reduction of 68.316 units (Fig. 4 B).

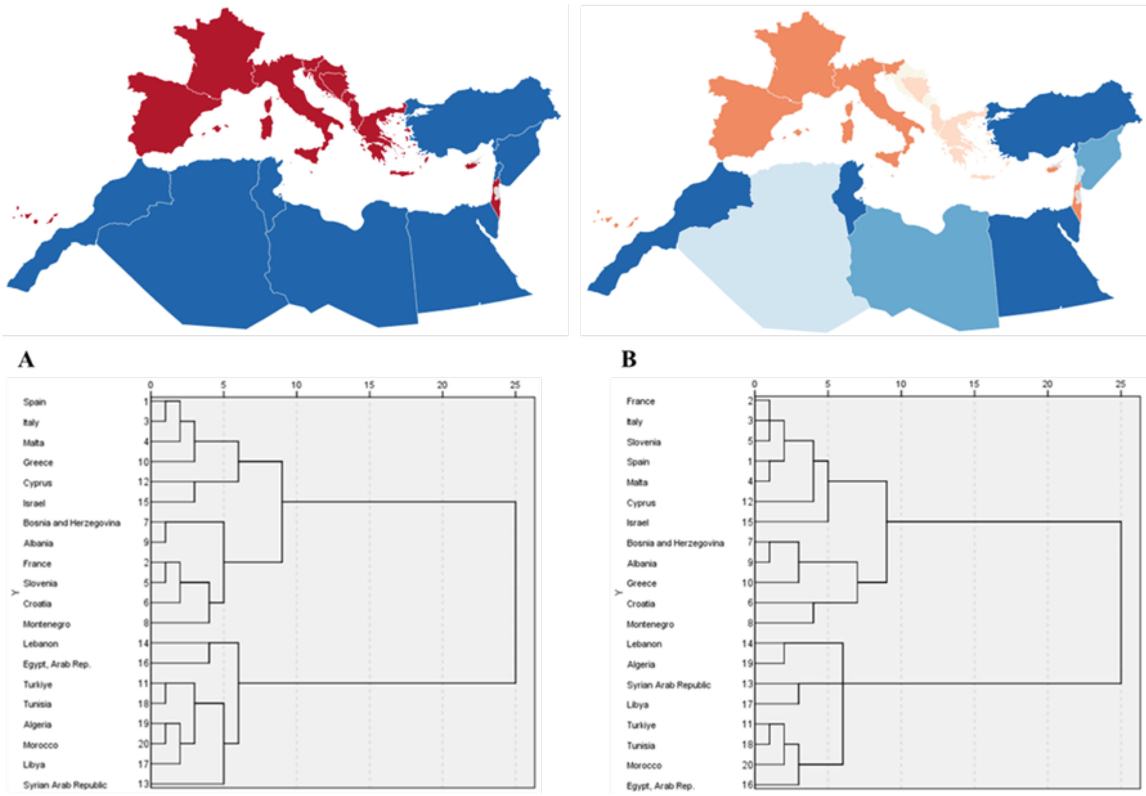

Figure 4. Dendrogram in 2030 (A) and 2050 (B). Source: Own elaboration based on the data in Table 1.

In 2030, the clustering algorithm segregates Europe and Israel from North African and Eastern countries (excluding Israel) into two distinct clusters.

By 2050, the clustering outcomes demonstrate more profound differences between the clusters. The European cluster strengthens as Slovenia joins its ranks, indicating closer ties among its member countries. Croatia and Montenegro form a separate cluster, suggesting a shift in their relations with the broader European group. Greece, Bosnia and Herzegovina, and Albania unite to form a distinct cluster, indicating a departure from the larger European majority. Fragmentation occurs among the Southern and Eastern countries, with Lebanon and Algeria forming one cluster and Syria and Libya forming another. Türkiye forms a close association with Tunisia, Morocco, and Egypt, implying increased collaboration with North Africa.

These changes reflect the evolving geopolitical landscape and the emergence of new alliances and relationships in the regions, shaping the future dynamics of Europe, Israel, North Africa, and the Eastern countries.

Table 5 presents a comprehensive overview of the year 2030, highlighting Cluster 1 as a standout performer across various indicators. This cluster demonstrates a higher prevalence of overweight population, cereal yield, agricultural value added, consumption of fertilisers, access to drinking water and sanitation services, income equality, renewable energy usage, and political stability. However, it also shows lower freshwater withdrawals and agricultural land compared to other clusters. Despite its strengths, Cluster 1 does exhibit a concerning characteristic: a high carbon footprint.

Fast forward to the year 2050, Table 6 reveals some striking forecasted values that surpass the maximum or minimum thresholds of their respective indicators. These values indicate significant variations in recent years, likely attributed to the forecasting algorithm's heavier reliance on the most recent available data within the sample. In Table 6, these instances are marked as “Min./Max. Logical value (Forecasted value)”, underlining the extreme nature of these deviations. It is essential to interpret these extreme values with caution due to their potential sensitivity to the most recent data inputs in the forecasting model.

Table 5. Profiles of the clusters in 2030

	Cluster 1	Cluster 2
Countries	Spain, Italy, Malta, Greece, Cyprus, Israel, Bosnia and Herzegovina, Albania, France, Slovenia, Croatia, and Montenegro	Lebanon, Egypt, Türkiye, Tunisia, Algeria, Morocco, Libya, and Syria
Pop Over	70.88	75.52
Var Agri Land	-0.0021	0.0016
Cer Yield	5467.85	2770.06
Agri VA	42299.96	17630.88
Fert Consump	194.30	165.59
Freshw Withd	40.11	73.63
Drink Wat Serv	96.07	83.40
Sanit Serv	80.33	52.80
Gini	31.48	33.71
Adj NNI	17593.52	7984.19
Ren Energ	25.08	4.74
Pol Stab	0.26	-2.15
C Footprint	9824054.90	3354755.24

Table 6. Profiles of the clusters in 2050

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Countries	France, Italy, Slovenia, Spain, Malta, Cyprus, and Israel	Bosnia and Herzegovina, Albania, and Greece	Croatia and Montenegro	Lebanon and Algeria	Syria and Libya	Türkiye, Tunisia, Morocco, and Egypt
Pop Over	81.25	82.73	81.54	96.61	91.68	93.53
Var Agri Land	0.0115	-0.0114	-0.0200	0.0053	-0.0068	0.0022
Cer Yield	6513.28	6872.47	6959.29	3286.33	1629.87	4246.55
Agri VA	83992.88	14954.49	29825.93	27506.65	44316.70	12555.47
Fert Consump	160.95	170.08	652.24	164.95	63.79	274.93
Freshw Withd	38.56	62.89	11.35	30.69	85.50	81.74
Drink Wat Serv	Max. 100.00 (104.78)	Max. 100.00 (102.79)	85.84	66.63	97.49	Max. 100.00 (102.03)
Sanit Serv	95.34	89.80	71.60	18.56	47.39	91.20
Gini	32.28	35.27	11.42	30.73	41.84	28.73
Adj NNI	26086.71	6630.31	14973.32	7169.57	15354.32	7398.53
Ren Energ	26.21	42.22	37.77	0.67	1.22	2.72
Pol Stab	0.56	-0.05	-0.02	-1.46	Min. -2.50 (-7.50)	-2.24
C Footprint	11437537.75	10765808.09	9565674.22	3057415.50	Min. 0 (-3836096.22)	4886482.31

Table 6 presents the clustering results for the year 2050, showcasing distinct characteristics and trends among the identified clusters:

Cluster 1 stands out for its remarkable positive variations in several indicators, including agricultural land, cereal yield, agricultural value added, drinking water and sanitation services, national income, political stability, and carbon footprint. Additionally, it exhibits the lowest prevalence of overweight population.

Similar to Cluster 1, Cluster 2 shares many characteristics, but it has lower levels of agricultural value added and national income.

Cluster 3 is characterised by a low prevalence of overweight population, a negative trend in agricultural land, high cereal yield, and fertiliser consumption. It also displays low freshwater withdrawals, along with high levels of equality and energy renewability.

In contrast to the previous clusters, Cluster 4 is defined by a very high prevalence of overweight population, along with low levels of drinking water and sanitation services, national income, and renewability.

Cluster 5 shares similarities with Cluster 4, but it features lower cereal yield and fertiliser consumption, reduced sanitation services, higher inequality, and poorer renewability.

Cluster 6 stands out with poor agricultural value added, high freshwater withdrawals, drinking and sanitation services, and lower income and renewability.

There are two cases where certain values exceed the maximum or minimum levels of their respective indicators. In European countries and Israel, as well as in Türkiye, Tunisia, Morocco, and Egypt, there has been a positive evolution in drinking water services. Particularly, the less adaptable countries in Southern and Eastern regions are gradually catching up with European countries. However, the evolution of sanitation services is more pessimistic in these regions. In Syria-Libya, the projected values adopt extreme rhythms of evolution due to recent security events observed in the cited countries, leading to a massive increase in political instability and a considerable reduction in carbon footprint.

4.3. Convergence

The index of convergence shows the following results in the average clustering (Table 7), 2006 (Table 8), 2015 (Table 9), 2030 (Table 10), and 2050 (Table 11).

The analysis uncovers noteworthy divergences between clusters, primarily revolving around agricultural land variation, political stability index, adjusted net national income per capita, and agricultural value added. Initially, the consumption of fertilisers shows convergence until 2030 but diverges again in 2050. In contrast, prominent convergences are observed in the Gini coefficient, prevalence of overweight population, and drinking water services. However, the Gini coefficient shifts towards significant divergence in 2050, primarily influenced by the behaviour of two clusters: Cluster 3 (comprising Croatia and Montenegro) and Cluster 5 (encompassing Syria and Libya). It is crucial to consider that the recent trends in these countries may drive significant future evolutions, which could potentially moderate in the forthcoming years, thus mitigating the apparent divergence.

It is evident that the Mediterranean region significantly differs in terms of agricultural evolution, productivity, income levels, and country stability. However, it shares similarities in terms of the prevalence of overweight populations, the progress of drinking water facilities, and to a noteworthy extent, the level of equality measured by the Gini coefficient.

Table 7. Index of convergence in the clustering of average values.

	Cluster 1	Cluster 2
Countries	Tunisia, Morocco, Türkiye, Syria, Algeria, Lebanon, Libya, Egypt, Bosnia and Herzegovina, Albania, and Montenegro	Slovenia, Croatia, France, Spain, Italy, Greece, Cyprus, Malta, and Israel
Pop Over	0.93	1.07
Var Agri Land	-0.66	2.66
Cer Yield	0.74	1.26
Agri VA	0.48	1.52
Fert Consump	0.69	1.31
Freshw Withd	1.22	0.78
Drink Wat Serv	0.88	1.12
Sanit Serv	0.67	1.33
Gini	1.04	0.96
Adj NNI	0.34	1.66
Ren Energ	1.09	0.91
Pol Stab	-4.27	2.27
C Footprint	0.68	1.32

Table 8. Index of convergence of the clusters in 2006.

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7
Countries	Spain, Greece, Cyprus, France, Italy, and Malta	Israel	Albania and Lebanon	Bosnia and Herzegovina, Algeria, Tunisia, Morocco, Syria, Türkiye, Libya	Slovenia and Croatia	Montenegro	Egypt
Pop Over	1.06	1.08	0.99	0.93	0.99	1.00	0.96
Var Agri Land	48.76	23.99	-86.33	5.43	21.30	0.00	-6.15
Cer Yield	1.04	0.61	0.81	0.51	1.35	0.76	1.92
Agri VA	1.37	3.58	0.21	0.43	0.40	0.82	0.19
Fert Consump	0.65	1.37	0.45	0.24	1.58	0.08	2.63
Freshw Withd	1.12	1.22	1.05	1.62	0.02	0.12	1.85
Drink Wat Serv	1.19	1.21	0.61	0.95	1.01	1.02	1.01
Sanit Serv	1.59	1.55	0.49	0.74	1.07	0.52	1.04
Gini	0.92	1.20	0.90	1.03	0.82	1.19	0.92
Adj NNI	2.12	2.33	0.37	0.32	1.22	0.41	0.23
Ren Energ	0.37	0.42	1.18	0.61	1.31	2.73	0.38
Pol Stab	1.36	-7.31	-3.61	-1.87	3.48	3.68	-2.73
C Footprint	1.65	1.58	0.53	0.50	1.24	1.09	0.40

Table 9. Index of convergence of the clusters in 2015.

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
Countries	Spain, Italy, Greece, Malta, France, and Israel	Cyprus	Slovenia, Croatia, Bosnia and Herzegovina, Albania, and Montenegro	Syria, Libya, Tunisia, Morocco, Algeria, and Türkiye	Lebanon and Egypt
Pop Over	1.09	1.00	0.83	1.02	1.06
Var Agri Land	-0.11	4.57	0.16	0.03	0.35
Cer Yield	1.36	0.72	1.07	0.44	1.40
Agri VA	2.52	0.94	0.47	0.75	0.31
Fert Consump	0.82	0.85	0.85	0.24	2.24
Freshw Withd	0.90	1.17	0.40	1.44	1.08
Drink Wat Serv	1.19	1.19	0.84	0.97	0.80
Sanit Serv	1.52	1.29	0.72	0.81	0.65
Gini	1.07	1.04	0.82	1.09	0.97
Adj NNI	1.94	1.75	0.56	0.34	0.41
Ren Energ	1.00	0.86	2.19	0.56	0.39
Pol Stab	0.54	1.33	0.78	-3.85	-3.79
C Footprint	1.41	1.60	0.87	0.57	0.55

Table 10. Index of convergence of the clusters in 2030.

	Cluster 1	Cluster 2
Countries	Spain, Italy, Malta, Greece, Cypurs, Israel, Bosnia and Herzegovina, Albania, France, Slovenia, Croatia, and Montenegro	Lebanon, Egypt, Türkiye, Tunisia, Algeria, Morocco, Libya, and Syria
Pop Over	0.97	1.03
Var Agri Land	8.12	-6.12
Cer Yield	1.33	0.67
Agri VA	1.41	0.59
Fert Consump	1.08	0.92
Freshw Withd	0.71	1.29
Drink Wat Serv	1.07	0.93
Sanit Serv	1.21	0.79
Gini	0.97	1.03
Adj NNI	1.38	0.62
Ren Energ	1.68	0.32
Pol Stab	0.28	-2.28
C Footprint	1.49	0.51

Table 11. Index of convergence of the clusters in 2050

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Countries	France, Italy, Slovenia, Spain, Malta, Cyprus, and Israel	Bosnia and Herzegovin, Albania, and Greece	Croatia and Montenegro	Lebanon and Algeria	Syria and Libya	Türkiye, Tunisia, Morocco, and Egypt
Pop Over	0.92	0.94	0.93	1.10	1.04	1.06
Var Agri Land	-3.58	3.55	6.22	-1.63	2.13	-0.69
Cer Yield	1.32	1.40	1.42	0.67	0.33	0.86
Agri VA	2.36	0.42	0.84	0.77	1.25	0.35
Fert Consump	0.65	0.69	2.63	0.67	0.26	1.11
Freshw Withd	0.74	1.21	0.22	0.59	1.65	1.58
Drink Wat Serv	1.12	1.10	0.92	0.71	1.05	1.09
Sanit Serv	1.38	1.30	1.04	0.27	0.69	1.32
Gini	1.07	1.17	0.38	1.02	1.39	0.96
Adj NNI	2.02	0.51	1.16	0.55	1.19	0.57
Ren Energ	1.42	2.29	2.05	0.04	0.07	0.15
Pol Stab	0.31	-0.03	-0.01	-0.82	-4.20	-1.25
C Footprint	1.91	1.80	1.60	0.51	-0.64	0.82

5. Discussion

The study's findings present an opportunity for policymakers to address pressing challenges and foster a more secure future for the Mediterranean region. To achieve this, several politically relevant actions and areas for future research can be proposed:

Firstly, climate adaptation measures should be a top priority for policymakers, especially in vulnerable Southern and Eastern Mediterranean countries. Rising sea levels, extreme weather events, and water scarcity necessitate urgent actions to enhance resilience and preparedness. Collaboration and information exchange between clusters of countries can facilitate mutual learning and accelerate adaptation efforts. Policymakers should actively promote regional cooperation to tackle shared climate challenges effectively.

Secondly, with evolving clustering patterns and potential geopolitical shifts, policymakers must engage in proactive diplomatic efforts. Building strong relationships and promoting dialogue can be instrumental in mitigating conflicts and enhancing regional stability. Diplomacy should focus on finding common ground and fostering cooperation among nations to ensure shared interests are addressed and tensions are minimised.

Furthermore, policymakers should adopt nexus-based policies that recognise the interconnected nature of water, energy, and food resources. Integrated approaches can promote sustainability, efficiency, and resilience across the region. By acknowledging the interdependencies between these critical resources, policymakers can design more effective and holistic policies that avoid unintended consequences and enhance overall security.

Long-term planning is crucial to navigating potential fragmentation and convergence trends identified in the study. Policymakers should develop flexible plans that account for changing geopolitical dynamics. This approach enables adjustments as new information emerges and ensures that policies remain relevant and effective over time.

Future research is essential for enhancing our understanding of the region's dynamics. Updating the study with more recent data and including additional indicators can provide a more comprehensive and up-to-date perspective. Investigating the impacts of specific events or policy interventions on clustering patterns will offer valuable insights for policymakers, guiding them in making informed decisions and evaluating the effectiveness of implemented measures.

Incorporating relevant stakeholders, such as governments, international organisations, academia, and civil society, in the decision-making processes is crucial for successful policy implementation. Engaging diverse perspectives can lead to more inclusive and robust policies and strategies. Stakeholders' involvement ensures that policies are well-rounded, practical, and reflect the needs and aspirations of various groups in the region.

6. Conclusions

This paper presents an analysis of the security status of the Mediterranean region, focusing on the water-energy-food nexus and its vulnerability to climate change. The study utilises a set of indicators chosen to reflect the nexus within the framework of the Sustainable Development Goals (SDGs) and augments it with data availability and timeliness. The Thorndike's optimal geopolitical groups are identified using the Ward's hierarchical clustering algorithm for two distinct time points (2006 and 2015) with factual data and two projected values for 2030 and 2050 using the exponential smoothing algorithm.

The average security status of the area is shaped by two main clusters: the Southern and Eastern countries (excluding Israel) and the European countries with lower adaptation capacity on one side, and the European countries with higher adaptation capacity, including Israel, on the other. However, the clustering pattern varies annually due to ongoing events, resulting in 7 clusters in 2006 and 5 clusters in 2015. Several noteworthy shifts occurred during this period, such as the role reversal between Cyprus and Israel, the clustering of Slovenia, Croatia, Bosnia and Herzegovina, Albania, and Montenegro, and Egypt's transition from a single-case cluster to a joint cluster with Lebanon.

Looking into the future, the study identifies 2 optimal clusters for 2030 and 6 clusters for 2050. Significant changes are observed between these forecasted periods, including Slovenia joining the vast European cluster, Croatia forming a cluster with Montenegro, and Greece separating from the European majority to create a cluster with Bosnia and Herzegovina and Albania. Additionally, there is fragmentation within the Southern and Eastern countries, with Lebanon and Algeria, Syria and Libya forming two-case clusters, and Türkiye clearly associated with Tunisia, Morocco, and Egypt.

To further delineate these groups, the paper calculates the index of convergence for each indicator in the resulting clusters. The indicators that exhibit recurrent divergences include variation in agricultural land, the index of political stability, adjusted net national income per capita, and agricultural value added. However, the consumption of fertilisers converges until 2030 and diverges in 2050. Furthermore, there are convergences in the Gini coefficient, the prevalence of overweight population, and drinking water services, with the Gini coefficient showing an evolution towards divergence in 2050.

The findings of this study hold significant importance for policymakers, researchers, and stakeholders concerned with the security and sustainability of the Mediterranean region. By focusing on the water-energy-food nexus and its vulnerability to climate change, the study sheds light on critical aspects that require attention to ensure the region's resilience and stability.

The identification of optimal geopolitical clusters provides valuable insights into the region's dynamics and interconnections. Understanding the clustering patterns helps in recognising potential alliances, partnerships, and shared challenges among countries. Policymakers can use this knowledge to foster cooperation and build adaptive strategies to tackle climate change impacts on the nexus components.

The study's forecasted scenarios for 2030 and 2050 offer valuable foresight into the region's potential trajectories. By identifying shifts and fragmentations in the clusters, decision-makers can anticipate geopolitical changes and proactively address emerging security challenges. These projections aid in preparing long-term policies and investments that align with the evolving geopolitical landscape.

Furthermore, the index of convergence for different indicators provides a nuanced understanding of the factors that drive or hinder regional cooperation and convergence. Policymakers can use this information to target specific areas for improvement, such as promoting sustainable agricultural practices, enhancing political stability, and addressing income disparities. By identifying areas of convergence, policymakers can also foster knowledge-sharing and capacity-building among countries facing similar challenges.

The study's findings offer an opportunity in the Mediterranean region to address pressing challenges and foster a more secure future. Key actions proposed include prioritising climate adaptation measures, engaging in proactive diplomacy, adopting integrated nexus-based policies for water, energy, and food resources, and developing long-term flexible planning to address geopolitical shifts. Future research is recommended to update data and indicators and investigate the impacts of specific events or policies. Additionally, involving diverse stakeholders in decision-making processes is essential for successful policy implementation, ensuring inclusivity and practicality in the region's policies and strategies. By implementing these actions and conducting further research, our societies can work towards a more secure and sustainable future for the Mediterranean.

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EXPLORING AGRICULTURE, CLIMATE CHANGE AND FOOD PLANNING NEXUS: WHERE DOES TERRITORIAL PLANNING STAND?

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ABSTRACT. In Portugal, local answers to climate change and food are basically twofold: the approval of a Climate Adaptive Strategy or Plan, which are largely being formulated by Portuguese municipalities and the voluntary signature of the Glasgow Food and Climate Declaration. As both folds are not binding their impact is limited. However, a recent Portuguese framework Law on Climate [2021], aligned with the European Green Deal, imposes that all municipalities must approve a municipal climate action plan before summer 2024. Such a context opens up a window of opportunity to reflect on the lessons learned from the already approved Climate Adaptive Plans and Strategies.

Therefore, we explore in this paper the following inter - connected questions: (1) to what extent Climate Adaptive Plans and Strategies include the increase of local food production; (2) Do they consider each step of the food chain or solely food production? (3) To what extent are those measures transcribed into the planning rules and regulations. In order to do so, we analysed 14 Climate Adaptive Strategies or Plans of a selected group of cities that entered the national competition ECO XXI, based on a sustainable framework of multiple dimensions. In 2021, as much as 57 out of the 308 Portuguese municipalities entered the competition.

Results suggest that adaptive measures relate to increasing local agriculture, mapping out land availability or highlighting the need for local agroecological practices. Moreover, Climate Adaptive Strategies or Plans, measures and actions are predominantly related to agriculture production, leaving behind subsequent food chain activities. This is probably happening due to a narrow and sectorial vision of agriculture that do not consider each one of the stages of the food chain. Lastly, the inclusion of several measures and actions into planning instruments is quite promising, even if still fragile to transform existing reality.

In conclusion, there is an urgent need to expand among food stakeholders the understanding of food and agriculture as part of the food system. In addition, there is a need to increase planner's awareness to these topics as in practice the link between food, climate and planning is still missing. Findings highlight that the potential role of planning is not being fully unleashed. Such a consideration is in line with other international studies confirming that Portugal is not an exception. Therefore, lessons we learned might turn useful for other countries.

Explorando el nexo entre agricultura, cambio climático y planificación alimentaria. ¿Dónde se encuentra la planificación territorial?

RESUMEN. En Portugal, las respuestas locales al cambio climático y a los alimentos son básicamente dos: la aprobación de una Estrategia o Plan de Adaptación al Clima, que está siendo formulada en gran medida por los municipios portugueses, y la firma voluntaria de la Declaración Climática y Alimentaria de Glasgow. Como ambas medidas no son vinculantes, su impacto es limitado. Sin embargo, una reciente ley portuguesa sobre el clima [2021], alineada con el Pacto Verde Europeo, impone que todos los municipios deben aprobar un plan de acción municipal sobre el clima antes del verano de 2024. Este contexto abre una ventana de oportunidad para reflexionar sobre las lecciones aprendidas de los Planes y Estrategias de Adaptación al Clima ya aprobados.

Por lo tanto, tratamos de responder en este trabajo las siguientes preguntas interrelacionadas: (1) ¿En qué medida los Planes y Estrategias de Adaptación al Clima incluyen el aumento de la producción local de alimentos?; (2)

¿Consideran cada paso de la cadena alimentaria o únicamente la producción de alimentos? (3) ¿En qué medida esas acciones se transcriben en normas y reglamentos de planificación?
Para ello, se analizaron 14 Estrategias o Planes de Adaptación al Clima de un grupo seleccionado de ciudades que ingresaron al concurso nacional ECO XXI, basado en un marco sostenible de múltiples dimensiones. En 2021, hasta 57 de los 308 municipios portugueses participaron en el concurso.
Los resultados sugieren que las medidas de adaptación se relacionan con el aumento de la agricultura local, la cartografía de disponibilidad de tierras o la necesidad de prácticas agroecológicas locales. Además, las Estrategias o Planes de Adaptación al Clima, medidas y acciones están relacionadas predominantemente con la producción agrícola, dejando atrás las actividades posteriores de la cadena alimentaria. Esto se debe probablemente a una visión estrecha y sectorial de la agricultura que no considera cada una de las etapas de la cadena alimentaria. Por último, la inclusión de varias medidas y acciones en los instrumentos de planificación es bastante prometedora, aunque todavía frágil para transformar la realidad existente.
En conclusión, hay una necesidad urgente de ampliar entre los interesados la comprensión de los alimentos y la agricultura como parte del sistema alimentario. Además, es necesario aumentar la conciencia de los planificadores sobre estos temas, ya que en la práctica todavía no existe un vínculo entre la alimentación, el clima y la planificación. Las conclusiones ponen de relieve que no se está aprovechando plenamente la función potencial de la planificación. Esta consideración coincide con otros estudios internacionales que confirman que Portugal no es una excepción. Por lo tanto, las lecciones que hemos aprendido pueden resultar útiles para otros países.

Key words: Climate change, climate plans, food system, agriculture, food planning.

Palabras clave: Cambio climático, planes climáticos, sistema alimentario, agricultura, planificación de la alimentación.

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1. Introduction

In 2021, the United Nations Intergovernmental Panel on Climate Change sounded the alarm on a looming crisis: Climate Change is generating a "red code for humanity" that requires urgent action (IPCC, 2022). Food systems are deeply entwined with this crisis. In many regions, especially in the developing world, Climate change has already started to reduce agricultural productivity and disrupt supply food chains. Therefore, putting pressure on the livelihoods and threatening significantly hunger and malnutrition, making adaptation efforts crucially important (IPCC, 2022). Recent estimates indicate that food systems contribute more than one third to Greenhouse Gas (GHG) emissions (E.C., 2020). Addressing the challenges of climate change already require a transformation of our food systems, that demands major policy reforms, substantial investment, and an enabling environment that fosters innovation (IPCC, 2022). The urgent need to put food and agriculture at the heart of the global response to the climate emergency is at the core of the Glasgow Food and Climate Declaration, launched in COP26 (2021) and already signed by 114 cities and regions (Nourish Scotland, 2020). Cities are part of the problem but also of the solution. For instance, C40, a network of 96 world cities committed to climate change adaptation and mitigation is recommending to the cities that are part of this network, early consideration of climate hazards and potential responses in order to reduce the risks and protect food supply chains (C40, 2019). The involvement of cities with climate change is in the agenda for the last decade under the umbrella of the European Commission. In 2013 the European Commission approved it Strategy to Climate Adaptation (European Comission, 2013). This strategy is at the core of both the Mayors Adapt initiative and the Covenant of Mayors Initiative on Climate Change Adaptation. Since its beginning, one key action adopted by the Mayors Adapt signatories was to formulate a comprehensive local adaptation strategy and to integrate adaptation to climate change measures into relevant existing plans. A large number of cities all over Europe, including Portugal, started to formulate such plans and strategies that will be analysed here.

More recently, the European Commission approved in 2020 the European Green Deal (EGD) which is at the forefront of European commitment to tackling climate and environmental-related challenges. One of its major components is the 'Farm to Fork': designing a fair, healthy and environmentally friendly food system strategy (E.C., 2020). Under this strategy several measures on impact and climate change adaption are being considered notably, the reductions of chemical pesticides, fertilisers and antibiotics, or the need to increase organic farming areas. Other measures refer to the need to reduce the environmental impact of the food processing and retail sectors by acting on transport, storage, packaging and food waste. EGD urges as well to increase sustainable food consumption and affordable healthy food for all, in order to reducing the environmental footprint. This is not an easy task as the development of an integrated food policy raises many challenges ahead (Candel and Pereira, 2017; Delgado, 2018, 2023). Within this new European framework, the Portuguese Law on Climate was approved at the end of 2021 (Law n. 98/2021). It recognized that the food chain, including production, fisheries and food consumption is part of a transition towards a more climate neutral society. It is highlighted that local authorities, within the scope of their attributions and competences, should plan and implement climate policies, ensuring their consistency with territorial planning instruments. Those policies, strategies and plans are now mandatory and should be formulated and approved by local authorities before mid-2024, under the Portuguese Law on Climate (Law nº 98/2021).

This new policy window is a unique opportunity to analyse and reflect upon what has been done so far. This paper main aim is to extract lessons from this first round of Climate Adaptive Strategies and Plans developed during the last decade in Portugal, as a tool to advance the forthcoming ones. In order to do this, this paper explores the following research questions: (1) to what extent Climate Adaptive Strategies and Plans include the increase of local food production; (2) Do they consider each step of the food chain or solely food production? (3) To what extent are those measures transcribed into the planning rules and regulations. Our analysis will refer to a selected group of 14 Portuguese municipalities that entered the national competition ECO XXI, based on a sustainable framework of multiple dimensions. All the 14 strategies and plans were developed at municipal level between 2016 and 2020 i.e., previously to the new European Green Deal.

Following the present introduction, section 2 posits the theoretical framework notably the missing conceptual links between agriculture, climate and planning. Section 3 introduces the Portuguese study case and explains the methodology used for investigating it. Section 4 highlights the results from the analysis of 14 selected Climate Adaptative Strategies and Plans focusing on the extent to which they consider food and agricultures as an answer to climate change adaptation. Section 5 discusses the findings, connects back to the theoretical framework and addresses both research questions. The paper concludes upon the relevance of strengthening and deepening investigations on the agriculture, climate change and food planning nexus, in Portugal and beyond.

2. Theoretical framework – the missing links between planning, food and climate

Urban planning still largely ignores food issues. In general, "food remained a stranger to the field of urban planning' until the early 2000s (Pothukuchi and Kaufman, 2000). A survey concluded that the perceived urban–rural divide was a central reason: food and agriculture were considered a rural topic; 'our city is in an agricultural area, but the city doesn't deal with agriculture or farming issues' (Pothukuchi and Kaufman, 2000). Some years later, Sonnino (2009) reached a similar conclusion: 'the urban–rural divide has misled planners and policy-makers into looking at urban food supply failure as farm failure, rather than as a failure in the food system. The prevailing sectoral planning and decision-making approach, and its lack of a holistic perspective, seems another reason explaining why 'food has been a stranger' to urban planning (Brinkley, 2013; Morgan, 2009; Raja *et al.,* 2008).

Those obstacles did not prevent some pioneers to developed guidelines on how to plan for food. In 2007 Pothkuchi (APA, 2007) formulated to the American Planning Association the Policy Guide on Community and Regional Food Planning. In 2011 White and Natelson (2011) published the guidelines Good Planning for Good Food. In 2012 Viljoen *et al.* (2012) published the book Continuous Productive Urban Landscapes. In 2018 Cabannes and Marocchino (2018) edited Integrating Food into Urban Planning highlighting city-based practices that are reducing these gaps in creative ways and reflecting on progress made world-wide and current obstacles. In 2021 Verzone and Woods published Food Urbanism (2021). Those are some of the examples that show that food is less a stranger to urban planning literature, at least, today than a couple of decades ago.

On the subject of climate change, there are as well several barriers to its inclusion in municipal plans. Ribeiro *et al.* (2018) identified multiple obstacles and limits, being the most relevant ones: the non-mandatory condition of the climate change agenda, the uncertainty associated with the downscaling of climate change scenarios, the scarce scientific insights on how adaptation can be integrated into planning tools, the inexistence of guidelines from central government, the urban planning tradition that ignore the issue of climate change, a predominant culture of reactive management, insufficient technical skills and financing mechanisms. In addition, the formulation and implementation of food and Climate Change Adaptation Strategies or Plans are both reliant on political will that often change according to political cycle, and this limits as well, their inclusion as part of municipal plans and strategies (Delgado, 2020; Doernberg *et al.,* 2019; Ribeiro *et al.,* 2018).

In Portugal a silent revolution has been taking place, especially from 2019 onwards. Several guidelines on planning and climate change were formulated at national level, such as: (1) The national programme for Territorial Planning Policies (2019) which suggests that master plans (Plano Director Municipal in Portuguese) should include climate change mitigation and adaptation measures; (2) The national agency in charge of spatial planning – "Direção Geral do Território", published a compendium of "Good Practices to Master Plans" (DGT, 2020) with a specific section on the role of food and urban agriculture to address climate change effects; (3) A national Agenda – "Terra Futura 2020-2030" - in line with the EGD and Farm to Fork Strategy identified targets to turn the country climate-neutral by 2050; (4) and, the Portuguese Law on Climate ("Lei de Bases do Clima in Portuguese)" published at the end of 2021 (Law n. 98/2021), which highlights the need for sectoral climate policy instruments among several other issues to take into account, such as the agri-food chain, carbon sequestration strategies, green economy and just transition. Moreover, the Roadmap to Carbon Neutrality in Portugal published within the Portuguese Law on Climate (Law n. 98/2021), clearly states the main vulnerabilities and expected impact of climate change in Portugal such as higher incidence and intensity of rural fires, heat waves, droughts and water shortages, desertification, high temperatures, or extreme precipitation events. The complexity and inter-related expected effects, implies that a comprehensive approach to mitigating and climate change adaptation requires both sectoral and integrated policies.

Besides, and this is clearly a window of opportunity for reflexion, the Portuguese Law on Climate turn compulsory, for each municipality and region, to develop and approve a Climate Adaptive Plan, before mid-2024. By the end of 2020, 271 out of a total of 308 municipalities in mainland Portugal, Azores, and Madeira had adopted at least a municipal, intermunicipal or metropolitan planning instrument (strategy or plan) related to climate change adaptation.

The progress towards SDG 13 - Climate Action, in Portugal, through the 2015-2021 period has been significant (INE, 2022) but results can be distorted by covid pandemic, which decreased economic activity and transport circulation and therefore less impact on CO2 emission. Despite such encouraging results, more efforts are needed to meet the 55% GHG reduction target by 2030, when compared to

2005. Moreover, the same INE report (2022) remains silent on data related to SDG 12 – Responsible Consumption and Production. More than 50% of the indicators are not being measure so far. In addition, when comparing existing data from 2015 to 2021, a regressive target tendency is observed. We argue that SGDs 12 and 13 (we recognize thar there are other related Food System SDGs that impact climate change, still this point is out of the scope of this paper) need to be considered as part of a holistic approach to meet GHG reduction target defined by the country's signatories of the Paris Agreement and included in the Portuguese Climate Strategies and Plans to come.

3. Sample and methodology

This paper explores 14 Climate Adaptive Strategies or Plans of a selected group of cities that entered ECO XXI (ECO XXI, 2022) national competition in 2021. The ECO XXI competition is coordinated by ABAE, which is the Portuguese branch of the international Foundation for Environmental Education (Foundation for Environmental Education, 2023). The competition is based on a multi-dimensional framework for sustainability embracing 21 categories, such as governance and participation; cooperation with civil society; climate change; or agriculture. The winning municipalities (i.e., those that summed up the highest results in each of the 21 categories) have the right to display a green flag for one year, which acknowledges city sustainable achievements. In 2021, as much as 57 out of the 308 Portuguese municipalities entered the competition: 40 of them had formulated and approved a Climate Adaptive Strategy or Plan, being 16 at municipal level and 24 as part of a broader metropolitan or regional plan.

Out of these 16 municipalities we closely examined 14 of them, for being predominantly urban, defined as with at least 51% of their population living in administratively considered urban areas. Figure 1 highlight their spread all over Portugal continent and islands. Table 1 summarizes relevant information regarding those 14 municipalities. The number of city inhabitants ranges from 30.374 (Lagos, Algarve Region) to 213.608 (Cascais, Lisbon Metropolitan area). The primary economic sector presence (mostly agriculture) ranges from 0,4% (Valongo) to 7,1% (Torres Vedras) being Portugal average 2,9% (Fundaçao Francisco Manuel dos Santos, 2021).

The oldest Climate Change Strategies were approved in 2016 (Braga, Amarante and Funchal) and the most recent one in 2020 (Valongo). Out of the 14, five municipalities (Maia, Águeda, Leiria, Torres Vedras and Lagos) have developed a subsequent Climate Change Adaptative Plan, which represents a step further the strategy. Such plans detail how a specific measure is going to be carried out e.g., which actions are going to be taken, and by which specific actor, e.g., city department, private sector, civil society, etc.

These 14 municipal strategies and plans were first analysed in order to find out on the one hand the key-sectors for climate change adaptation that were included, and on the other the extent to which agriculture and planning were considered. We then analysed the type of agriculture and food adaptation measures (as part of the strategy) or actions (in the plans)[1] using a double strand approach: food production on the one hand and other stages of the food chain on the other.

Actions or measures that only considered the forest without the agro-forest dimensions were discarded. Water was only considered when directly related to agricultural activities. The last round of examination consisted in a deeper examination of those five cities with a Climate Adaptation Plan - CAP (Cascais, Agueda, Maia, Leiria, Lagos) in order to better understand if and how those cities were foreseeing the integration of their Climate Change adaptation actions into territorial / spatial planning. Finally, we asked for an interview the Planning Department directors of the three cities (Lagos, Maia and Leiria) that had included food and agriculture actions as part of their Climate Change Adaptative Plans. As a result,

[1] Each strategy and plans adopt slightly different designations still usually the strategies refer to measures and plans refer actions, the later one being specific about how and who and eventually which fund could be used.

two semi-structured interviews could be carried out, one with Maia and the second with Leiria. Lagos city preferred to send a clarification note. The online interviews took place in July 2022 and lasted about one hour and mainly focused on the extent to which the planning department collaborated on Climate Adaptative Plans formulation, and how this collaboration is currently maintained. Director's reflections on how and why the selected actions were transposed into planning instruments were welcomed as well.

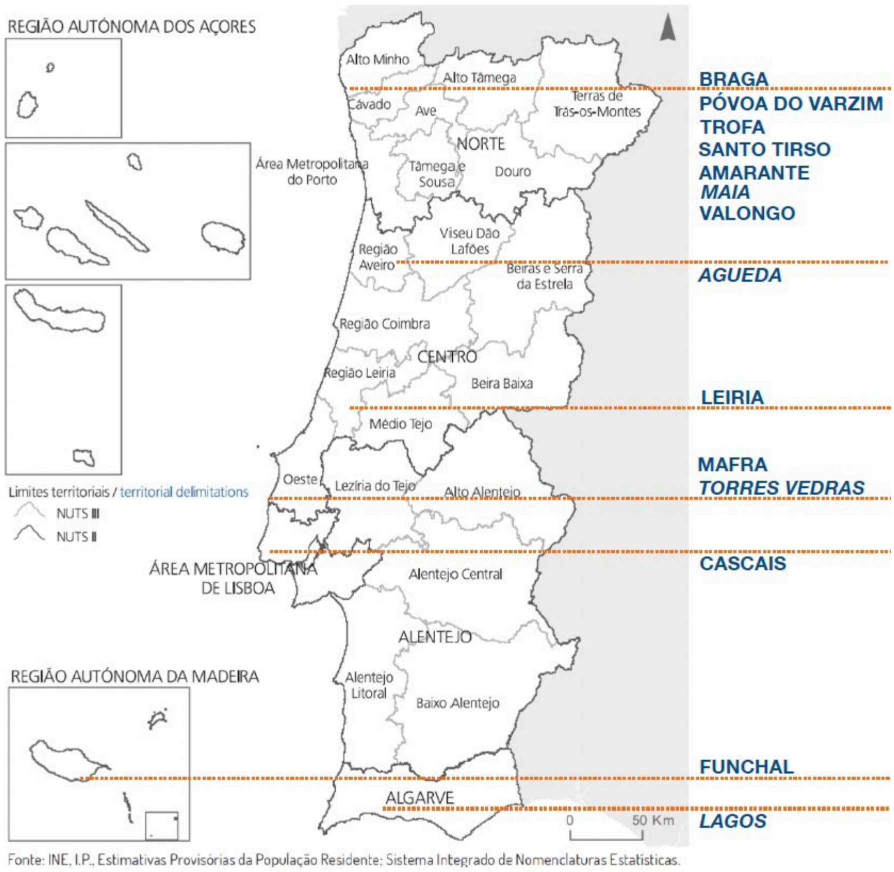

Figure 1. Location of the 14 municipalities analysed.

Table 1. Basic profile of the 14 municipalities analysed.

Municipality	Strategy/ Plan	Year of approval	N. Inhabitants (INE, 2020)	% Inhabitants living in urban area (INE, XXX)	% Primary sector
Águeda	Plan	2018	46 075	79%	1.5%
Amarante	Strategy	2016	53 193	58%	2.3%
Braga	Strategy	2016	182 679	93%	0.6%
Cascais	Plan	2017	213 608	99%	0.5%
Funchal	Strategy	2016	104 024	100%	0.8%
Lagos	Plan	2018	30 374	74%	1.9%
Leiria	Plan	2018	125 267	76%	1.8%
Mafra	Strategy	2017	84 816	72%	2.2%
Maia	Plan	2019	138 971	98%	0.6%
Póvoa de Varzim	Strategy	2019	62 784	81%	5.9%
Santo Tirso	Strategy	2019	68 055	88%	0.8%
Torres Vedras	Strategy	2019	78 530	82%	7.1%
Trofa	Strategy	2019	38 418	87%	1.3%
Valongo	Strategy	2022	97 444	100%	0.4%

4. Results

When analysing the 14 Climate Adaptative Strategies and Plans, 16 different sectors were listed as relevant to climate change (Table 2). Besides Water (although, water, agriculture and climate change being an extremely important nexus to consider, it will not be explored in the present paper) and Health sectors, "Agriculture, forest, and fisheries" appeared as the most frequently referred sectors along with "Biodiversity and landscape" [13 cases out of 14]. "Urban planning and cities" came next [10 cases]. The only city that did not included agriculture as a relevant sector for climate change was Funchal, on Madeira Island, despite having signed the Milan Urban Food Policy Pact, that expressed their commitment to strengthen their food system. These results tend to illustrate the variety of entries through which climate change is being addressed by these cities, and at the same time the disconnect between those entries.

Table 2. Key sectors considered on the 14 CAPES.

Key sectors	Agueda	Amarante	Braga	Cascais	Funchal	Lagos	Leiria	Mafra	Maia	Povoa do Varzim	Santo Tirso	Torres Vedras	Trofa	Valongo	Total
1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	14
2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	14
3	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	13
4	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	13
5		✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	11
6	✓	✓	✓	✓	✓			✓		✓	✓	✓	✓	✓	11
7		✓	✓			✓	✓	✓		✓	✓	✓	✓	✓	10
8		✓	✓		✓			✓	✓	✓	✓	✓	✓	✓	10
9			✓	✓		✓	✓	✓				✓			6
10						✓	✓								2
11						✓	✓								2
12	✓														1
13	✓														1
14	✓														1
15									✓						1
16									✓						1

Key sectors: 1. Water resources; 2. Health; 3. Agriculture, forests, and fisheries; 4. Biodiversity (and landscape); 5. People and goods safety; 6. Tourism; 7. Energy and industry / economy; 8. Urban planning and cities; 9. Coastal zone and sea; 10. Demographic Dynamics; 11. Transport and communications; 12. Financial sector; 13. Disaster risks reduction; 14. Infrastructures; 15. Monitoring, info/, awareness-raising; 16. Building.

The analysis indicates as well that although 13 out of the 14 considered agriculture as a relevant sector for climate change adaptation, only 10 of them included clear measures and actions directly related to food production or other stages of the food chain. Despite considering agriculture as a relevant sector for climate change, the four remaining ones, Póvoa do Varzim, Trofa, Valongo, and Funchal did not include clear measures and actions. As previously mentioned, Funchal did not considered agriculture as a relevant sector for climate change adaptation.

The 10 remaining strategies and plans analysed summed up the impressive figure of 407 measures and actions for climate change adaption. However, only 44 of them are related to food and agriculture (10.8%). The lowest proportion of measures devoted to food and agriculture refers to Torres Vedras (5,0%) while Maia (14,5%) posits at the other end of the scale. Such an overall surprisingly low result clearly indicates the thin relation existing at municipal level between planning, agriculture and climate change adaptation.

Table 3 zooms in the 44 measures and actions related to our major entries: “food production” and “other stages of the food chain”. Results indicate that 27 of the 44 are connected with food production. Seven of them (listed in half of the plans) relate to the use of native species adapted to climate change; followed by access to land (counting 6) consisting of either mapping idle land, improving access, or preserving land; and then five relate to increasing agroecological production and other related practices. Then, 17 out of the 44 measures and actions refer to different stages of the food chain: water access being the most frequent, either through retention basins or use of treated water. Another important finding of the research is the qualitative wealth of measures and actions, in an extremely low proportion of measures [27 out of 407 that were identified].

Table 3. Brief description of the measures and actions considered in the 14 Strategies and Plans analysed.

Topics related with food production	**Nº**
Boost native crops / crops more adapted to climate change /crops diversification	8
Improve land access / make use of idle land/ preserving land for agricultural purposes	6
Increase agroecological production and other related practices	5
Create a seeds bank / preservation of genetic material	2
Create an agriculture agency	1
Develop school community gardens	1
Re-plant forest (eucalyptus) with orchards adapted to climate change	1
Boost agro-pastoral uses	1
Creation of a farmers' stock exchange	1
Setting up a manual for agricultural practices	1
Total measures / actions	27
Topics related with other entry points of the food chain	**Nº**
Create dams and water retention ponds for agricultural use / use of treated water	5
Assessing initiatives	3
Regeneration of local food markets	2
Strength trading and consumption of local products	2
Control supermarkets territorial dissemination	1
Commercial promotion of new fish varieties	1
Assist the conversion of fleets and fishing gears	1
Award for the best practice regarding water for agricultural irrigation	1
Community composters	1
Total measures/actions	17

The next step of the investigation was to better understand if those measures and actions where integrated into territorial instruments primary Master Plans (Plano Diretor Municipal in Portuguese), Detailed Plans and regional Plans that represent the main planning documents in the Portuguese context.

The analysis to the 14 CAPEs reveals that 11 have a chapter on the integration of their measures and actions into territorial planning. However, a closer look to the five municipalities with Climate Adaptation Plans i.e., the ones with detailed actions and an implementation factsheet, indicates that only two of them, Maia and Leiria, included their Climate Change adaptation actions into their municipal territorial plans. This being said, each one of them proposed actions related to agriculture and food: Cascais (5/78); Agueda (6/68); Lagos (15/145); Leiria (5/54); and Maia (9/62). Such finding strongly suggests that the inclusion of food and agriculture’s actions into territorial planning is not perceived as a mandatory step by the most advanced Portuguese local governments in relation to climate change planning.

Table 4 lists down each one of the agriculture and food actions envisioned by Leiria and Maia municipal Climate Adaptation Plans. It summarizes as well how they are expected to be integrated into the planning instruments. One needs to highlight that in Leiria only half of proposed actions are included into planning instruments, while in Maia, all of them are. An interesting finding when examining the inclusion of actions into territorial planning is the lack of consistency from one city to the other and the subjectivity of policy decisions. For instance, Leiria did not transposed to the Master Plan the regeneration of the city cover market, in opposition to Maia that did so.

Table 4. Brief description of the related food and agricultural action and their inclusion into planning instruments.

Municipality	**Action - Description**	**Yes/No**	**How actions are being transposed to planning – based on CAP**
Leiria (5) *	Regeneration of the local food market	No	Not applicable
	Funding incentives to local livestock and food production and trade	Yes	Master Plan Charter – Positive discrimination and/or fiscal incentives
	Lis Valley pilot case to validate new horticultural and/or fruit crops	Yes	Master Plan Charter – Positive discrimination and/or fiscal incentives
	Regeneration of Junqueira Salt Pans	No	Not applicable
	Prize for best practices on agriculture irrigation	No	No
Maia (9)	Promoting sustainable agricultural practices adapted to climate change	Yes	Master Plan Charter – Proposal of pilot areas
	Mapping of rural and mixed areas including abandoned land with agricultural potential	Yes	Master Plan Charter – Re-classify the soil in the Land use map
	Creation of a land exchange bank	Yes	
	Creation of a farmer's stock exchange	Yes	
	Manual of agricultural best practices		Master Plan Charter – Foresee in the Report as a strategic option.
	Promotion of a sustainable irrigation system	Yes	
	Promotion of native species panting	Yes	
	Revitalization of local food market	Yes	
	Community compost boxes	Yes	

*The CC Leiria Plan doesn't specify for each action how it is translated into urban planning.
Table 4 resulted from author interpretation of a broader list.

As seen in table 4 how those actions are going to be integrated remains largely unclear, even in the most developed and cutting-edge cases at national level: Maia and Leiria municipalities the inclusion of the Climate Change related actions as part of the master plan chapter. Leiria goes one step further in detailing a positive discrimination and/or fiscal incentives for some of its actions.

Finally, the qualitative results obtained through the interviews with the heads of two municipalities planning departments, indicate that the urban planning departments were not always involved in the strategy or the plan formulation process. For instance, Maia representative participated in the elaboration of the strategy, but not of the plan. Both interviewees expressed some astonishment about food planning relevance, both as a topic per se or a relevant one for climate change related actions, although expressing openness to debating about it. Both agreed that master plans' scope mostly relates to land-uses regimes either for agricultural or urban land. They stressed as well that these measures are the only ones to be considered to integrate agriculture and food into planning instruments. It echoes Lagos municipality position, when rejecting our proposal for interview, upon similar grounds. There is a clear convergence that Master plans cannot consider the development of specific actions such as the formulation of pilot cases, creation of land banks, or promotion of agroecological practices. According to the interviewees those actions are outside the planning domain, and even if those actions were included in their respective Climate Change Plans. These findings highlight the gap between what is detailed in the climate plans and what is city planners' perspective. For instance, both interviewees considered that creating land banks for agriculture should be part of Detailed Plans instead of Master Plan. This planning instrument allows to specify actions such as assets preservation, specify locations for agriculture, or allocation of funding. In addition, both agreed that Climate Change Adaptation Plans should be normative and not binding. It resulted clear from the interviews that some of the actions envisioned in the Climate Plans notably regarding Leiria, were projects that had been previously approved by the municipality. Such is the case of the Leiria local food market that was included in the Plan, but not as a result of a collaborative effort for the Climate Change Plan. At implementation level, the planning departments either in Leiria or Maia have a limited impact, as such projects are led by the Environmental Department, leaving aside Urban Planning. Last but not least, such strategies and plans are non-mandatory, in other words, their implementation relies on political willingness, confirming the silos administrative culture.

5. Discussion

Back to the leading questions: 1) to what extent Climate Adaptive Plans and Strategies include the increase of local food production as a way to address the effects of climate change; (2) Do they consider each step of the food chain or solely food production; (3) How those measures are transcribed to the planning rules and regulations.

Based on the cases we examined in Portugal-one can safely conclude that strategies and plans do include an increase of local food production as a strategy to face Climate Change. However, these measures and action remain limited when compared with the overall number of measures considered (average 10,8% of total number of measures as an average for the 10 cities studied). In conclusion, those numbers substantiate the weak nexus between agriculture, climate change and planning. Such conclusions are in tune with those from different authors (Brinkley, 2013; Morgan, 2009; Raja *et al.,* 2008). Based on this we advocate that efforts and additional practices are needed to illustrate how sectorial issues relating to food could be integrated into Climate Change strategic and operation plans and into Master Plans and sectorial plans in cities. A preliminary way to go might be making data available to planners and policy makers on the impact of food systems on GHG emissions. Unfortunately, these data are limited, and in Portugal alone, metrics regarding SDG 12 (INE, 2021) are only produced for 50 % of the required indicators. In a scenario where more progress is required to meet the 55% GHG reduction by 2030, those metrics are an important tool to have a clear picture of what Food System entail.

Regarding the second question results suggest that indeed food production is being considered, while the other stages of the food chain are less so. Measures related to food loss, waste prevention, food distribution and food consumption are notably missing. Why is this happening? We argue that stakeholders involved in strategies and plans formulation largely miss what Food System entail, and its potential positive impact on climate change adaptation. This is a limit that confirms conclusions from various authors (Candel and Pereira, 2017; Delgado, 2023). Both findings are pointing out that more awareness raising is needed on the positive or negative roles that Food Systems, and each stage of the food chain can play on climate change adaptation. The so far weak consideration for the food system positive and negative impact on climate cannot be missed as a new round of Climate Change adaptation strategies and plans are coming up. Besides, the European Green Deal (2020) is nowadays at the forefront of European commitment to tackling climate and environmental-related challenges and one of its major components is the 'Farm to Fork strategy' which call for a more holistic food systems approach.

Lastly, even if the inclusion of several measures and actions into planning instruments, as identified in the present investigation looks promising, not much seems happening in the field. Several reason might explain such a situation: first, strategies and plans remain normative and in addition are essentially non-mandatory. This means that their implementation relies primarily on political will; Second, lack of planner's awareness on the subject and, finally an entrenched administrative silo culture often limits communication between agriculture, environmental and planning departments. In short, the findings strongly suggest that the potential role of planning and more precisely food planning in adaptation to Climate change is not being fully unleashed. Such a consideration is in line with various previous findings in other countries, by authors such as Reckien *et al.* (2018) or Doernberg *et al.* (2019) confirming that Portugal is not an exception.

We acknowledge some limitations in our research. Firstly, we don´t clearly know the profile of stakeholders involved on the formulation of the Climate Change adaptation strategies plans, if any, and the technicians involved, besides why they were chosen. Limited information is available on their professional backgrounds, agendas, power, values, and motivations. Further research could somehow complement and nuance our findings.

Secondly, more research is needed to deepen our understanding of the missing links between planning and food. We would like in future research to explore a broader span of municipal urban planners, notably the ones at local level that are in charge of city plan departments. This would eventually introduce additional insights that would complement our findings and help to build an enabling approach to better explore climate change, agriculture, and food planning nexus.

6. Conclusions

This paper clearly calls for the urgent need to posit food chain as a fundamental part of climate change debate and actions. At this point in time, we need to establish supportive and enabling policy mechanisms that will support the formulation of more integrated local climate change adaptation plans.

What does these changes would mean for municipal planners and food planning as a whole? Firstly, it is important to assure that measures included in strategies and plans will be mirrored in planning instruments. So far, it is not happening. Planners' argument stating that master plans are not the right scale instrument for food and urban agriculture development.

Secondly, in countries such as Portugal without a strong urban planning tradition (in Portugal there is not a specific degree on urban planning. Traditionally planning is being led by geographics, engineers, architect, economists), the connection between different disciplines can be an additional challenge as food requires a holistic perspective, often not required in the architecture schools and not present either in planning faculties. This could generate a huge opportunity for some training institutions to lead the way to an emergent topic as food planning.

Thirdly, several guidelines on planning and climate change have been formulated at national level. At the same time other mechanisms such as Municipal Fund for Environmental and Urban Sustainability exist since 2015: they could be used as a way to better consider food issues.

In conclusion, there is a need to increase awareness and outreach among planners and other stakeholders. This process should be supported through information campaigns, broad debates, participatory planning and research on the ground. Bridging the gap between an innovative and facilitating legal environment at the national level and planners addressing these topics at the city level.

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EVOLUTION AND STATEMENT OF THE RURAL STUDIES IN LATIN AMERICA. A CURRENT BIBLIOGRAPHICAL REVIEW

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ABSTRACT. The structure and evolutionary dynamic of the rural world of Latin America has always been a privileged topic in research and scientific reflection, not only at the level of the continent, but also at the international level. Scientific production has always reflected the problems of this vast rural world, but always under the influence of the social, political, and economic conditions of each historical moment. In this paper, we analyze the current scientific production on the rural world with a historical perspective, to understand the evolution of scientific thought and production. We appeal to a very simple bibliometric method based on the analysis of the most prestigious journals about the rural reality of the continent. The analysis allows us to observe a clear trend towards new topics, linked to the problems of the rural world, such as the new relationship between the countryside and the city, environmental problems, the emergence of new ways of producing, among others.

Evolución y estado de los estudios rurales en América Latina. Una revisión bibliográfica actual

RESUMEN. La estructura y dinámica evolutiva del mundo rural de América Latina ha sido siempre un tema privilegiado en la investigación y la reflexión científica, no solo a nivel del continente, sino también a nivel internacional. La producción científica siempre ha reflejado los problemas de este vasto mundo rural, pero siempre bajo la influencia de las condiciones sociales, políticas y económicas de cada momento histórico. En este trabajo, se analiza la producción científica actual sobre el mundo rural con una perspectiva histórica, para entender la evolución del pensamiento científico y la producción. Se utiliza un método bibliométrico sencillo basado en el análisis de las revistas más prestigiosas sobre la realidad rural del continente. El análisis permite observar una clara tendencia hacia nuevos temas, vinculados a los problemas del mundo rural, como la nueva relación entre el campo y la ciudad, los problemas ambientales, la aparición de nuevas formas de producción, entre otros.

Keywords. Latin America, rural studies, bibliometric analysis.

Palabras clave: América Latina, estudios rurales, análisis bibliométrico.

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1. Introduction

Until the mid-20th century, the Latin American rural world was characterized by the preeminence of a dichotomous agricultural and rural development model, with the presence of numerous small farmers (peasants) and large estates. In the mid-century (1940s and 1950s), the national States implemented new development policies, focused mainly on import substitution processes, which required large amounts of capital for their sustainability and development (Moncayo Jiménez, 2001). In this context, the agricultural sector is seen as the main sector capable of providing low-cost food for the growing masses of urban population, and exportable products capable of providing the foreign exchange needed to sustain this import substitution process. During this period, many initiatives were implemented to promote production, including production protection, price control, market regulation, agrarian reform and colonization programs, and the creation of infrastructure and equipment.

This first stage of strong intervention in agricultural policies was followed in the 1960s by policies of strong support for technological change, thus creating research and technology transfer agencies with large resources and technical capabilities throughout the region (Chonchol, 1994), which allowed the development of innovations and substantial growth in agricultural production throughout the region (Riffo, 2013). By the late 1960s and early 1970s, and thanks to the technological development process achieved in the previous decade, the green revolution process was consolidated, which involved the adoption of new varieties and cultural practices, but also the creation and development of large irrigation and drainage infrastructure projects (Muzlera and Salomon, 2022). Throughout this historical period, scientific production around the rural world was clearly focused on supporting the process of agrarian modernization, and on increasing the production and productivity of the agricultural sector (Arenas *et al.,* 2004).

At the end of the 1970s and mainly in the 1980s and 1990s, policies to support the agricultural and rural sector were gradually dismantled and the countries (with time differences among them) adopted structural adjustment policies that included market deregulation, trade liberalization, privatization, sanitary improvements, development of agro-export logistics, technological development and bureaucratic and administrative decentralization (Sili, 1995). Clearly, the emphasis of policies related to the rural world was on increasing production and productivity, which promoted the development of agribusiness, the consolidation of production chains and exports, all in the hands of the productive business sectors linked to the export agroindustry. The agricultural sector performed well overall and there was a growing adoption of technologies that made it possible to maintain a growth path despite the poor or regular macroeconomic conditions of the countries. Scientific and technological production during this period was focused on supporting modernization processes, but numerous scientific papers also emerged that analyzed the impact of adjustment processes, especially social disparity, land issues and migration (Teubal, 2001).

At the beginning of the new century, several governments emerged in Latin America that, under the paradigm of neo-development, advanced with new policies and practices that attempted to reverse the structural problems of the rural world, focusing their support on family agriculture and food security (Tzeiman, 2013). This did not prevent policies and practices to support the most dynamic sectors of export agriculture; on the contrary, in this period, unsustainable production practices intensified, especially deforestation, pollution due to unsustainable mining practices and loss of biodiversity. The scientific production of this historical moment was closely linked to issues such as family agriculture, land tenure, and public policies to support rural development, among others.

Currently, the Latin American rural world is going through new paths of greater complexity and diversity in which four major elements are combined, which we will analyze below.

A first relevant fact in the region is the persistence of a deep crisis and re-composition of family farming (a sector made up of small family farmers engaged in agriculture, livestock, fishing, artisanal activities, and tourism) (Craviotti, 2014) (World Bank, 2007) (Salcedo and Guzman, 2014). Family farming in Latin America manifests structural problems derived from: a) the scarce amount of land owned by these farmers -according to FAO, in Latin America these producers have, on average, 13 ha- (Soto Baquero y Gómez, 2014), and b) the low technological level and marketing difficulties, which does not allow them to increase their production and productivity or, therefore, to be competitive in terms of market in the production of traditional agricultural goods, compared to larger and more capitalized sectors. These production conditions are in addition to other problems inherent to the territories where family farming is concentrated, such as structural deficits in infrastructure and equipment (World Bank, 2007); this considerably reduces the quality of life and production possibilities (lack or deterioration of roads, lack of electricity, low levels of education, problems of access to health care, lack of water, and others). Clearly, this affects even more the areas far from cities and areas with very low population densities.

A second element that characterizes the rural situation in Latin America is the strong entrepreneurial dynamism in the agricultural and agroindustrial sector, as a result of the new international scenario in terms of prices and demand for primary goods. This growth dynamic has been analyzed by numerous authors (Gras and Hernández, 2021; Villagómez Velázquez e*t al.,* 2011; Guibert and Sili, 2011) and institutions and organizations (IICA-CEPAL-FAO, 2010); in general terms, they all point to the same factors as drivers of this new dynamism. Thus, technological changes in agriculture (new varieties, machinery, practices and inputs), management and marketing processes, the emergence of new actors more closely linked to the world of services and finance (contractors, services, agricultural trusts, among others) (Guibert, *et al.,* 2011) and an international context increasingly demanding of raw materials (Quenan and Velut, 2014) have constituted a highly attractive environment for the growth of productivity and production that is clearly visualized in recent decades and that allowed the consolidation of a remarkable agricultural boom (Villagómez Velázquez *et al.,* 2011). Although the main productive transformations in the rural world are related to the agricultural sector, it is not possible to ignore the strong impact of mining and oil exploitation, and as some authors point out, it has generated a reprimarization of Latin American economies (Teubal and Palmisano, 2015). The new investments made since the 1990s have had a significant impact on all countries in the region.

The third characteristic factor of the Latin American rural world is the growing presence of new environmental and territorial conflicts (CEPAL*,* 2016; Teubal and Palmisano, 2015). The growth of the agricultural sector was not only the result of an improvement in productivity per hectare, but was also, and above all, the result of an accelerated advance on new lands, many of them tropical and subtropical forests that were deforested, or desert areas on which new irrigation systems were installed. The advance over new lands, evident in Brazil, Paraguay, Argentina, and Bolivia, among others, and the capture of new water sources (cases of Chile, Peru, Ecuador, Colombia, among others) have generated, on the other hand, numerous conflicts with family farmers - evicted or without availability of water use (Graziano da Silva *et al.,* 2010). This also generates conflicts with the non-agricultural population, which suffers from the advance of new productive ventures that do not always respect local environmental conditions and values (contamination by agrochemicals and mining by-products, deforestation, and loss of biodiversity, among others).

A final dynamic of the Latin American rural world is the persistence of rural exodus but also the growing process of demographic and social rebirth under construction. The process of rural exodus has been evident in the region from the mid-20th century onwards (Dirven *et al.,* 2011). However, the depopulation process would be in its final stage and would now enter a new period of stabilization of the rural population and in many cases of demographic renaissance due to migration from cities to the countryside and towns. This situation can be observed especially in small towns, in areas of high landscape value, in coastal areas, and in the vicinity of important communication routes. This does not mean that there are no areas that still suffer from rural exodus processes, especially areas of dispersed population, but rather that the dynamics and rate of depopulation has changed substantially, and many areas are beginning to experience new dynamics of repopulation, which to a large extent is not directly related to agricultural activities, but rather to other forms of employment and occupation. Several factors are generating this change. First, the loss of quality of life in cities due to congestion, the lack or deterioration of infrastructure and equipment, and the resurgence of violence and marginalization (World Bank, 2008 and 2009). Hundreds of cases exemplify this process whereby artisans, professionals, workers, new entrepreneurs, retirees seek a new way of life and new ways of connecting with nature. This "return" to rural areas (countryside, villages, or small towns) is complemented by the strong development of secondary residences or tourism in rural areas, also with the objective of seeking open spaces, in contact with nature and associated with rural values. A second factor contributing to this process of construction of a new rurality is the generation of new and multiple activities in rural areas, with the creation of new commercial activities, production services, hotels, restaurants, personal services, and others. This responds to the demands generated by the expansion of primary activities, the growing importance of agriculture and, above all, the growing rural domestic consumption; that is, the consumption of the rural population, both the original population and the population that migrates to these areas.

These four elements are undoubtedly reconfiguring the rural territories of the region, generating new dynamics, and making viable the emergence of innovative processes and the construction of new models and approaches to development in the territories.

In general terms, we can observe that all processes of political and economic change in each historical moment were always accompanied by a significant base of ideas, concepts, and knowledge, which are mostly visualized or reflected in the international scientific literature (Kay, 2007). Considering this dynamic, the hypothesis we propose is that the current emerging issues related to rural issues are no longer the same as those raised before the 1980s or 1990s; there has been a clear evolution towards new issues. From the well-known problems of the gap between peasant and business agriculture, rural poverty, infrastructure problems, agrarian reform, among others, there has been a gradual shift to other issues, among which environmental problems, the new rural-urban relationship, the dynamics of the actors, among others, are gaining much more strength, thus accompanying the processes of change in the rural world. The change in reflection on rural issues reflects the political and social changes in the different countries, but we also consider that scientific production plays a very important role because it can open the doors to a more powerful reflection in the region on the need for a transition to new models of rural development, in a regional context marked by persistent economic crises, with strong volatility and political changes, and with increasingly critical environmental scenarios.

In summary, and in terms of work objectives, we are interested in analyzing the major emerging themes of analysis and reflection on the rural world in Latin America since the 1990s, and especially at the present time (2018-2023). It is interesting to note the persistence of some key issues identified almost three decades ago, but especially the emergence of new issues, which reflect new concerns about the rural world in the region, and which could open the door to a more intense reflection on the need to build new paradigms of more sustainable and inclusive rural development, capable of overcoming the historical structural problems of the Latin American rural world. For this purpose, a very simple bibliometric analysis is used, based on the analysis of publications in numerous international journals, and especially six specialized journals on rural issues, three from Latin America and three in English.

The first part of this paper presents the materials and methods used for the analysis, describing the database of scientific articles constructed specifically for this work. Secondly, we present the basic bibliometric data by country, journals, and topics. Thirdly, we emphasize the evolutionary analysis of the different topics and the current situation, describing in detail the research topics.

2. Materials and Methods

It is presented a quantitative, retrospective, and descriptive study of the scientific production on the rural environment in Latin America, which according to Buitrago-Pulido (2019), will allow the selection and organization of the documents. Only original articles were considered in the bibliometric analysis.

To begin the study, the database was elaborated. It started with research in Google Scholar and Google *Académico,* utilizing keywords like rural, territory, development, agricultural, and their synonyms. The time lapse was from year 2018 to 2023 (until January 2023), and the region of study was Latin America.

For more accurate results, a research equation was utilized for each Web search engine, Google Scholar and Google *Académico*, one in English and other in Spanish, respectively. The equations were:

- Google Scholar: (rural) AND (territory OR territorial) AND (development) AND (agrarian OR agricultural).
- Google *Académico*: *(rural)* AND *(territorio* OR *territorial)* AND *(desarrollo)* AND *(agrario* OR *agraria).*

Once both databases were integrated, due to the experience of the researchers, the database was complemented with all the papers published by the most prestigious journals directly linked to rural topics in Latin America in said time lapse like: "Mundo Agrario", "Revista de Economía y Sociología Rural", "Cuadernos de Desarrollo Rural", "Journal of Rural Studies", "Journal of Agrarian Changes", and "Rural Sociology".

The primary database contained a sample of 559 articles about agricultural and rural issues in Latin America, during the period 2018-2023. The database contained the following data:

- Authors: name of the authors
- Title of article: complete name of the article
- Year: year of publication
- Journal: journal of publication
- Country of reference: Indicates the country where the paper was published.

Then, new variables were created to enhance the data analysis. The first dichotomous variable was the geographic origin of the paper, being able to be LAC (papers published by journals originating from Latin American countries) and NO LAC (papers published by journals originating from no Latin American countries). The second variable generated was the subject matter on which the paper focused. No previous classification was used for this purpose, but rather these categories were created inductively from the key words and the subject areas of the same publications. These categories were as follow:

1. Actors, networks, and institutions: It is about papers that stress the dynamic of actors, network construction and functioning of the institutions.
2. Agribusiness: Papers focused on agribusiness.
3. Agricultural technology: Papers on general technology in agricultural production systems.
4. Agroecology: Papers focused on agroecology.
5. Bioeconomy: Papers related to bioeconomy.
6. Commercialization: Papers focused on commercialization issues.
7. Competitiveness and efficiency: Papers focused on sectoral competitiveness issues and the search for productive efficiency.
8. Conflicts: Papers focused on analyzing conflicts between actors and sectors, especially over the control of resources.

9. Cooperativism: Papers focused on cooperativism in general.
10. Credit and financing: Papers focused on access to finance and credit issues.
11. Economy: General papers on economic topics not included in other categories.
12. Environment: Papers on environmental issues in general.
13. Extension and innovation: Papers focused on innovation, extension, and development promotion.
14. Family agriculture: These are papers that emphasize in the dynamics and organization of family farming.
15. Food safety: Papers on food safety issues in general.
16. Gender: Papers on gender issues.
17. Identity and representations: Papers emphasizing identity and representations about rural and development.
18. Infrastructure: Papers on different types of infrastructure problems and their relation to rural development.
19. Land: Paper on land issues in the region.
20. Policies: Papers focused on public policies in support of rural development, the fight against poverty and hunger.
21. Production systems: Papers describing and analyzing production systems and value chains in rural areas.
22. Society: Papers on social issues in rural areas.
23. Territory: Papers on territorial problems and intervention models with a territorial approach.
24. Tourism: Papers on tourism in the rural areas.

The collected data was edited, tabulated, and processed to generate tables and figures that help to visualize the findings. This process was elaborated through the Microsoft Excel program.

The analysis part focuses on the main topics by locations, groups, and main journals, through the calculation of the frequencies and percentages of the indicated variables, to provide an overview of what is being studied in Latin America about agricultural and rural issues. Additionally, it was considered appropriate to include a comparative analysis on topics by year/period (1992, 2007, 2018-January 2023), to see the evolution of the study on the subject. It should be noted that the publications analyzed in the years 1992 and 2007 only correspond to the 6 main journals analyzed: "Mundo Agrario", "Revista de Economía y Sociología Rural", "Cuadernos de Desarrollo Rural", "Journal of Rural Studies", "Journal of Agrarian Changes, and Rural Sociology". In this way, these two years contain less publications than the 2018-january 2023 period, which, although it may imply a slight bias in the information, it does not prevent the construction of a global view of the mayor research topics over the year.

Moreover, an index was sought to measure the dispersion of the results; for example, how dispersed are the publications in the journals by country, or in the countries by journals. For this purpose, the coefficient of variation is an appropriate indicator, which consists of the ratio between the standard deviation and the mean. The equation below represents the coefficient of variation.

$$CV_i = \frac{s_i}{\bar{x}_i} \qquad i=1, \ldots, \text{n countries or journals}$$

Where *CV* denotes the coefficient of variation of *i*, *s* is the standard deviation of *i* in the sample and $\overline{x}$ is the mean of *i* in the sample. When the result of the coefficient approaches 0, the dispersion is greater (less concentration), and as the resulting number moves away from 0, it indicates less dispersion (greater concentration). Note that saying that something has greater dispersion is equal to saying that it has less concentration, or vice versa; i.e., there is an inverse relationship between dispersion and concentration.

The logic is that, for example, when measuring publications in journals by country, those countries that publish in several journals have a greater dispersion (less concentration). While those countries that publish in one or a few journals have less dispersion (greater concentration).

3. Results

3.1. Scientific production around the rural world in Latin America. Journals and countries

The number of papers that could be evaluated for the period 2018-2023 is 559 articles, which represents a very significant number of scientific works for the region and denotes the importance given to the agricultural and rural topic.

These are very unevenly distributed by country (Fig. 1). Five main groups of countries can be identified.

- **Brazil** is a separate case because it has the largest absolute number of publications, with a total of 258, that is, 46.2% of the database.
- **Group 1,** composed of Argentina, Mexico and Colombia with a total of 173 publications, 30.9%.
- **Group 2,** composed of Ecuador, Chile, Peru and Uruguay, with 54 publications or 9.7%.
- **Group 3,** composed of Bolivia, Costa Rica, Cuba, Guatemala, Honduras, Nicaragua, Paraguay, Puerto Rico, Puerto Rico and Venezuela, totaled 23 publications, only 4.1%.
- **Group 4** Latin America. Are the publications in general for the entire region, or for several countries in the region, these are 51 publications, or 9.1% of the total.

The volume of publications per country shows two elements. First, the number of articles depends on the size of the national economics and the importance of the rural sector in general. Secondly, it also depends on the scientific and technological apparatus of each country; country that are very advanced from this point of view, such as Brazil, for example contrast with countries with a less developed scientific apparatus, such as Paraguay, for example.

The coefficient of variation shows high concentration for the following countries: Paraguay, Puerto Rico, Haiti, Honduras, and Jamaica (Table 1). This means that those countries usually publish in just one or a few journals about rural topics. This also could mean just one publication of those countries in the sample. On the other hand, the coefficient shows greater dispersion for Latin America (in general), Colombia, and Mexico. This result means that those countries usually publish in several journals, i.e., publications in more than 10 journals.

While studying the publications in the countries by journal, the coefficient of variation shows the highest concentration for “Revista de Economía e Sociologia Rural”, a journal from Brazil, and greater dispersion for “Journal of Rural Studies” and “Journal of Agrarian Change”, with publications about rural topics in more than 10 Latin America countries (Table 2).

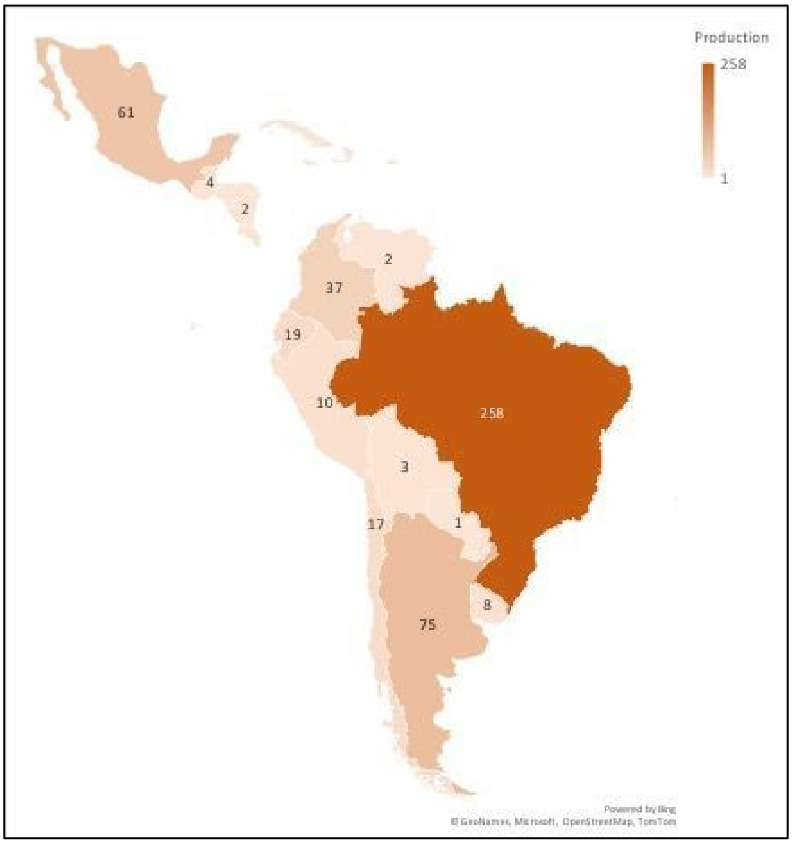

Figure 1. Distribution of selected scientific articles by country.

Table 1. Coefficient of variation of publications in the journals, by country.

Country	CV
Paraguay	8.66
Puerto Rico	8.66
Haiti	8.66
Honduras	8.66
Jamaica	8.66
Brazil	7.49
Argentina	6.51
Nicaragua	6.08
Venezuela	6.08
Guatemala	5.24
Uruguay	5.24
Cuba	4.93
Costa Rica	4.93
Bolivia	4.93
Ecuador	3.95
Perú	3.56
Chile	3.37
Mexico	3.15
Colombia	3.11
Latin America	2.15

Table 2. Coefficient of variation of publications in the countries, by journal.

Journal	CV
Revista de economía e sociología rural	4.00
Mundo Agrario	2.84
Cuadernos de Desarrollo Rural	2.19
Rural Sociology	2.05
Journal of Rural Studies	1.18
Journal of Agrarian Change	1.13

Another notable difference in the journals is their level of concentration on articles from their own countries of origin. The journal “Economía y Sociología Rural” is heavily referenced to articles on its country origin, publishing 86% of its articles on specific cases in Brazil, especially papers about economy (18%), family agriculture (8,8%), environment (7,7%) and agricultural technology (7%).

In the case of the journal “Mundo Agrario”, 63% of its articles are published on its country of origin, Argentina, mainly on social issues (15.9%), family farming (10.2%) and, in third place, conflict issues (9.1%) and land (9.1%). The Colombian journal “Cuadernos de Desarrollo Rural” is much more balanced in terms of the countries about which it publishes, the main topics being rural tourism (17%), followed by the environment (14.9%) and economics (12.8%). English-language journals publish articles on numerous countries, with no special emphasis on any one topic. The “Journal of Rural Studies” gives priority to articles on the environment (14.3%), secondly to production systems and social issues (12.9%) and thirdly to actors, networks and institutions (8.6%). The “Journal of Agrarian Change” gives priority to policy issues (17.9%), family farming, production systems and land (10.3%).

It should also be noted that there are thematic differences between the journals that publish only in English and the Latin American journals that publish in Spanish, Portuguese and English. As the data show, the journals published in Latin America have approximately 50% of their articles focused on economics, society, environment, family farming, extension and production technologies, while in the journals published in English, approximately 50% are focused on environment, society, production systems, policies and territory, which means that the focus of attention between journals published in Latin America and those published in Europe and the USA is significantly different.

There are also major differences in the topics according to the countries (Fig. 2). In the case of Brazil, the main concerns are focused on the economy (17.8%), family farming (8.9%) and agricultural technology (7%) (which is consistent with the country's agro-export efforts on the one hand, and the support of family farming and rural territories on the other). In the case of Argentina, the main topics are much more centered on agrarian conflicts (12%), social issues (16%) and family farming (10.7%), which is the result of a very particular historical moment in which two very dichotomous production models are facing each other: the agro-export model based mainly on soybean production, with strong environmental impacts, and the family farming model, which is being displaced. Although this dichotomy is a reality throughout the region, in Argentina it is more acute due to the prevalence of strong political conflicts between different sectors.

In the case of Colombia, the main topics are the environment 21.6%, extension and innovation 13.5%, and production systems and territory 8.1%. In Mexico, the most outstanding topics are production systems, 16.4%, society 14.8%, and environment and tourism 11.5%. Publications in Colombia and Mexico show a greater concern for innovation and change. The countries in group 2 (Ecuador, Chile, Peru and Uruguay) are also increasingly focused on environmental issues, as are the countries in group 3 (Bolivia, Costa Rica, Cuba, Guatemala, Honduras, Nicaragua, Paraguay, Peru, Puerto Rico and Venezuela). However, if we consider the publications produced for the region as a whole, three key themes emerge: agroecology, the environment and gender issues; in these cases, these publications tend to be cross-cutting and provide a general reflection on these issues for the entire region.

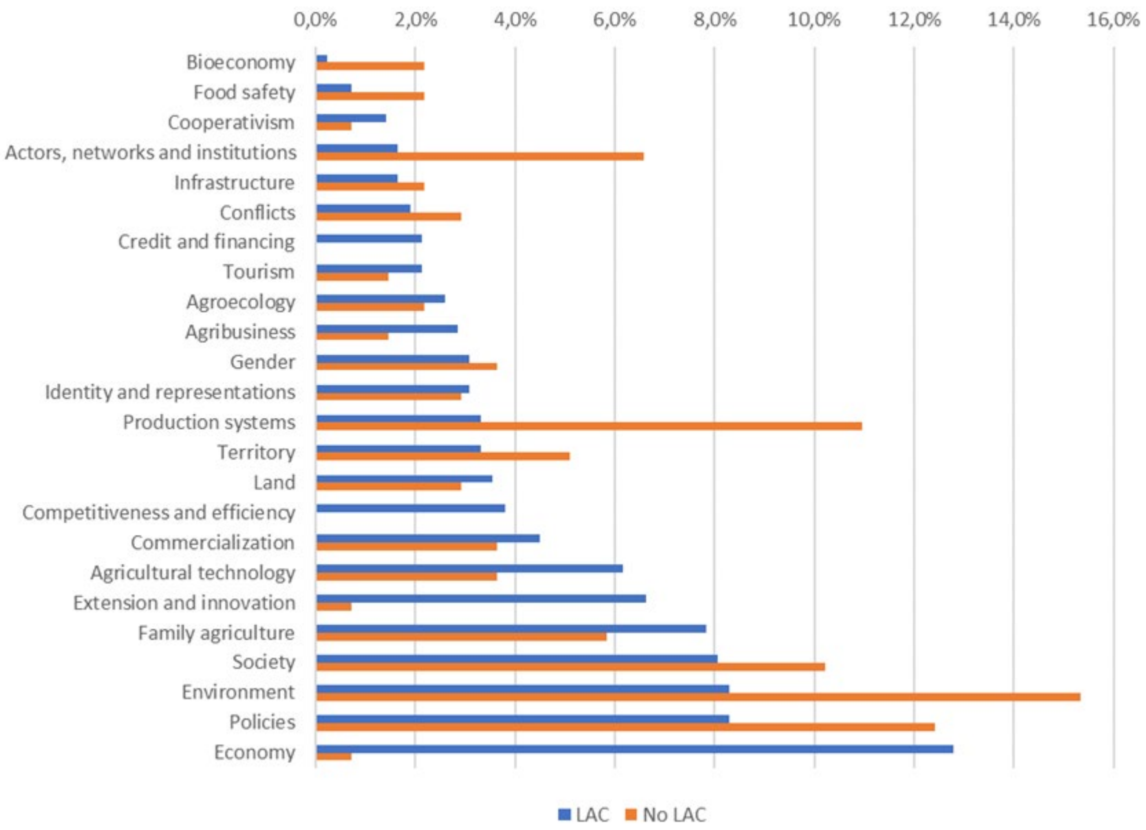

Figure 2. Main research topics in LAC and NON-LAC journals.

3.2. Key issues for the analysis of the rural reality in Latin America

In 1992, scientific publications were concentrated on economic development issues, with 31% of scientific articles, followed by production systems issues with a little more than 10%, and then production technology, agribusiness, cooperativism and social issues with 7% each. Issues related to tourism, land, food security, identity, gender, agroecology, among others, were not present in scientific production in the 1992 survey (Fig. 3). These thematic concerns were consistent with the political and economic reality of the countries that were during a process of structural adjustment and economic liberalization.

By 2007, the topics had changed significantly (Fig. 4). This is a period marked by neo-development policies in the region, with dual policies of support for exports on one hand (as an instrument for generating foreign exchange) and for maintaining family agriculture on the other. At this time, the most frequent topics were economic and productive issues, trade issues and issues compatible with the need for agro-export development, but there were also social and land issues and the policies needed to support family farming and rural territories, which had been neglected during the 1990s.

Indeed, the scientific production observed for 2007 is associated with the profound changes that took place in the 2000s, with the emergence of new policies and greater State intervention in agricultural and rural development, aimed at resolving the problems of family agriculture, problems of land concentration or land tenure and other social problems resulting from the deterioration of vast socio-productive sectors following the structural adjustment process of the 1990s. In this sense, the scientific production of this historical moment is consistent with the political and economic reality of the countries of the region.

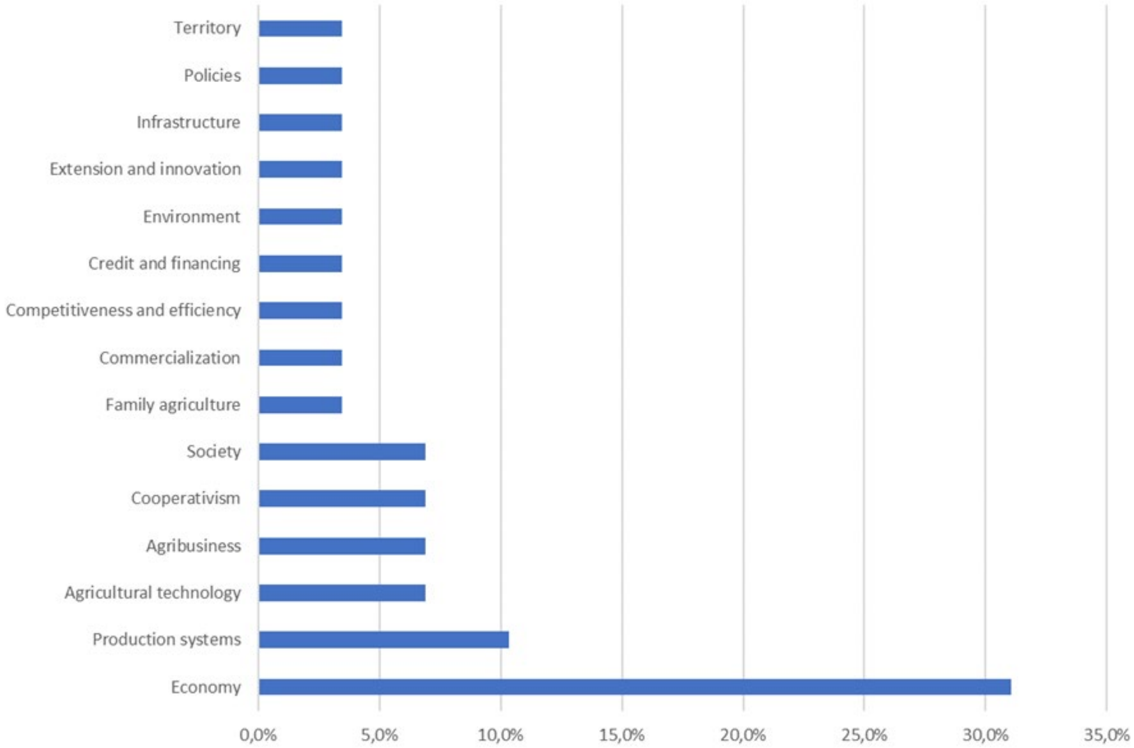

Figure 3. Distribution of scientific articles by subject matter in 1992.

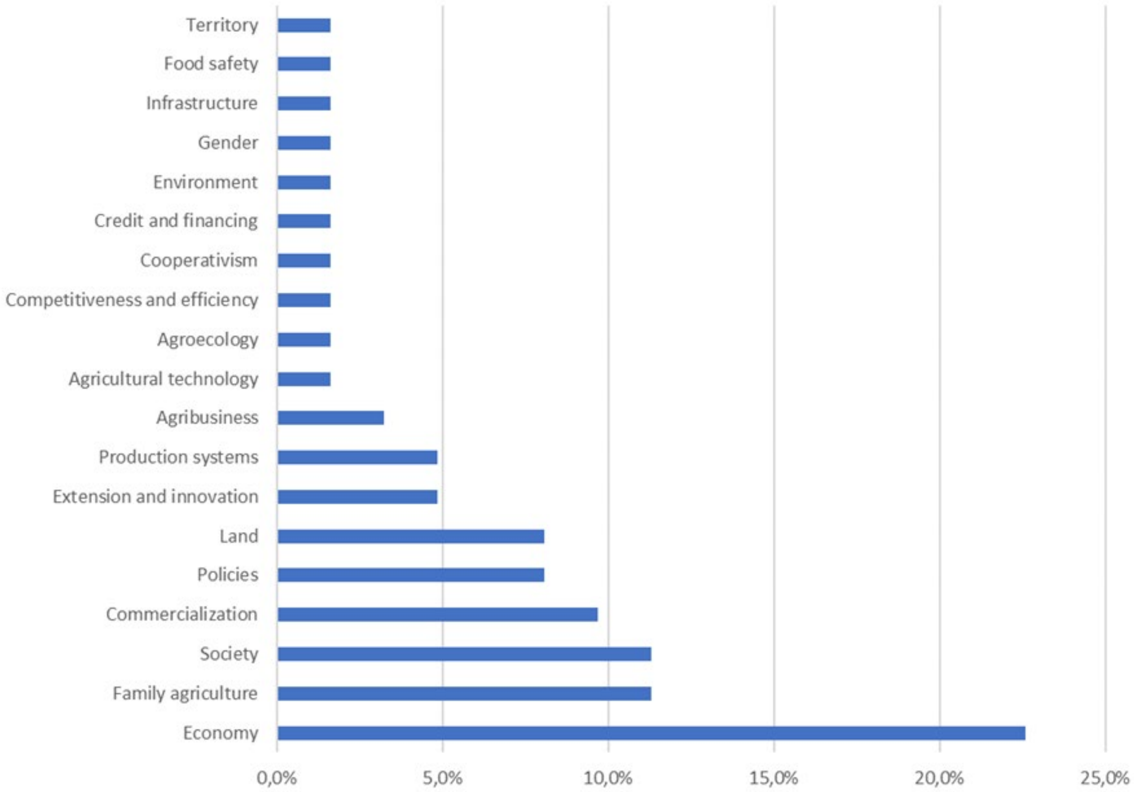

Figure 4. Distribution of scientific articles by subject matter in 2007.

As shown in Figure 5, the scientific production published in the period 2018-2023 is very different from that of the years previously analyzed. The inertia of several research topics typical of the 1990s and 2000s is maintained, i.e. the concern for productive and agroexport development on the one hand and the sustainability of family farming on the other, but the environmental topic emerges as the most studied and published topic. Environmental, economic and social issues, family farming, policies and agricultural technology account for nearly 50% of the scientific articles.

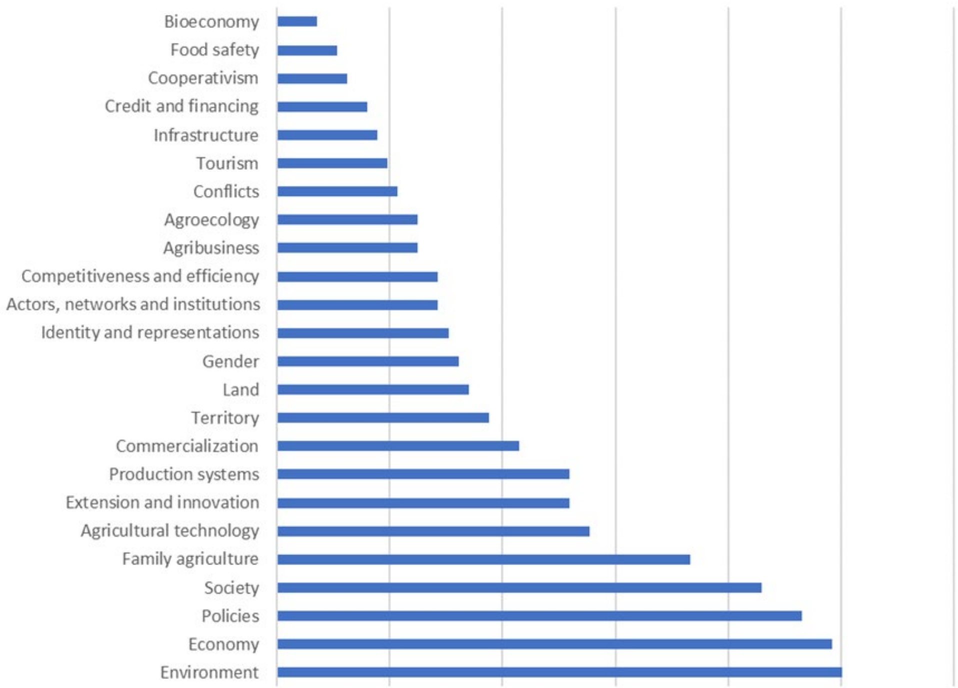

Figure 5. Distribution of scientific articles by subject matter during the period 2018-2023.

In short, from a concern focused on increasing production and productivity in the 1990s, we moved on to a period of concern for production issues and the sustainability of family farming in the 2000s, before finally moving on to a greater concern for environmental issues and the search for new alternatives to the more traditional production models, which is also reflected in the discussion of policies.

However, what stands out is the evolutionary process of the publications, which marks certain trends and behaviors, reflecting the changing times, political and economic conditions in the region.

Beyond the weight and importance of the different themes of analysis, different dynamics can be observed over time (Table 3). As Figure 6 shows, two main trends can be observed. On the one hand, the topics that tend to grow in terms of the number of publications. Within this large group, there are many topics that have grown significantly in the last decade, such as environmental issues, technology, policies, territory, agroecology, identity and many others. Meanwhile, there are issues that have varied greatly over time, but have a slight tendency to grow, such as those linked to production systems, extension and innovation, sectoral competitiveness, credit, financing and trade. However, there are other topics that have always been part of the scientific agenda but are decreasing in importance. The first set of issues have declined significantly, such as agribusiness economics and cooperativism. The second set of issues are those that have been very important at other times in history but have now declined considerably in importance, such as social issues, family farming, land issues and food security.

The variation in published topics reflects the region's problems and economic, political and institutional conditions.

Table 3. Evolution of the topics of the publications over time.

Topics	1992	2007	Currently	Trend
Environment	3.4%	1.6%	10.0%	strong growth
Economy	31.0%	22.6%	9.8%	strong decrease
Policies	3.4%	8.1%	9.3%	strong growth
Society	6.9%	11.3%	8.6%	decreasing trend
Family agriculture	3.4%	11.3%	7.3%	decreasing trend
Agricultural technology	6.9%	1.6%	5.5%	strong growth
Extension and innovation	3.4%	4.8%	5.2%	growing trend
Production systems	10.3%	4.8%	5.2%	growing trend
Commercialization	3.4%	9.7%	4.3%	strong decrease
Territory	3.4%	1.6%	3.8%	strong growth
Land	0.0%	8.1%	3.4%	strong decrease
Gender	0.0%	1.6%	3.2%	strong growth
Identity and representations	0.0%	0.0%	3.0%	strong growth
Competitiveness and efficiency	3.4%	1.6%	2.9%	growing trend
Actors, networks and institutions	0.0%	0.0%	2.9%	strong growth
Agribusiness	6.9%	3.2%	2.5%	growing trend
Agroecology	0.0%	1.6%	2.5%	strong growth
Conflicts	0.0%	0.0%	2.1%	strong growth
Tourism	0.0%	0.0%	2.0%	strong growth
Infrastructure	3.4%	1.6%	1.8%	growing trend
Credit and financing	3.4%	1.6%	1.6%	decreasing trend
Cooperativism	6.9%	1.6%	1.3%	strong decrease
Food safety	0.0%	1.6%	1.1%	decreasing trend
Bioeconomy	0.0%	0.0%	0.7%	growing trend

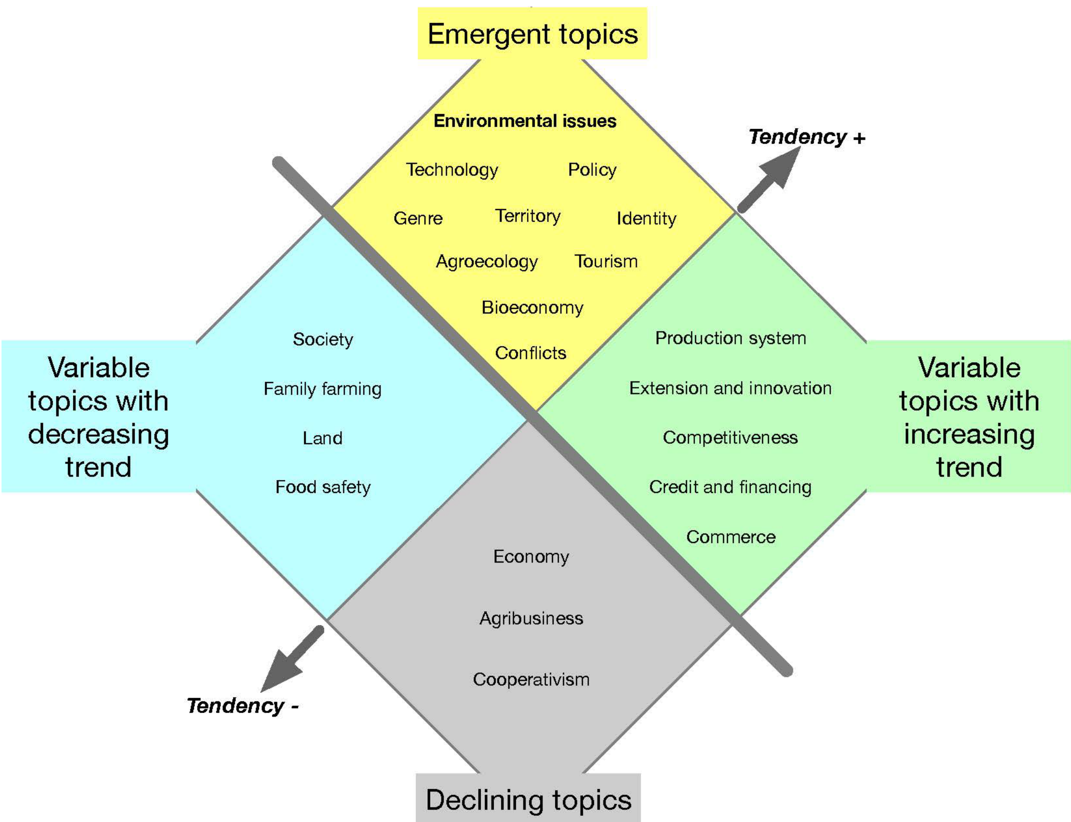

Figure 6. Dynamics of the topics published in scientific journals over time.

3.3. Emergent topics

These are themes that have been consolidated over time, especially given their importance in this historical context.

Environmental issues. The number of publications on environmental issues has grown significantly in recent years. Of the total number of articles surveyed, 33% correspond to environmental policy and governance issues, followed by diagnoses of environmental problems (28%). This is followed by environmental management issues (17%), climate change (11%) and articles related to the economic valuation of natural resources and environmental services in general (9%). Thus, the environmental issue in general has been rediscovered in recent years as a key factor in rural development, which is also a product of greater environmental awareness and the transformation generated by climate change in the region's rural territories. We consider that the growing interest in environmental issues is significant and points to a greater concern for building new scenarios of transition and greater sustainability.

Policy publications. Another emerging theme in studies on the rural world in the region is the dynamics of policies, although with notable changes depending on the historical moment. Rural policy issues emerged very strongly in the 2000s, with publications focusing on evaluating social policies aimed at family farming, assessing their impacts and their suitability as tools for change, especially transfer policies, financing for family farming, public procurement, among others (Bandeira Greño *et al.,* 2003; IICA-ECLAC-FAO, 2010). Currently, publications on policies have multiplied, with articles focusing on the review of development policies accounting for 34% of the total, followed by articles on production policies in general (32%), followed by 17% of articles on food policies and rural and territorial development policies. Once again, the importance of articles focused on evaluating the performance of policies can be seen, especially in countries with greater density and public programs oriented towards rural development, such as Brazil.

Agricultural technology. Another subject that is growing in importance in terms of publications are articles related to agricultural technology in general. Although it is not a topic of great importance in general, it was important in the 1990s, then declined in the 2000s, a period in which the technological issue was not as important as poverty and policy issues. Of the total number of articles surveyed (34), most correspond to works on management technologies (36%) and technical diagnoses (33%). The rest of the articles focus on analyses of types of productive activities and varieties (15%) and articles focused on the analysis of technological change (15%).

Territorial issues Already in the 2000s, concern for territorial issues (territorial organization and planning, land use, rural-urban relations) began to emerge as an issue of interest in the region (Perico and Ribero, 2002). The visualization of the problems of the rural world as systemic phenomena that went beyond mere production issues, and the emergence of the concept of rural territorial development by RIMISP, IICA, FAO and other national organizations was an incentive for the generation of studies and publications on the subject (Guzmán *et al.,* 2006). At the present time, publications on territorial issues, although only 23 cases were published, are notably higher than in previous periods, reflecting the emergence of new discussions and problems in the region, such as rural territorial development (45% of the articles), territorial diagnoses (25%), the valorization of heritage resources and rural pluriactivity (20%) and the problems of rural-urban relations, decentralization processes and especially the issue of land use planning (10%), which are increasingly key issues in the development of rural territories (Sili, 2022).

Genre. Another emerging issue in recent years is the question of gender and the role of women in the rural world. Although the number of articles is lower (19 articles), the number of articles has increased with respect to the periods analyzed above, which is consistent with current discussions. The most important topic linked to the gender issue refers to the working conditions of women in the rural world in general and around different productive activities.

Identity and representations. Also, as with gender issues, there was an increase in the number of articles focused on issues of identity and representations by the rural population. Although there are few articles (17), they are focused on analyzing the representations of the population on rurality, life in rural areas, the relationship with nature and, in some cases, on technological change and production systems. In a certain way, there is a revaluation of the meaning of rural life, which is "rediscovered" in its unique aspects and symbolic attributes. They are associated with the authenticity of customs, with identity references that link them with the traditional, with the autochthonous, with the deep values of national identity. They are also valued in their environmental conditions and lifestyles, in contrast to urban spaces.

Actors, networks and institutions. The number of articles on actors, networks and institutions has also increased with respect to previous periods, most of them dealing with collective action, social movements and institutional arrangements. Most of these articles refer to family farming organizations and networks.

Agroecology. Agroecology, although it has very few articles, is clearly an emerging topic, which shows the concern in the region for the construction of new models of production and rural development, such as the logic of circular economy and agroecology (Betancourt Morales and Zartha Sossa, 2020; Altieri and Nicholls, 2012; Muñoz *et al.,* 2021). Most of these articles focus on promoting and substantiating, with empirical evidence from the field, the importance of agroecology as an alternative production model.

Tourism. There are very few articles focused on tourism, although this topic has grown considerably with respect to other years. Most of these articles focus on Mexico. The growth of this topic highlights the importance of this activity in the rural world of Latin America, an activity that has been responsible for the revitalization of many marginalized rural territories (Sarasa, 2014).

Bioeconomy. The bioeconomy, like tourism, is beginning to appear in the literature on the rural world in Latin America as a set of innovative productive activities capable of dynamizing production chains and territories. (Sasson and Malpica, 2018). Most of these articles are published in English-language journals, often by authors from countries outside the region.

Conflict over the control of resources. Finally, within this category of emerging issues, there are publications on conflicts over the control and management of natural resources (Palmisano, 2015; Manzanal and Villareal, 2010). Indeed, the expansion of the production of primary goods has a spatial correlate, since growth was not only the result of an improvement in productivity per hectare, but also, and above all, the result of an accelerated advance on new lands, many of them tropical and subtropical forests that were deforested, or desert areas on which new irrigation systems were installed (Slipak, 2015; Gligo *et al.,* 2020). The advance on new lands, evident in Brazil, Paraguay, Argentina and Bolivia, among others, and the capture of new water sources (cases of Chile, Peru, Ecuador, Colombia, among others) have generated, on the other hand, numerous conflicts with family farmers - evicted from their lands or without availability of water use. These conflicts over the appropriation and use of natural resources have given rise to articles, preferably focused on the case of Argentina and Brazil. In many cases these conflict processes are analyzed through articles under the policy theme.

3.4. Variable topics with increasing trend

There is another set of publication topics that has had a variable behavior over time, but which show a growing trend in recent years.

Production system. The literature on agricultural production systems in general has been very important in the period of the 1990s, a time when there was a strong orientation in policies towards improving production and increasing economic competitiveness (Gazzano *et al.,* 2019). The importance of these articles decreased notably and remains stable at present. The most relevant topics on those that describe and analyze different production systems, especially of agricultural origin, using different approaches, many of them linked to the analysis of value chains, analyzing the types of products, scales of production and the actors linked to these products or production chains.

Extension and innovation. Directly linked to production systems, there is many publications focused on extension systems and the emergence of innovation processes. These are growing topics, and in recent years more oriented to innovation issues for adaptation to climate change and new environmental conditions. Within this set of articles an expanded concept of innovation is put forward, understood in a broad sense that includes not only the generation of new products, processes, services or forms of management, but also the search for creative solutions to problems faced by communities, strategies to increase efficiency and for the construction of new development processes (Pyburn and Woodhill, 2014; Horlings and Marsden, 2014; Sili and Martin, 2022).

Competitiveness efficiency. The articles related to competitiveness and efficiency of production system were important during the 1990s, then they declined and reappeared as important topics now days. These are orientated to measure the level of competitiveness of the products or production activities and the efficiency in the use of resources. Most of these articles are focused on the case of Brazil.

Credit and financing. Similarly, articles related to credit and financing have decreased over the years, being scarce at present (11) and very focused on the case of Brazil.

Commerce. The articles related to trade have decreased with respect to previous years (31 articles), which follows the trend observed with the other articles related to competitiveness, credit and agribusiness. These articles are heavily concentrated on three topics: export markets, markets for family farming products, and national marketing chains through supermarkets or other instruments. Within these articles, there is a clear reference to new forms of consumption and changes in consumer preferences, which stimulate the production of new, more natural products that are closer to the traditions and values of the territories.

3.5. Variable topics with decreasing trend

There is a large set of analysis topics that are highly variable over time but have a declining historical trend. These are the ones that were in vogue during the period of the 2000s and that were directly linked to the social problems of the rural world.

Social issues. The social issues and problems of the rural world in Latin America continue to be a key topic on the scientific agenda, but their importance is declining. The main topics of interest are the organization and transformation of rural societies (22%), followed by the analysis of workers and their dynamics (15%), the analysis of social capital (14%), the problem of education in rural areas (12%), the situation of indigenous communities (11%), the problem of rural youth (6%), rural poverty (6%) and finally issues related to migration (2%). This last topic of migration is not considered a topic of great importance as it has been in other historical moments, as well as the topic of poverty, a topic that was treated with much greater emphasis in other historical moments.

Studies on family farming. It is evident that the problems of this vast social sector continue to be a permanent topic of analysis in the region, which has generated numerous research and publications in recent decades (Grisa and Sabourin, 2019; Obschatko *et al.,* 2007; Salcedo and Guzman, 2014). However, and seen through the number of scientific publications observed over time, this topic does not occupy the same place of importance. It was a topic that received little work in 1992 (3.4% of publications), which is consistent with the level of concern at that time, focused on issues of development and competitiveness; it then occupied a privileged place in 2007 (11.3% of publications), i.e. in the midst of a period of momentum, with numerous policies to support the family farming sector, and then declined again in percentage terms in the current period, with 7.3% of the publications surveyed. At present, the topics most frequently dealt with are the characterization of family farming (33%), the development of the family farming sector (23%), aspects of technology and production in family farming (19%), strategies for persistence and sustainability (14%) and finally topics related to marketing (9%).

Land. The subject of land, a key issue in rural development in Latin America, has been studied extensively between the 1950s and 1980s, when different agrarian reform measures were implemented. Then, and in the context of reforms and structural adjustment, its importance declined to become relevant again in the years 2000, at which time many policies aimed at strengthening family farming and solving the historical land tenure problems in the region emerge (Soto Baquero y Gómez, 2014). However, the importance of this topic has diminished at present, with only 3.4% of articles published.

Food safety. The issue of food security is a minority topic in publications on the rural and agricultural world, accounting for only 1.1% of publications, less than in the 2000s, when the topics of family farming, poverty and food security were more widely addressed. This topic is much more developed by cooperation agencies, in the form of reports (IICA, 2020).

3.6.Declining topics

There is another set of issues that have become less important over the years.

Economic issues. Latin America has a strong dependence on primary production; the region contributes 45% of global food exports, much more than any other region in the world (Barrantes *et al.,* 2013). The agricultural sector grows at an average of 2.8% per year, supported by the expansion of exports and by the dynamics of domestic demand (Rodríguez *et al.,* 2017). It is not surprising then that scientific production around growth and productive development linked to the agricultural sector continues to be one of the main topics of scientific publications (about 10%). However, the most salient fact is that this topic has been decreasing in recent years in relative terms compared to other emerging issues. Latin America has reached very important levels of production and development in the agricultural sector; the problem does not seem to be there, but in the impacts that this productive growth has had in social, environmental, and territorial terms in general, which is reflected in the growing importance of other topics of analysis. The topics addressed are, in first place, economic diagnoses of activities or chains (25%), studies linked to consumption and demand for products derived from the agricultural sector (22%), studies linked to economic policies (15%), studies on the transformation of productive structures (12%), studies on productive strategies linked to the agricultural sector (10%), studies linked to finance (4%), employment (4%) and finally, studies on insurance (3%).

Agribusiness. Only 18 articles related to agribusiness have been surveyed, most of them focused on Brazil and Argentina, the two countries most closely linked to this topic. The key topics are the organization and dynamics of the agribusiness sector and its relationship with markets and resources. However, the importance of this topic has declined at present, compared to the 1990s.

Cooperativism. The topics related to cooperativism have also decreased throughout the period analyzed, being currently a minority topic.

4. Conclusions

Clearly, this study has limitations that could be resolved in new studies. Thus, there are numerous bibliometric indicators such as authors' age, sex, productivity indexes of the authors themselves, multi-authorship indexes, journal impact factor, self-citation indexes, descriptors, isolation indexes, the national impact factor, among others, which have not been used in this work and which would allow a more detailed analysis of the publications and their trends (González de Dios *et al.,* 1997). Another limitation of this work is the method and technique used to link each article to a topic, this has been a work done by the authors based on titles and keywords, which may have generated biases since an article was linked to only one topic, when in some cases an article could be linked to two or more topics.

However, this work was not intended to be bibliometrically exhaustive, but rather to understand the major trends in terms of analysis and reflection on rural studies in Latin America, relating these changes to the political and economic transformation of the region. With this in mind, there are several elements that can be highlighted.

Scientific production on the rural and agricultural world in the Americas is very important. Only three Latin American journals specialized in rural issues publish approximately 60 articles per year, to which must be added the articles of numerous other journals published in Latin America, plus all the international journals, especially English-language ones, that publish articles on the subject and on the region. This shows the importance of rural issues in general, which is consistent with the economic and political reality of the continent, a continent that, although it is rapidly urbanizing, has a strongly rural economic and social base.

Scientific production on the rural world has evolved significantly in the last thirty years, from topics more focused on production and productivity in the 1990s, we have moved in the 2000s to social issues, family agriculture and policies, in response to the impact of production models that do not respect the environment and rural societies, to advance in recent years to topics where the environment, new activities and productive modalities (tourism, bioeconomy, agroecology) and policy issues appear more strongly. This thematic evolution shows that there is a change in the way rural issues are viewed, from a productive and agricultural perspective to a much broader rural perspective, interested in the dynamics of the territories, in the multiple resources of the rural world and in thinking of the rural thing as living and dynamic territories where people can build their life projects.

The approaches of the journals differ from one another and are conditioned by the reality of their own countries and their networks of authors. In the case of Latin America, the journals are very focused on their own countries, and therefore more closely linked to the political and economic agendas of the countries; in the case of English-language publications, they maintain greater autonomy in their editorial policies and a more balanced distribution of the countries on which they publish their articles.

The changes in the topics published suggest that research and reflection are increasingly oriented towards new models and paradigms of development. However, and perhaps the greatest shortfall in terms of the publications surveyed, is that there are no clear publications focused on the analysis and reflection of new paradigms or emerging rural development models. Thus, only two publications out of a total of 559 explicitly mention in their titles the issue of transition to new sustainable models, and only 5 articles explicitly mention the term sustainability. In this sense, although it can be affirmed that there are conceptual advances in scientific publications on the rural world in Latin America in relation to previous decades, accompanying the changes occurring in the rural world, research and reflection on the rural world in Latin America is still tied to the old problems inherited from the modernization periods of the mid and late twentieth century.

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ANALYSIS OF PLANT PHENOLOGY DYNAMICS IN SPAIN FROM 1983 TO 2020 USING SATELLITE IMAGERY

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ABSTRACT. This study spatially analyzes plant phenology and its variations over time in mainland Spain and the Balearic Islands. To conduct the analysis, a nearly 40-year span time series (1983-2020) was generated by merging NDVI vegetation index values from satellite images sourced from NOAA-AVHRR and MODIS sensors. The phenological variables were calculated using TIMESAT 3.3, which extracted 13 phenometrics whose trends were evaluated using the Theil-Sen model, and their significance was assessed with the Mann-Kendall test. The results reveal regional differences between Eurosiberian Spain and the Mediterranean region regarding the start and end phases of the season. On average, the Eurosiberian zones have experienced delays in their season start and end dates, by approximately 0.35 and 0.22 days per year over the study period, respectively, while the Mediterranean region has seen an advancement in leaf-out and senescence dates by about 0.07 and 0.05 days per year. A greening trend across the entire study area and significant contrasts among land covers have also been observed, opening avenues for future studies to delve deeper into these behavioral differences and their interactions with changes in climate and land management.

Evaluación espacialmente continua de la dinámica de la fenología vegetal en España entre 1983 y 2020 a partir de imágenes de satélite

RESUMEN. En este estudio se analiza espacialmente la fenología vegetal y sus variaciones a lo largo del tiempo en la España peninsular e Islas Baleares. Para realizar el análisis se ha generado una serie temporal de casi 40 años (1983-2020) a partir de la fusión de valores del índice de vegetación NDVI de imágenes de satélite procedentes de los sensores NOAA-AVHRR y MODIS. El cálculo de las variables fenológicas se ha realizado con TIMESAT 3.3. que ha extraído 13 fenométricas cuya tendencia se ha evaluado a partir del modelo Theil-Sen y la significación de esta con el test de Mann Kendal. Los resultados muestran diferencias regionales entre la España eurosiberiana y la mediterránea respecto a las fenofases de inicio y final de temporada. Las zonas eurosiberianas de media han visto retrasadas sus fechas de inicio y final de temporada, en torno a 0,35 y 0,22 días cada año a lo largo del periodo de estudio respectivamente, mientras que la región mediterránea ha adelantado las fechas de salida de las hojas y la senescencia de media alrededor de 0,07 y 0,05 días al año. También se ha observado una tendencia al reverdecimiento de toda el área de estudio e importantes contrastes entre las cubiertas del suelo que abren la puerta a futuros estudios que profundicen en estas diferencias de comportamiento y en sus interacciones con los cambios en el clima y en la gestión del territorio.

Keywords: Plant phenology, remote sensing, global change, NOAA-AVHRR, MODIS, NDVI.

Palabras clave: fenología vegetal, teledetección, cambio global, NOAA-AVHRR, MODIS, NDVI.

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1. Introduction

Vegetation dynamics are a primary indicator of global change, encapsulating alterations in both the climate system and land use and cover management (Cleland *et al.,* 2007; Menzel, 2002). In this context, various metrics obtained through field observations (e.g., radial growth in trees) (Prislan *et al.*, 2019; Rossi *et al.*, 2011; Rubio-Cuadrado *et al.*, 2021) and remote sensing (several vegetation activity or greenness indices) (Motohka *et al.*, 2010; Reed *et al.*, 2009) have been employed to examine vegetation changes due to climate change (Badeck *et al.*, 2004; White *et al.*, 2009). Among these methods to measure vegetation dynamics, one of the most robust relates to plant phenology (Bertin, 2008; Cleland *et al.*, 2007), referring to the periodic growth and development cycles of vegetation, typically on an annual scale (Lieth, 1974). From these cycles, several metrics such as the start of growth or the onset of senescence can be derived (Helman, 2018; Reed *et al.*, 2009; Schwartz, 2013), which are recurrent biological processes encompassing various biotic and abiotic causes. Biotic factors influencing vegetation phenology are primarily linked to plant physiology, and the different stages of the phenological cycle are commonly called phenophases. These phenophases are determined by factors such as plant species and development stage, as well as environmental factors like temperature, photoperiod, and availability of water and nutrients, along with their interactions. These factors significantly affect the period during which vegetation is active, easily detectable as this stage usually coincides with the presence of leaves (Lim *et al.*, 2007). Several studies have demonstrated the impact of climate variability and changes on plant phenology (Menzel *et al.*, 2006; Richardson *et al.*, 2013), where the trend towards increasing temperatures has been associated with shifts in key phenological stages, such as the start of the season (leaf unfolding) and the end of the season (color change), leading to an earlier spring, an extension of the vegetative activity period, and a delay in the phenological autumn (Gill *et al.*, 2015; Jeong *et al.*, 2011; Piao *et al.*, 2019).

Plant phenology has multiple ecological implications, as changes therein can alter seasonal interactions among different species (Rathcke and Lacey, 1985; Yang and Rudolf, 2010), with notable consequences for ecosystem biodiversity and productivity (Kharouba *et al.*, 2018). For example, these changes can affect plant-pollinator relationships (Kudo and Ida, 2013), increase vegetative activity, and enhance carbon absorption (Piao *et al.*, 2006; Piao *et al.*, 2019), which in turn have impacts on the ecosystem as a whole. For these reasons, the study of phenology has gained importance, evolving from mere notation of different key moments for vegetation (e.g., the start or end of the season or flowering) to becoming an integral field of experimentation and model generation with broad ecological and climatic significance (Piao *et al.*, 2019; Richardson *et al.*, 2013). In recent decades, there has been a rapid increase in the number of studies focused on plant phenology (Piao *et al.*, 2019), particularly those related to the effects of climate change on vegetation (Menzel *et al.*, 2006; Piao *et al.*, 2019). For instance, both in situ (terrestrial) and satellite measurements have observed a trend of changing phenological patterns in Europe, North America, and East Asia, with an earlier season start over recent decades (Ge *et al.*, 2015; Fu *et al.*, 2014; Wolfe *et al.*, 2005). To a lesser extent, it has also been noted that in Europe, the end of the vegetative period seems to be delayed (Gill *et al.*, 2015).

National and international phenological networks have recorded various parameters of vegetation phenology (Piao *et al.*, 2019). Although there are occasionally very long temporal records (e.g., several centuries for cherry blossom in Japan), the spatial coverage of the records is usually limited (Rodriguez-Galiano *et al.*, 2015) and primarily focused on temperate and subalpine forest areas. Moreover, records are often obtained by different observers and with different methods, without a uniform protocol, making it difficult to integrate and exchange this type of information between different regions (Piao *et al.*, 2019). In Spain, although there is a national phenological observation network maintained by the Spanish Meteorological Agency (AEMET) (MITECO, n.d.), the records are very short and scarce, except in a few locations (García-Mozo *et al.*, 2010; Oteros *et al.*, 2015). For these reasons, in recent decades, numerous research efforts have been made to analyze plant phenology and its changes using data provided by Earth observation satellites. This approach offers an advantageous way to study these terrestrial vegetation cycles due to the existence of continuous and systematic global information.

For these types of studies, images from the AVHRR (Advanced Very High Resolution Radiometer) sensors aboard NOAA (National Oceanic and Atmospheric Administration) satellites, with information since 1981 (Caparros-Santiago and Rodríguez-Galiano 2020; Piao *et al.*, 2019), as well as from MODIS (Moderate Resolution Imaging Spectroradiometer) images from Terra and Aqua satellites (Novillo *et al.*, 2019; Zhang *et al.*, 2003), and even high-resolution studies from the Landsat and Sentinel image series satellites (Fisher *et al.*, 2006; Vrieling *et al.*, 2018), have been particularly used. Phenological parameters are usually extracted using different vegetation activity indicators derived from radiometric information. Among the most used indicators are the NDVI (Normalized Difference Vegetation Index), EVI (Enhanced Vegetation Index), or LAI (Leaf Area Index), among others (Karkauskaite *et al.*, 2017; Verger *et al.*, 2016; Zhang *et al.*, 2003). From these indices, phenological variables corresponding to the start of the season, the end, or the duration of the same can be extracted, provided the observations have been taken with an adequate temporal frequency. These variables are also called phenometrics. There are different methodologies and algorithms for phenological analysis (Jönsson and Eklundh, 2002; Sakamoto *et al.*, 2005; White *et al.*, 2014), but all of them obtain the phenometric variables from time series of vegetation indices through three stages: i) improving the quality of the input indices, ii) fitting functions to the vegetation cycles, and iii) identifying the start and end dates of the growing season by establishing thresholds or inflection points (Liu *et al.*, 2016), from which to derive other phenological variables.

In Spain, studies have analyzed vegetation dynamics in recent decades, mainly through long series of observations in some specific locations (García-Mozo *et al.*, 2010; Gordo and Sanz, 2009; Peñuelas *et al.*, 2002). The results of these studies suggest phenological changes due to the current warming process (Caparros-Santiago and Rodríguez-Galiano 2020; Gordo and Sanz, 2009). Although there have been some approaches to characterize Spain's phenology from satellite images (Alcaraz Segura, 2006; Amorós-López, *et al.*, 2013; Caparros-Santiago and Rodríguez-Galiano 2020; Gutiérrez-Hernández, 2020; Martínez and Gilabert, 2009; Novillo *et al.*, 2019), the studies have covered short periods. For this reason, this study addresses the study of plant phenology in Spain over the last four decades using satellite image series at a medium spatial resolution (1.1 km^2), which is considered sufficient to determine possible patterns of change based on a good number of vegetation phenology parameters.

The objectives are to spatially characterize the phenology of vegetation in Spain in the long term and determine, from a set of phenological variables, both its average conditions and variations over time and space, as well as the changes recorded since the beginning of the 1980s in mainland Spain including the Balearic Islands.

2. Data and methods

2.1. Study Area

The study area encompasses mainland Spain, including the Balearic Islands. From an ecological perspective, Spain can be divided into two macro-biogeographic regions: Mediterranean and Eurosiberian. The Eurosiberian zone covers the northern and northwestern territories, as well as mountainous areas, while the remainder of the country falls within the Mediterranean region. Spain is also one of Europe's most diverse territories, not only in terms of its natural environment but also in its land use, which is highly varied (Fig. 1). In the Mediterranean region, vegetation comprises many functional plant types whose phenological responses vary according to environmental signals, with temperature being the key factor for most species (Peñuelas *et al.*, 2002). However, it is the summer drought in the peninsula that controls the vegetative activity in the Mediterranean area, with the growth phase occurring during the cooler, wetter part of the year (Matesanz *et al.*, 2009; Prieto *et al.*, 2008); unlike the Eurosiberian region, which exhibits growth during warmer temperatures.

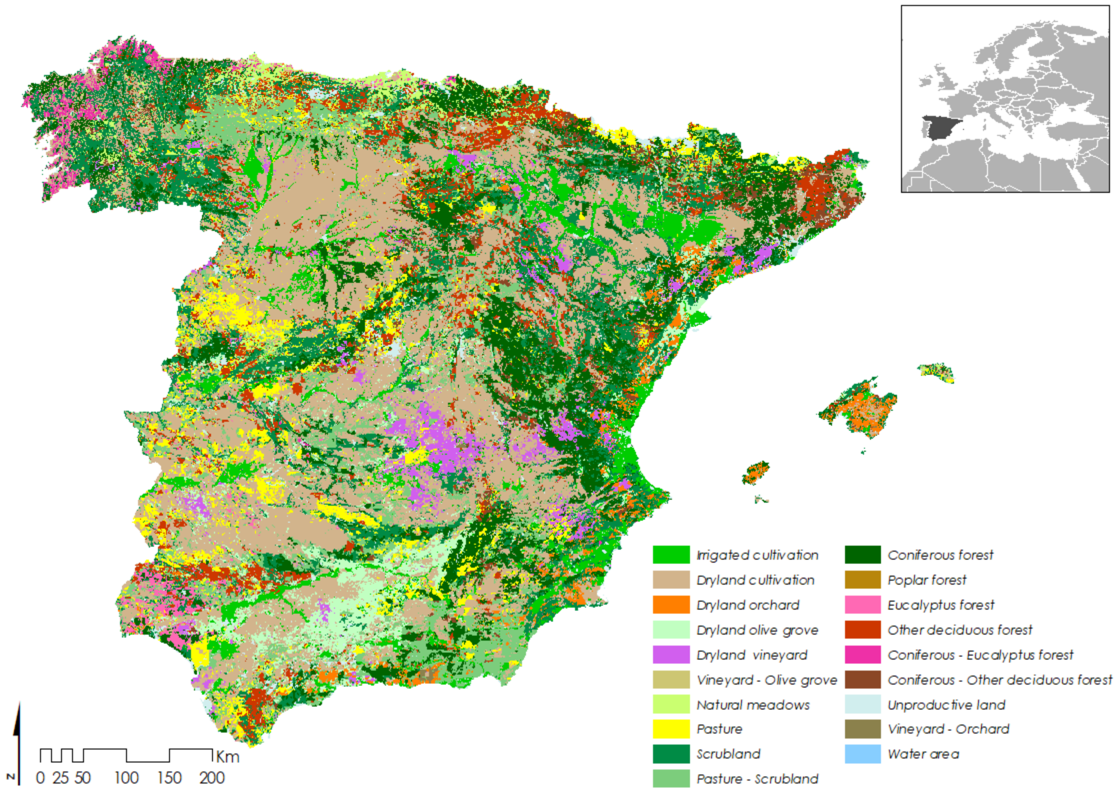

Figure 1. Map of crops and uses, 1980. Source: MAPA.

2.2. Generation of a 40-Year NDVI Time Series

The foundational data for this study were two databases of the Normalized Difference Vegetation Index (NDVI). The first database was generated from NOAA-AVHRR satellite images from 1981 to 2015, developed through georeferencing, calibration, and radiometric correction of over 10,000 satellite images. This database offers a spatial resolution of 1.1 km² and a semi-monthly temporal frequency, with two images each month made from the composites of the daily images available. This database does not exhibit information gaps. Complete information on this database can be consulted in Vicente-Serrano *et al.* (2020). The second database comes from MODIS (Moderate Resolution Imaging Spectroradiometer) satellites for the period 2001-2021. NDVI data are from the MOD13A2 product and are available at a spatial resolution of 1 km and a temporal frequency of 16 days. Complete information on the database can be found at https://lpdaac.usgs.gov/products/mod13a2v006/. To analyze long-term phenology (between 1981 and

2021), it was necessary to combine both sources of information. This involved transforming the spatial resolution of the MODIS images (1 km) to match the 1.1 km of the NOAA-AVHRR images, considering the same envelope and spatial extension through bilinear convolution. Subsequently, it was necessary to transform the temporal frequency of the MODIS images from their temporal location every 16 days to the fixed frequency of the NOAA-AVHRR images (one image corresponding to days 1-15 and another from 16 to the end of the month). A linear interpolation process of the image values was applied on a daily basis, and the average NDVI within the same temporal intervals as the database from the NOAA-AVHRR images. Due to the significant difference, both in the total magnitude of NDVI and in its annual range of variation, between both databases (Fig. S1), a fusion of the data was performed to adapt the NDVI data from the NOAA-AVHRR images to those of the MODIS images.

To carry out the fusion of both databases, the NDVI series were transformed into standardized values, using the common period 2001-2021. Different probability distributions (exponential, Gamma, log-normal, Weibull, Pearson-III, normal, general Pareto, general normal, general extreme values, and general logistic) were tested for the adjustment of each of the semi-monthly series for each of the pixels in the database. The equations for these distributions can be consulted in Vicente-Serrano *et al.* (2012). The selection of the most suitable distribution for each pixel and semi-monthly series was made using the highest value of the Shapiro-Wilks test with the aim of obtaining standardized values, which perfectly follow a standard normal distribution according to Stagge *et al.* (2015).

Finally, the anomaly series from the NOAA-AVHRR images were transformed into NDVI values based on the parameters obtained from the MODIS series of the common period. This procedure allowed obtaining AVHRR series perfectly comparable in terms of magnitude and variability range of the MODIS NDVI series, with a high degree of adjustment during the common period (Fig. S2). In the common period, the MODIS image series from the year 2001 were preserved, so the NOAA-AVHRR images contained in the final database correspond to the period 1981-2001. Figure S3 shows, using the D index (Willmott, 1981), the analysis of the goodness of the reconstruction in a spatial and summarized manner for different periods of the year and land uses. The maps of the index in different weeks show a predominance of values above 0.6 throughout Spain, meaning that the reconstructions are generally acceptable, and quite good in broad regions showing values close to 1. In fact, the reconstruction presents less uncertainty on the scale of specific weeks, and particularly during the summer, when the reconstructed NDVI values from the AVHRR images show a high degree of adjustment with the NDVI data from MODIS. The differences between semi-monthly periods are scarce, although the reconstruction is better for the summer months, and no significant bias is observed in the goodness of the reconstructions among different land uses. Although there are some uncertainties in the reconstruction at the local level, it can be considered that the procedure used provides very acceptable results and allows the use of the series for the estimation of phenological parameters over the last four decades.

2.3. Calculation of Phenological Variables

For the analysis of vegetation phenology, 960 semi-monthly periods from 1983 to 2021 were worked with. Applying time series analysis algorithms of vegetation indices implemented in TIMESAT (https://web.nateko.lu.se/timesat/timesat.asp), a series of 13 plant phenology parameters were extracted: date of the start of the season, date of the end of the season, mid-season date, duration of the season, the maximum index value in the season, the index value at the start date, the index value at the end date, base value (average of the start and end of season values), amplitude (difference between the maximum and base value), left derivative, right derivative, large integral (area under the curve for the entire season), and small integral (area under the curve for the entire season relative to the base value) (Eklundh and Jönsson, 2017; Jönsson and Eklundh, 2002).

For the fitting of functions to the NDVI series, a Savitzky-Golay filter (Kim *et al.*, 2014) with a moving window size of 2 was used, which is conservative in relation to the maintenance of the original

NDVI data. This filter was chosen because it is more accurate and advantageous in periodic time series and particularly in processed NDVI series, as these are relatively unaffected by atypical observations (Eklundh and Jönsson, 2017). Likewise, by using this filter, more complex behaviors can be distinguished as it closely follows seasonal changes, by iteratively adjusting the window that captures the increase and decrease of the data (Eklundh and Jönsson, 2015). Additionally, this procedure is effective in characterizing certain soil covers, such as semi-arid grasslands that change their activity in short periods of time (Jönsson and Eklundh, 2004).

A key aspect in determining phenological cycles is establishing the start and end of the vegetative season. For this, a test was conducted based on different soil covers considering the amplitude of the vegetative season, defined between the base level and the maximum value of the data distribution for each season. The start occurs when a specified fraction from the left of the adjusted curve relative to the base level is reached, set at 0.3 units since this value shows a good fit for different soil covers at the national level. Conversely, the end of the season was defined at a value of 0.2, which showed more consistent results in different soil covers such as deciduous forests, grasslands, rainfed crops, etc. The preliminary analysis of the data allowed verifying that, given the characteristics of some of the covers and certain phenological cycles, the model obtained incoherent results in some areas, with very variable vegetative activity seasons, like certain irrigated crop areas. In order to eliminate the data where the confidence in the phenology estimation was very low, the areas where the interannual deviation corresponding to the start date data was greater than 75 days (5.3% of the study area) were removed, as the uncertainty of the phenological estimates in these areas was very high. Also, the first and last year of the time series of all phenological variables were removed to avoid artifacts in the estimation of incomplete phenological periods, so the temporal analysis was finally limited to the period 1983-2020.

2.4. Analysis of Vegetation Phenology

The analysis of the different phenological variables was based on the spatial characterization of the phenological variables through averages and coefficient of variation. To evaluate changes in the different variables, two non-parametric statistics were used: the Theil-Sen regression to estimate the trend, a consistent method for asymmetric distributions and with high tolerance to error deviations (Fernandes and Leblanc, 2005; Peng *et al.*, 2008), and the Mann-Kendall test (Mann, 1945; Kendall, 1948), which allows determining the statistical significance of the observed changes in the trends of the variables. A significance threshold $\alpha = 0.05$ was used. The results were obtained for each of the 1.1 km pixels, but a grouping of the results for the main soil covers of Spain was also carried out. For this, the crop and land use map between 1980 and 1990 at a scale of 1:50,000 generated by the Ministry of Agriculture, Fisheries and Food (MAPA, https://www.mapa.gob.es/es/cartografia-y-sig/publicaciones/agricultura/mac_1980_1990.aspx) was used.

3. Results

The average start of the vegetative activity season exhibits clear spatial differences between the Eurosiberian region, some mountain areas of inland Spain, and certain irrigated zones, which begin their season at the end of the first quarter of the year, and the rest of Spain's vegetation, the Mediterranean, which starts its season between September and November (Fig. 2). During the study period, a strong interannual variation in the season's start is observed in the Duero basin and the Southern Plateau, corresponding to rainfed areas, and the irrigated zones of the Guadalquivir and Ebro, as well as most of Galicia. The magnitude of change shows negative values across most of Spain, suggesting an advancement in the start of vegetative periods, between 1 and 2 days per year and exceeding 2 days in some areas of the northern and southern plateaus and in the Guadalquivir valley. Conversely, a delay in the start of vegetative activity of between 1 and 2 days per year is observed in Galicia. The changes in these areas are statistically significant.

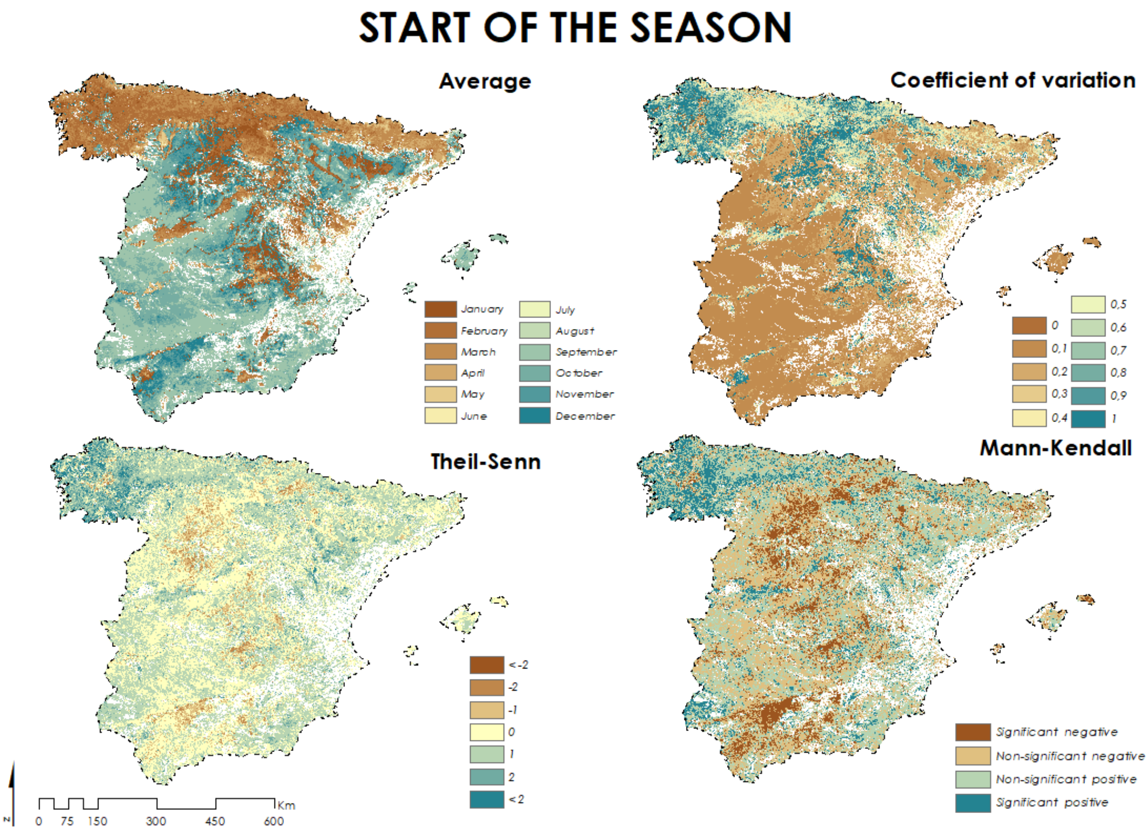

Figure 2. Maps of the statistics for the start of the season.

The analysis by different land covers shows high variability in the average start dates of the season for some cover types (Fig. 3 a)), suggesting broad subregional differences. Irrigated lands, vineyards, rainfed areas, scrublands, conifers, eucalyptus, and deciduous forests, among others, have a very asymmetric distribution of the average. The lowest variability in the average start date of vegetative activity is presented by natural meadows, grasslands, some rainfed crops, and mixed forests of eucalyptus with conifers. The highest interannual variability in the start of vegetative activity (Fig. 3 b)) is recorded in mixed forests of eucalyptus with conifers and in natural meadows, and the lowest variability is recorded in rainfed crops. In general, the trend for all land covers has been towards an advancement in the start date of the vegetative season, especially in areas of poplars and willows and irrigated surfaces.

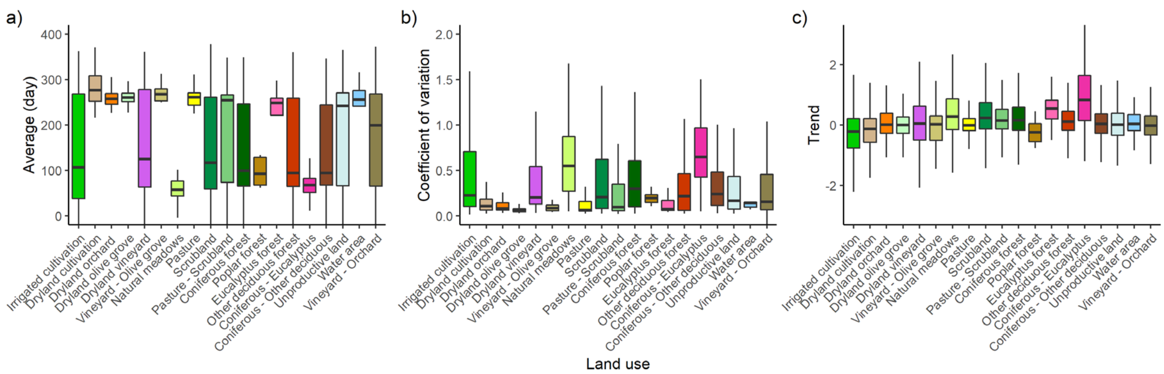

Figure 3. Season start statistics throughout the series according to different types of land cover.

The percentage of surface area showing statistically significant changes in each of the land covers indicates that nearly 50% of Spain's eucalyptus surface area has delayed the start of the season. The same occurs in 40% of the extension of mixed forests of eucalyptus with conifers and in 20% of natural meadows (Fig. 4). On the other hand, it is notable that around 20% of the areas of rainfed and irrigated crops and natural riverbanks show a significant advancement in the start dates of vegetative activity.

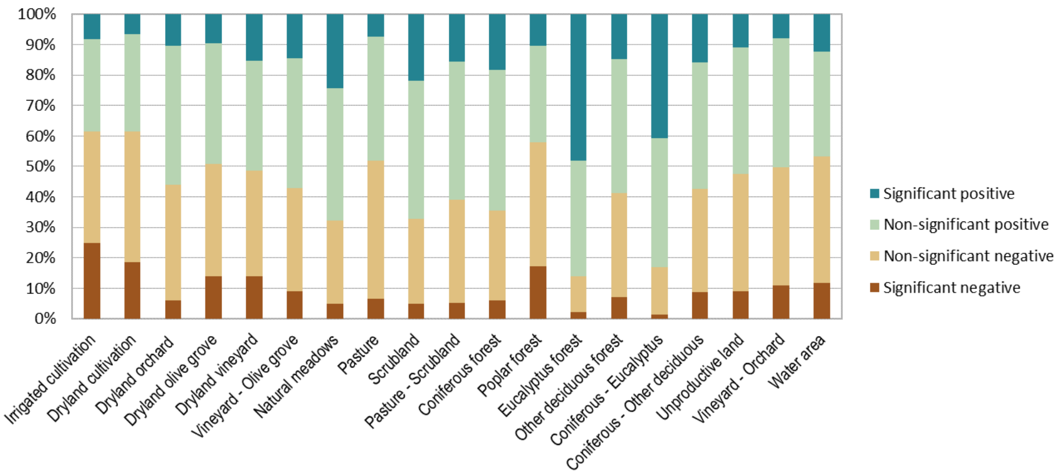

Figure 4. Changes in season start by land use.

The end of the season also presents notable spatial differences (Fig. 5). In general, the interannual variability of the end date of the season is low and very homogeneously spatially across the country. However, the magnitude of change indicates negative variations in the floodplains of the large rivers, where the end of the season advances between 1 and 2 days per year; with even greater advancements in areas located along the riverbanks. Conversely, in areas of Galicia and Extremadura, a delay of between 1 and 2 days per year is observed during the study period.

The analysis performed based on the different land covers shows a great difference in the average end date of the season (Fig. 6 a), suggesting subregional differences. The variability of the end of the vegetative period is low in all covers, being the most variable the irrigated zones and conifers with eucalyptus (Fig. 6 b). The trend is practically null in all covers. However, mixed forests of conifers with eucalyptus present a clear tendency to delay the same (Fig. 6 c).

It is important to highlight a delay in the end of the season in 35% of the surface of mixed forests of eucalyptus with conifers and 20% of the surface of eucalyptus (Fig. 7). Around 10% of all surfaces have delayed their senescence. Whereas in the areas of irrigated land, rainfed farming, and natural riverbanks, this date has been advanced in 30% of the surface.

The average date of mid-season follows a very marked spatial pattern: the northern area has its mid-season in summer, while in the rest of Spain, it occurs during winter and early spring (Fig. 8). The analysis of the magnitude of change shows an advancement of the mid-season date in irrigated areas around the riverbanks. This advancement is 2 days per year since the beginning of the 1980s, while in the rainfed areas of the Duero and Guadalquivir valleys, the advancement is usually about 1 day. Conversely, in Galicia and the Ebro valley, a delay of around 1 day per year is observed.

The analysis by different covers shows high variability in the mid-season date in all of them, with greater subregional differences in vineyard areas, scrublands, conifers, and deciduous forests (Fig. S4). Most covers have their mid-season between January and March (month 1 and month 3), except natural meadows, conifers, deciduous forests, and mixed forests of conifers with eucalyptus and other deciduous trees, which tend to register the mid-season date around July. The trend in all covers is the advancement of this date. Similarly, a higher percentage of surface area advancing the mid-season date has been identified in most land uses (Fig. S5).

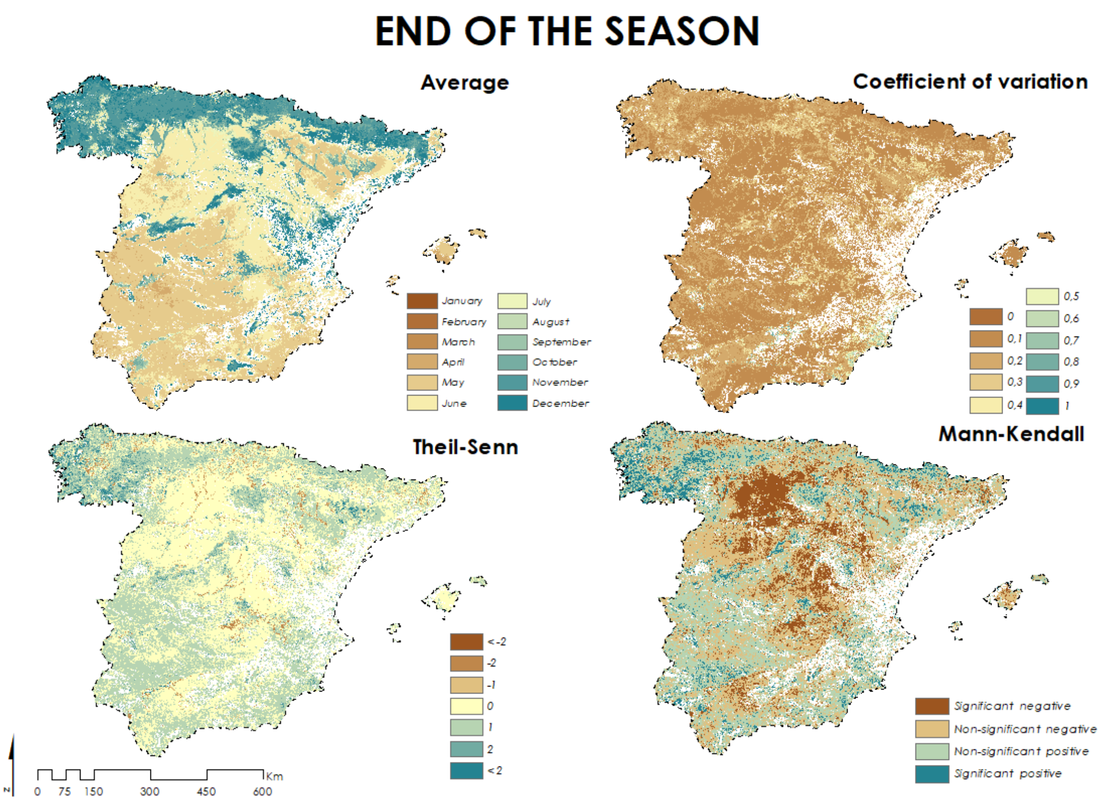

Figure 5. Maps of the statistics for the end of the season.

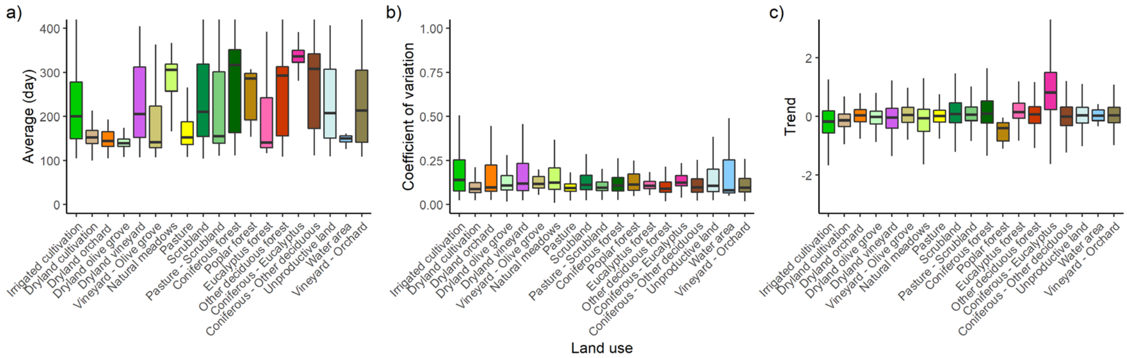

Figure 6. End-of-season statistics throughout the series according to different types of land cover.

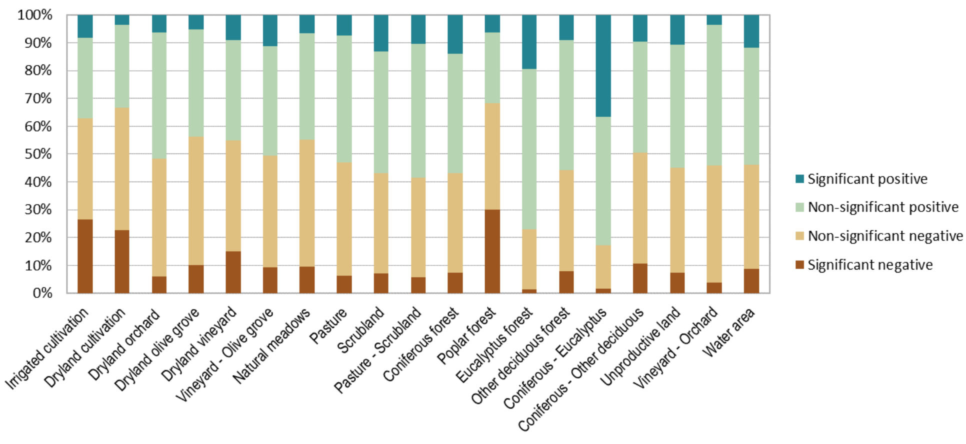

Figure 7. Changes in the end of season by land use.

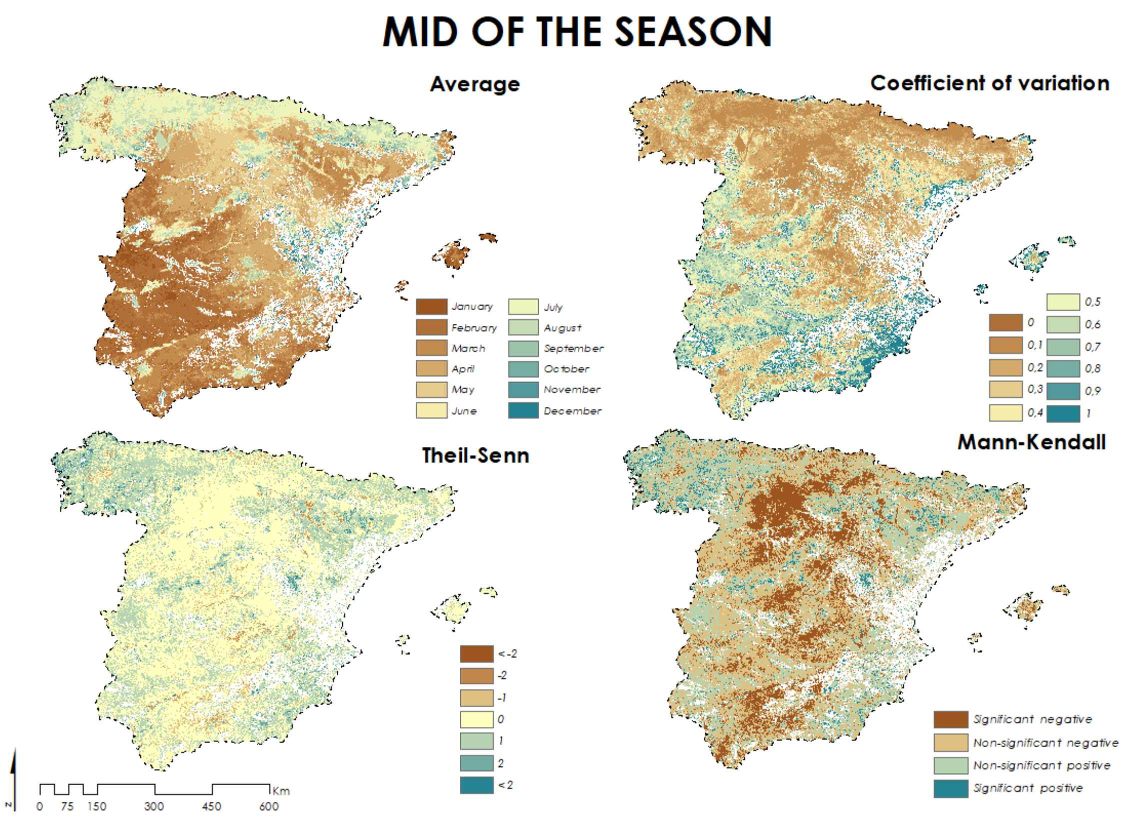

Figure 8. Maps of the statistics for the mid-season date.

The average duration of the vegetative activity season in Spain is between 7 and 9 months, except in the interior areas of the large basins, where the season lasts about 6 months (Fig. 9). The interannual variability in the duration of the season series marks a southeast-northwest line starting in the region of Murcia and ending in Galicia, dividing the study area into two parts, with the area north of the line characterized by greater variation over time. The magnitude of change shows, in general, an increase of 1 day in the duration of the season per year, except in the north and in some of the interior Mediterranean mountain ranges where the duration has decreased by 1 day or more, especially in Galicia. The changes in these areas tend to be statistically significant, especially in areas of the Guadalquivir valley.

In the analysis conducted for the different covers, it is noteworthy that the average duration of the vegetative season is very homogeneous, between 6 and 8 months (Fig. S6), and presents few subregional differences. Notable interannual variability is detected in all covers, being the most variable annually the irrigated crops and poplar and willow groves. Most covers show a dominance of negative values in the magnitude of change of the vegetative period, especially in natural meadows and poplars and willows, while the duration of the vegetative season increases in rainfed farming, olive groves, vineyards, and grasslands.

Between 5% and 10% of the surface area of all soil types has experienced a significant decrease in the duration of the vegetative season (Fig. S7). Notably, natural riverbank areas and eucalyptus forests have done so in more than 15% of their surface area. On the other hand, irrigated areas are those with the most surface area (10%) showing an increase in the activity period, along with rainfed surfaces and grasslands.

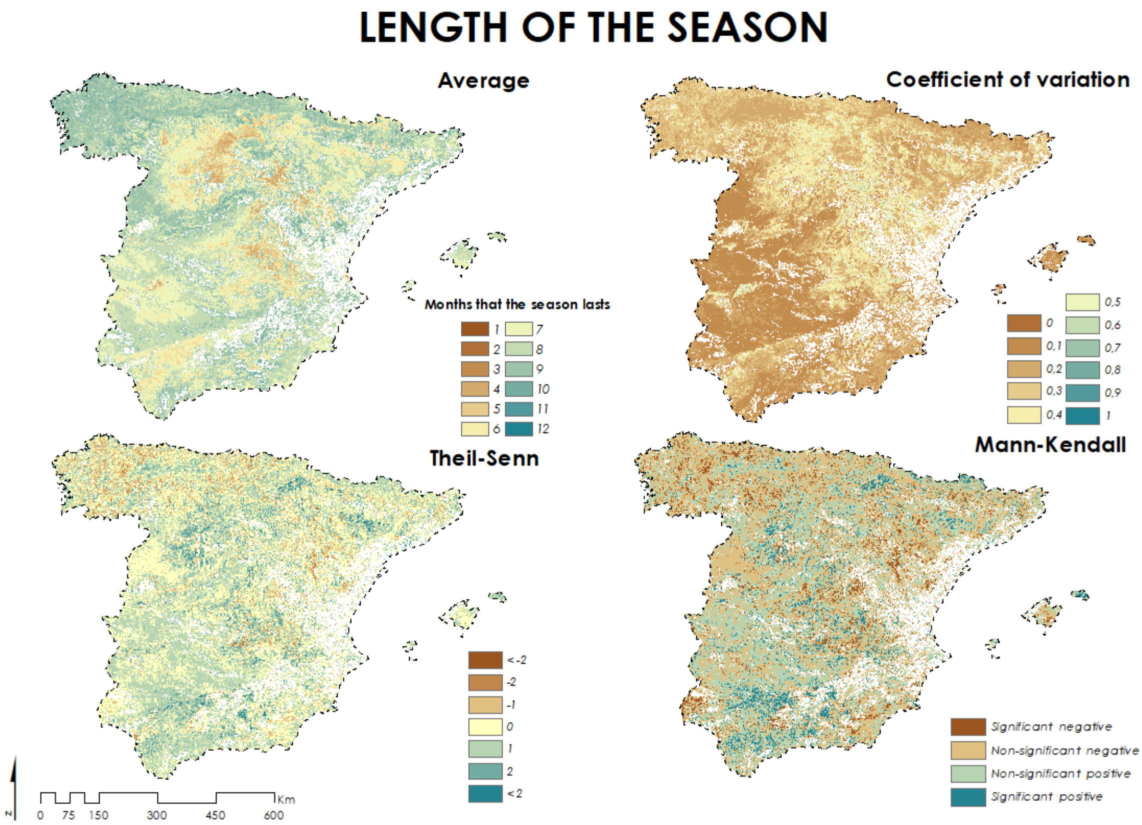

Figure 9. Maps of the statistics for the duration of the vegetative season.

The average base value of NDVI presents very notable spatial differences (Fig. 10). On one hand, Galicia, the Atlantic coast, and the Pyrenees show very high base values, while the rest of Spain has a much lower value. The Cantabrian Mountains, Pyrenees, and Sierra Nevada stand out in their base value with a base value of 0. Its variability is very high in the northern area, the Iberian System, and some irrigated areas. It presents positive variations in most of Spain, increasing more than one-hundredth per year, except in the Southern Plateau and the Duero Basin where the value remains the same or decreases slightly. The changes in almost all of Spain are positive and statistically significant, so it can be stated that the NDVI values at the start and end of the season are generally increasing.

The highest average base values are observed in eucalyptus with conifers and natural meadows, while the lowest occur in rainfed crops (Fig. S8). The interannual variation in the base value tends to be low, and the general trend of all covers is towards an increase in this metric.

There is a statistically significant increase in base value in 50% or more of the surface area of all covers (Fig. S9). Irrigated areas, vineyards, and eucalyptus stand out from the rest of the covers where the change in their surface is smaller, and especially coniferous forests and other deciduous forests, in which 80% of their surface area has seen this value increase.

The average maximum NDVI value presents clear spatial differences between the northern and western part of the country, where values are higher (0.7-0.8), and the eastern zone where they are much lower (0.2-0.5), highlighting the Ebro basin, as well as the regions of Almería, Murcia, and La Mancha (Fig. 11). The interannual variability of the season's maximum is low, with greater variation observed in the basins of the Ebro, Duero, Guadalquivir, and in the Southern Plateau. The magnitude of change of the maximum value shows an increase of more than one-hundredth of NDVI each year, except in the Guadalquivir valley and small areas in the center of the country where the value decreases more than one-hundredth. The changes in almost all of Spain are statistically significant.

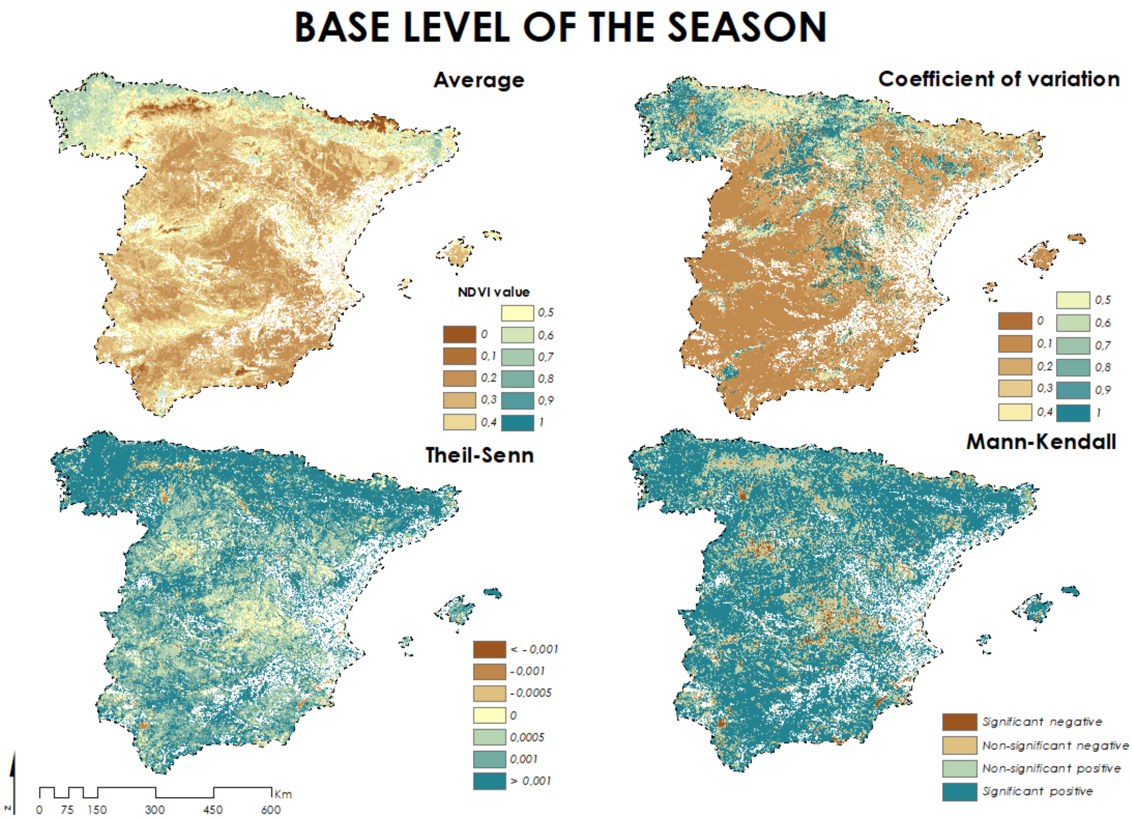

Figure 10. Maps of the statistics for the base value of the season.

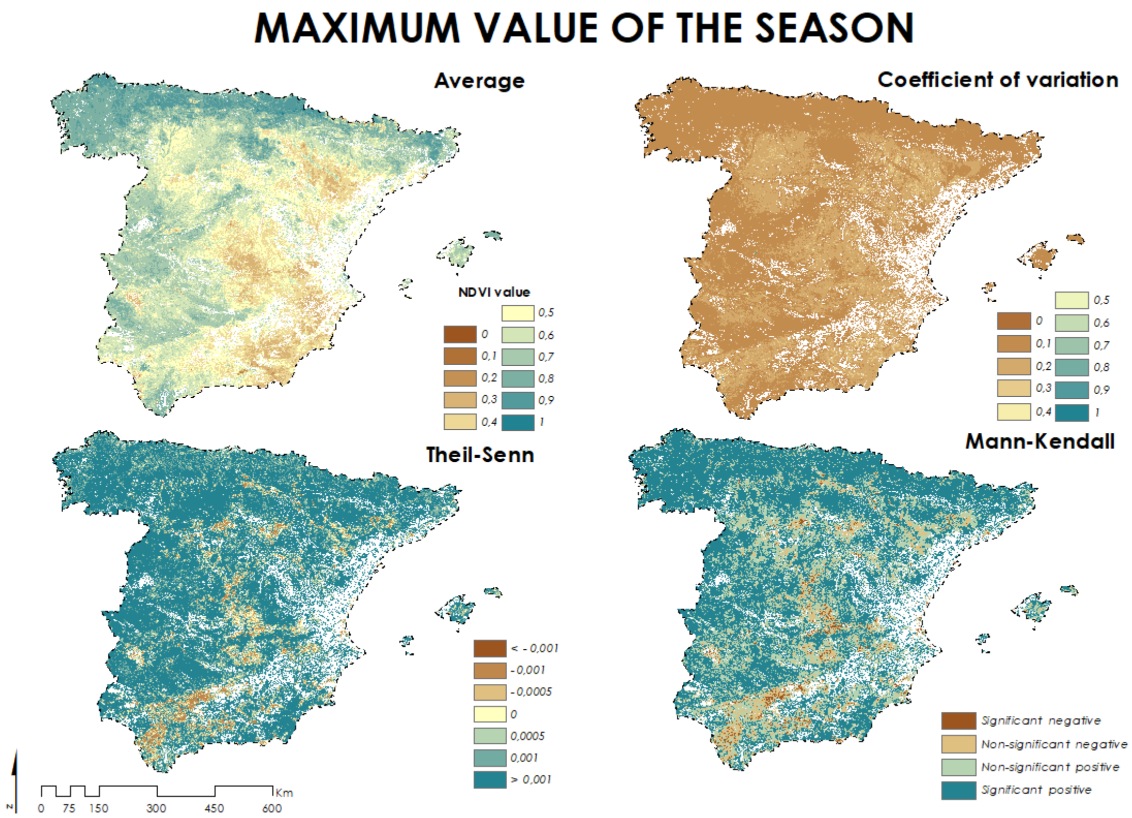

Figure 11. Maps of the statistics for the maximum value of the season.

The highest average maximum NDVI values in the different land covers are recorded in natural meadows, deciduous forests, and eucalyptus with conifers, and the lowest in rainfed crops (Fig. S10). The interannual variations are low, with rainfed farming being the most variable cover and natural meadows and conifers with eucalyptus being the least variable. The trend in all soil covers is towards an increase in the maximum NDVI value. The maximum NDVI value has increased in at least 45% of the surface area of all categories (Fig. S11), with conifers and natural meadows being the categories where the surface area affected by significant changes is higher (80%).

The average amplitude of NDVI values shows homogeneity across Spain, with values between 0.2 and 0.3 in most of Spain (Fig. 12), except in the Cantabrian and Pyrenean ranges, with amplitudes higher than 0.6, and areas in the west of the country, with amplitudes around 0.5. The interannual variability of this variable is low in areas where the amplitude is higher, while it is higher in the east of the country and in the northern area of Galicia. The magnitude of change shows a decrease of one-hundredth in the amplitude each year in the north, in the Central System, and in part of the Guadalquivir depression, while in the rest of Spain, it increases by one-hundredth. In wide areas of the interior of Spain, there is a statistically significant increase in the annual amplitude of NDVI values throughout the study period, as well as significant decreases of NDVI in the northern part of the country.

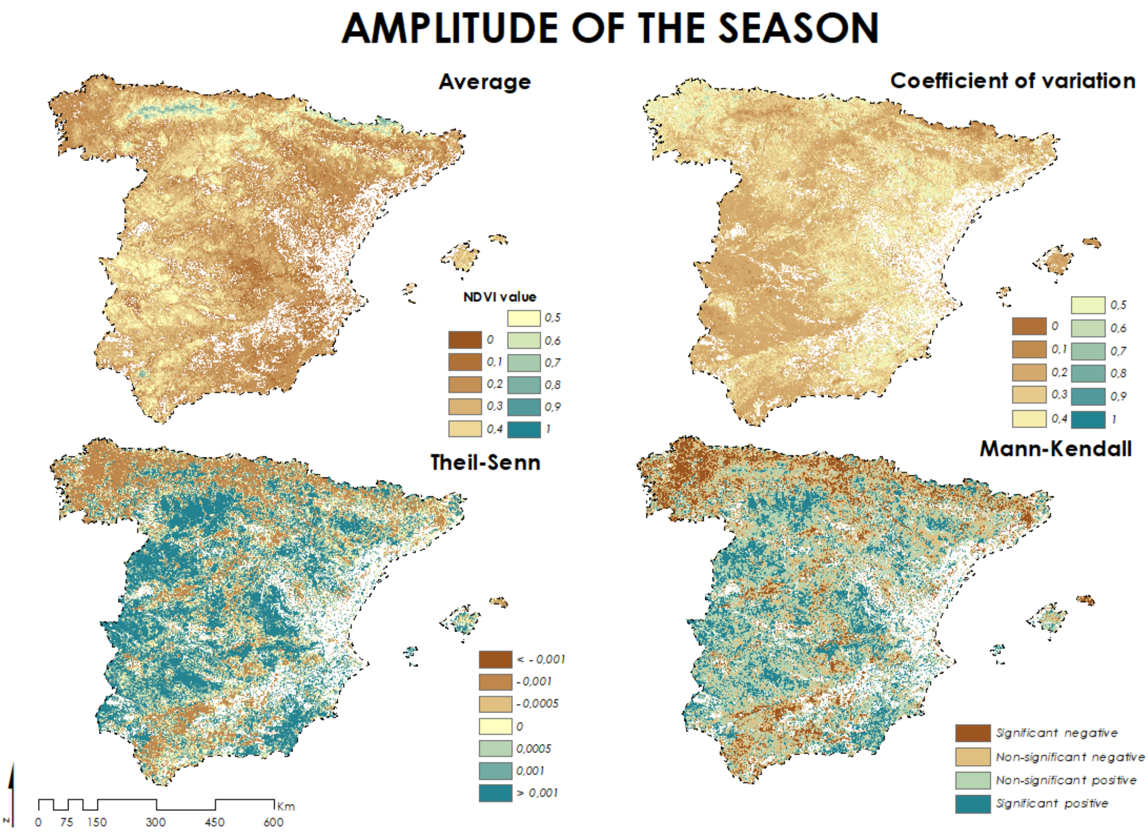

Figure 12. Maps of the statistics for the amplitude of the season.

The average amplitude among the different covers is very similar (Fig. S12). Similarly, the interannual variability of the NDVI amplitude is similar in the different soil classes, although it tends to be higher in mixed areas of conifers and eucalyptus, in dry vineyards, and in grasslands. The trends of this variable are similar in all covers, positive, except for natural meadows and forests of eucalyptus with conifers showing dominant negative trends. All covers have experienced an increase in amplitude in at least 5% of their surface area (Fig. S13), while also suffering a decrease in almost 10% of their surface area. Vineyards with fruit trees stand out where 50% of their surface area has experienced increases in amplitude and olive groves and dry fruit trees have done so in 30% of the surface area. On the contrary, natural meadows, mixed forests of conifers with eucalyptus, and poplars and willows are the covers that have seen a reduction in amplitude on a larger surface area, of 30%.

The evolution of other secondary phenological variables also shows some relevant results. For example, the rate of decline at the end of the season (right derivative) (Fig. S14) and the rate of growth at the start of the same (left derivative) (Fig. S15), show very notable spatial differences, with higher average values in the Pyrenees and Cantabrian Mountains, as well as in the most western regions of Spain. Conversely, the average values are lower in the eastern zone. The data present high interannual variability for both derivatives, observing very high variation coefficients of the right derivative in the northern area of Spain and of the left derivative almost in the entirety of the country. The magnitude of change of the two derivatives shows a decrease in the rate of one-hundredth in Galicia and interior Mediterranean mountain areas and an increase of one-hundredth in the west of Spain. All changes tend to be statistically significant. The analysis by different soil covers (Fig. S16 and S17) shows very similar averages, being the grasslands the ones presenting the highest average rates, and natural meadows and conifers with eucalyptus the ones that have varied the most. These two covers are the ones presenting a negative trend, both their start and end rate of the season have decreased, as have also done the areas of riparian forests, while in the rest the rates have remained or increased. The percentage of surface area showing statistically significant changes in each of the covers is similar in both derivatives (Fig. S18 and S19), although there is more surface area affected by an increase in the start rate.

The analyses of the large integral (Fig. S20) present the same spatial differences as the maximum NDVI value, distinguishing the northern and western areas, which show the highest values, and on the other hand the river basins and the east of the country, which present the lowest values. There is a dominance towards the increase of the area of the integral, being the changes predominantly significant. The large integral presents a similar variation and a positive trend in all soil covers (Fig. S21). The percentage of surface area showing statistically significant changes for each of the soil covers shows an increase in the integral in 20% of the surface area of all covers, finding the maximum surface area affected in dryland and grassland areas in 40% of their surface area (Fig. S22). On the other hand, the small integral (Fig. S23) shows higher values in the Cantabrian Mountains and the Pyrenees, as well as in the western part of the country. The variability is high throughout the country, except in the southwest. The magnitude of change and its significance show a decrease in the north of the country and an increase of the variable in the rest. All surfaces present the same pattern in the small integral (Fig. S24) and without a very contrasting behavior between soil covers on the surface characterized by significant changes (Fig. S25).

The initial average value of the season (Fig. S26) is practically the same as the average base value and very similar to the average end value of the season (Fig. S27). Although it is true that the coefficient of variation is very low in initial and final values compared to the base value, the magnitude of change and the significance is the same or greater, that is, in all three there is a notable increase in NDVI throughout the country except in part of the Guadalquivir basin and the Southern Plateau. The analyses by different soil covers in the initial and final values (Fig. S28 and S29) are practically the same among them and compared to the analysis of the base value. Similarly, the figures for percentages of soil affected by significant changes (Fig. S30 and S31) mostly present more than 50% of the surface area of all covers with a significant increase in the variables and practically no effect by the decrease of this.

Generally speaking, the percentage of surface area with statistically significant changes in each of the variables does not demonstrate a clear dominance towards temporal changes in the start and end of the vegetative period (Fig. 13). However, there has been a dominant significant increase in NDVI values (base, maximum, start, and end of the season) that has affected between 60% and 70% of Spain's surface area. Likewise, the mid-season date advances almost in 20% of Spain and the NDVI amplitude throughout the season has had similar significant positive and negative changes, although the amplitude increases in 10% more surface area than it decreases.

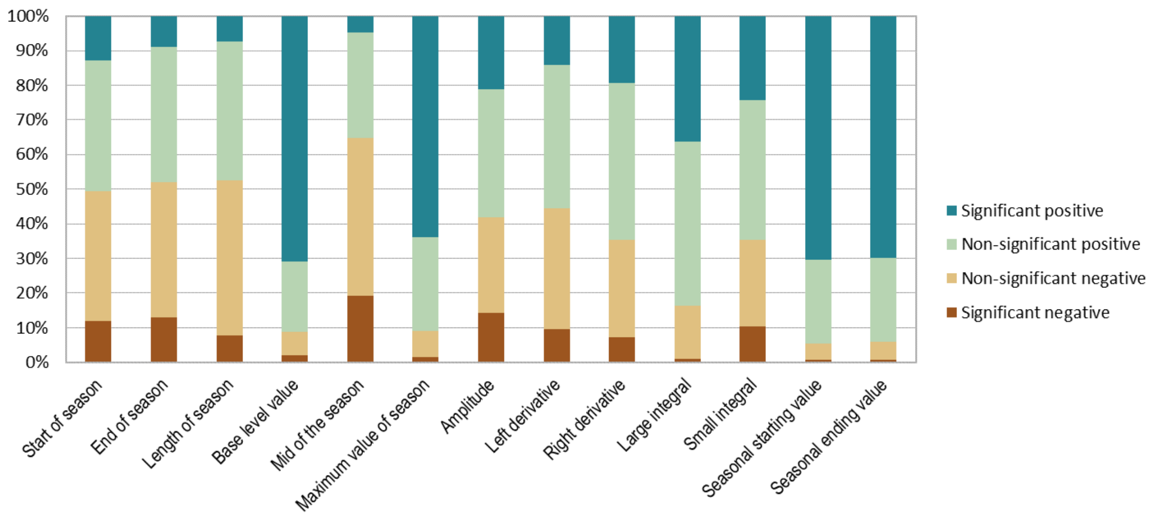

Figure 13. Percentages of changes in the total surface area of Spain for the 13 phenological variables extracted from TIMESAT.

4. Discussion and conclusion

This study analyzed plant phenology in Spain from the early 1980s to the early 2020s, using low and medium-resolution satellite imagery based on a database developed for this purpose that merges NDVI values obtained from NOAA-AVHRR and MODIS images. The interest in such studies is significant from an environmental perspective, as various continental and global studies since the 1980s suggest phenological changes in response to climate change (Bertín, 2008).

Previous studies on phenology in Spain have focused on specific locations within the country, particularly in the Mediterranean region (García-Mozo *et al.*, 2010; Gordo and Sanz, 2009; Peñuelas *et al.*, 2002). Although there are recent studies covering the entire peninsula (Alcaraz-Segura *et al.*, 2009; Caparros-Santiago and Rodríguez-Galiano, 2020; Novillo *et al.*, 2019), they have been conducted over shorter time periods. For this reason, a robust database was developed to allow for phenological analysis in Spain based on biweekly NDVI data from 1981 to 2021, enabling a study with a broad temporal perspective. This study does not delve into detail but analyzes general patterns of different phenological variables at the national level that may allow for future detailed analysis of the identified changes (e.g., using higher spatial resolution sensors) and to determine the role of observed climate changes on plant phenology, as suggested by various previous studies (Lunetta *et al.*, 2006; Zhang *et al.*, 2017; Fu *et al.*, 2014; Jeong *et al.*, 2017; Piao *et al.*, 2019).

The methodology of this study was based on the TIMESAT tool (Eklundh and Jönsson, 2017), which allowed for the processing of approximately one million pixels to study phenology in satellite image series with extensive temporal coverage. Phenology was characterized from NDVI series as objectively as possible. This is not straightforward, as thresholds for defining the start and end of the vegetative season can vary. For example, changes in coniferous forests are slow, but in semi-arid grasslands, they are very rapid, creating problems in capturing seasonal changes in various types of cover. This means there are no universal thresholds for defining the start and end of the season (Eklundh and Jönsson, 2015). Thus, for this work we had to establish thresholds that allowed the objective evaluation of the phenological variables of interest. One limitation observed in the applied methodology was the difficulty in analyzing spaces with high interannual variability; variability that could be due to land use changes caused by urban expansion and tourist infrastructures, especially on the Valencian coast (Marraccini *et al.*, 2015; Palazón *et al.*, 2016), an increase in irrigated area, changes in sowing decisions (Oteros *et al.*, 2015; Stellmes *et al.*, 2013), the succession of forest fires (Díaz-Delgado *et al.*, 2002), or the difficult detection of changes in evergreen coniferous forests (Eklundh & Jönsson, 2015).

The main results of the phenological analysis of Spain highlight that the start of the season has advanced in wide areas by between 1 and 2 days per year. These are considerable figures that suggest significant phenological changes are occurring in Spain. The most affected covers by this early start are natural riverbanks and rainfed and irrigated crops. These results are consistent with those observed in previous studies like those of Caparros-Santiago and Rodríguez-Galiano (2020) and Oteros *et al.* (2015), which also detected this dominant advancement through both remote sensing and field data. These studies suggest that such advancement could be related to the increase in air temperature (Oteros *et al.*, 2015). Additionally, this trend coincides with various studies conducted in Europe (Ahas *et al.*, 2002; Stöckli and Vidal, 2004), North America (Reed, 2006), Asia (Piao *et al.*, 2006), and across the Northern Hemisphere (De Beurs and Henebry, 2005; Eastman, *et al.*, 2013; Jeong, *et al.*, 2011; Zhou *et al.*, 2001), all emphasizing an early advancement since 1960 in the start of the season, both in satellite observations and ground observations, but whose magnitude differs according to the study region, scale, period, and species (Piao *et al.*, 2019).

Notable subregional differences were found in this work. For example, in areas of eucalyptus, conifers, natural meadows, and deciduous forests, there is a certain delay in the start dates of vegetative activity, results that also align with the regional outcomes of Caparros-Santiago and Rodríguez-Galiano (2020) and Jato *et al.* (2002), which could be due to changes in air temperature (Lieth, 1974; Cleland *et al.*, 2012).

The results reveal a certain concordance between changes in the start and end of the season. In places and covers where the start of the season advances between 1 and 2 days per year, so does the end of it in a similar interval, except for river forest areas where the advancement is more than 2 days per year. Meanwhile, delays between 1 and 2 days are observed in areas of Galicia and Extremadura, especially in surfaces of eucalyptus and broadleaf and mixed forests of both with conifers. In general, trends towards a certain delay and advancement in the end of the vegetative season have been evidenced, although in a weaker magnitude than the change in the start of the season. In this sense, and although there are fewer local, regional, and global studies focused on this, it is important to note that most of them agree in showing a dominant delay in wide regions of temperate climates (Miao, *et al.*, 2017; Piao *et al.*, 2019), which aligns with the delay seen in this study in the Spanish Eurosiberian region. On the other hand, the advancement of the end of the season could be associated with the previously described advancement of the start. Similar patterns are observed in the mid-season date, with advancements between 1 and 2 days across Spain except in Galicia, corresponding with the shortening of the vegetative growth season detected by Oteros *et al.* (2015).

Some regional results and differential behaviors by land covers present notable interest. For example, the high variability between the end and start dates of the season in farming areas could be due to various anthropogenic factors such as crop change or rotation, land use changes, or even decisions on changing sowing and harvesting dates (Oteros *et al.*, 2015; Van Oort *et al.*, 2012). These phenological changes in cultivated areas can have notable economic impacts, as the advancement of phenophases could increase crops' exposure to extreme weather events (such as late frosts), modify production, and even favor the relocation of crops due to changes in areas traditionally suitable for cultivation (Chmielewski *et al.*, 2004; Oteros *et al.*, 2015).

In addition to the highlighted phenological changes, one of the most important results of this study is the increase in NDVI (the initial and final values of the season, the maximum value, and the base value) throughout the entire time series in practically all of Spain and in all covers. The increasing photosynthetic activity aligns with other studies that have used time series of satellite images on a global scale and have documented a generalized greening in recent decades in response to climate changes

(Nemani *et al.*, 2003; Zhu *et al.*, 2013). At the national level, during the period 1982-1999, Alcaraz-Segura *et al.* (2010) also recorded positive NDVI trends, while Gutiérrez Hernández (2022) between 2000 and 2020 and Novillo *et al.* (2019) between 2001 and 2016 observed a positive trend across the peninsula except in the Atlantic region, where the trend was negative (Vicente-Serrano *et al.*, 2020). In the present work, an increase in the maximum NDVI value was observed in 70% of Spain, with decreases in the index value being practically irrelevant. The factors behind this change can be diverse, among which would be the generalized increase in temperature (favoring photosynthesis and plant activity (Lieth, 1974)) and changes in land management characterized by the intensification of some areas (e.g., through the creation of irrigated areas) (Stellmes *et al.*, 2013) and the extensification of others (e.g., due to the abandonment of traditional economic activities such as mountain agriculture and grazing) (Batllori and Gutiérrez, 2008). While this is true, small areas in the south of Spain and the center have shown a decrease in NDVI values. Many of them correspond with rainfed areas, where water availability has a greater impact on NDVI than temperature. This is corroborated by different studies showing that despite the notable increase in temperature on the Iberian Peninsula (del Río *et al.*, 2012; del Río *et al.*, 2011; Khorchani *et al.*, 2018), droughts have also increased, mostly associated with the decrease in precipitation and the increase in evaporative demand of the air (Vicente-Serrano *et al.*, 2017).

Finally, the results obtained in the study have shown two different behaviors between the phenophases of the Mediterranean biogeographic region, which begins the season during the rainy season (autumn) and ends it in the warmer season; and the Eurosiberian and the interior Mediterranean mountain regions, which present similar behavior as they start their season at the end of winter and end it at the end of autumn. While the variability in some phenometrics seems to have a biogeographic distribution, there is internal variability derived from the behavior of different covers, for example, there may exist in the same region covers with both advancement and delay of the start and end dates of the season. This has been seen in different studies developed both at the national (Caparros-Santiago and Rodríguez-Galiano, 2020; Novillo *et al.*, 2019) and European level (Menzel *et al.*, 2006).

This work, focused on the description of phenological characteristics and changes observed in recent decades, constitutes a first stage that opens up new and interesting lines of future research. The results shown here can be the start of other studies that seek to explain both the variability and the observed phenological changes based on the relationship of the phenometrics with changes in land management and climate observed in Spain, both at the national and regional levels.

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Supplementary material

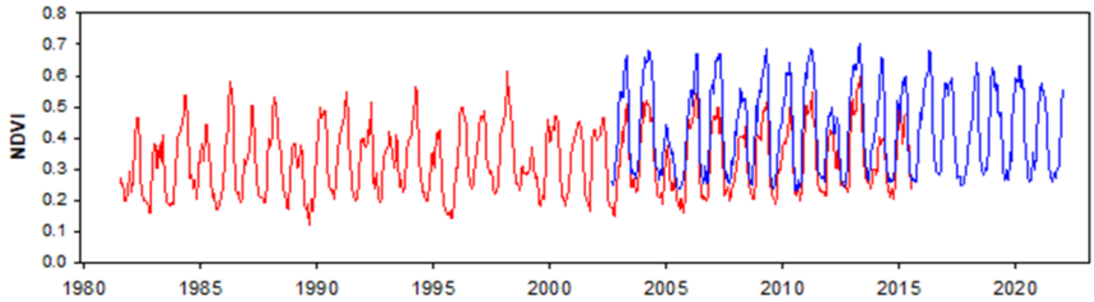

Figure S1. Evolution of the NDVI time series for a specific pixel corresponding to the series from NOAA-AVHRR satellites (red) and MODIS (blue).

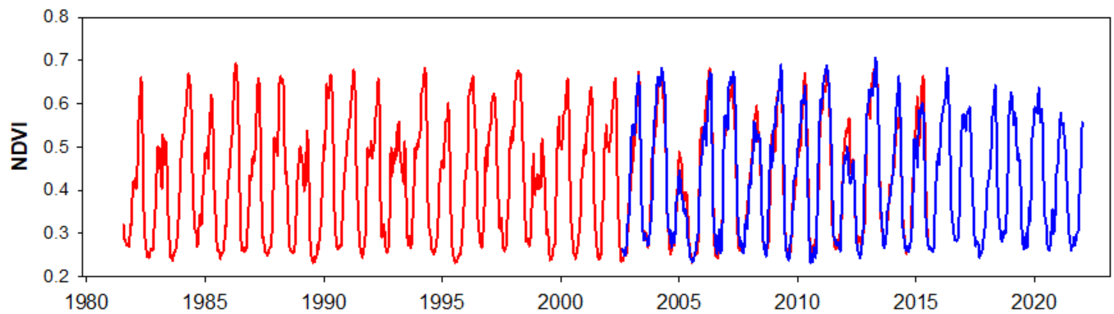

Figure S2. NDVI series from MODIS (blue) and NDVI series from NOAA-AVHRR satellites (red) merged with the MODIS series. 1982-2021.

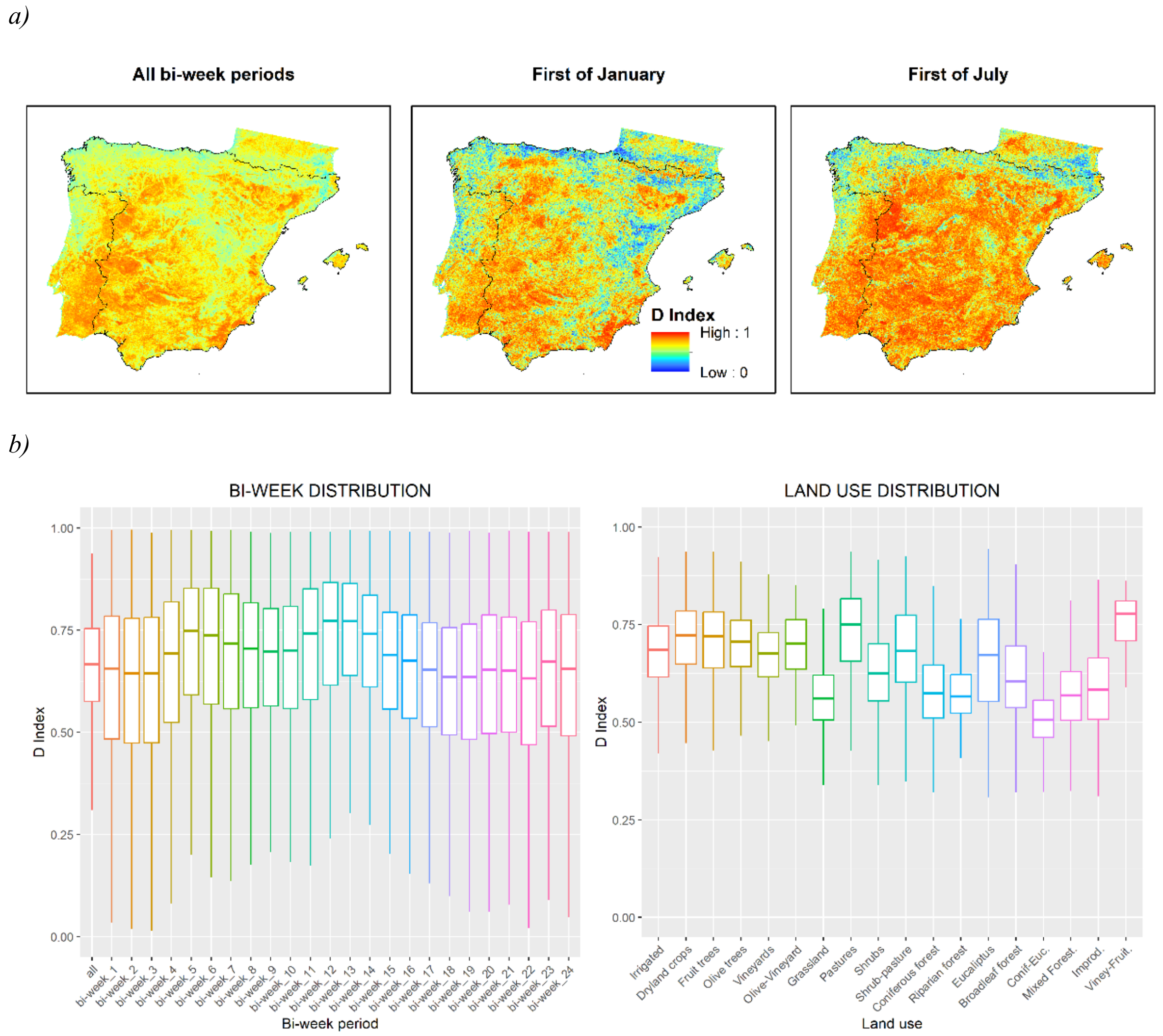

Figure S3. a) Distribution of the D index calculated for all fortnightly periods, the first in January and the first in July, b) Distribution of D index values for all weeks of the year and also by land use. 1982-2021.

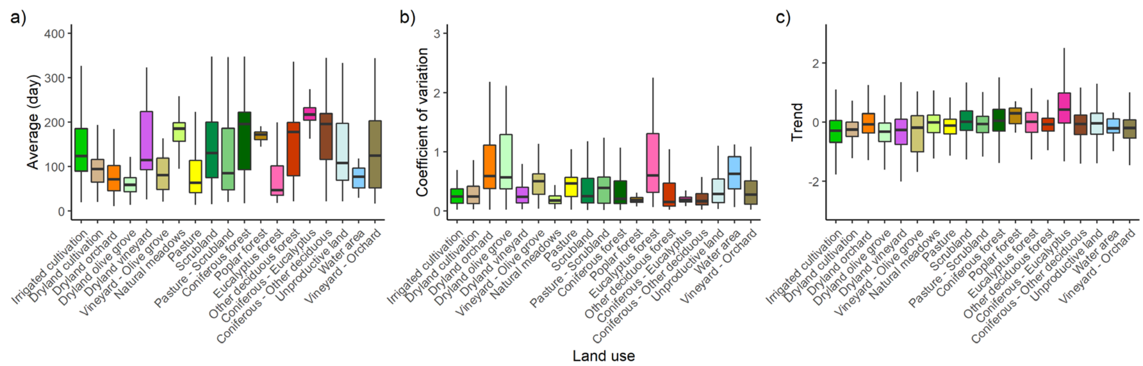

Figure S4. Mid-season date statistics throughout the series according to different types of land cover.

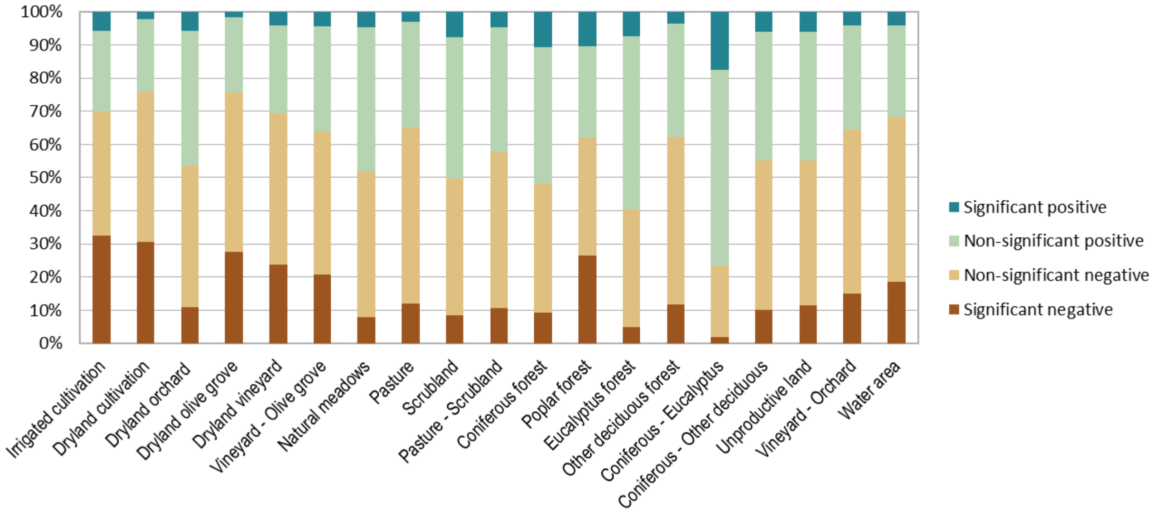

Figure S5. Changes in mid-season date by land use.

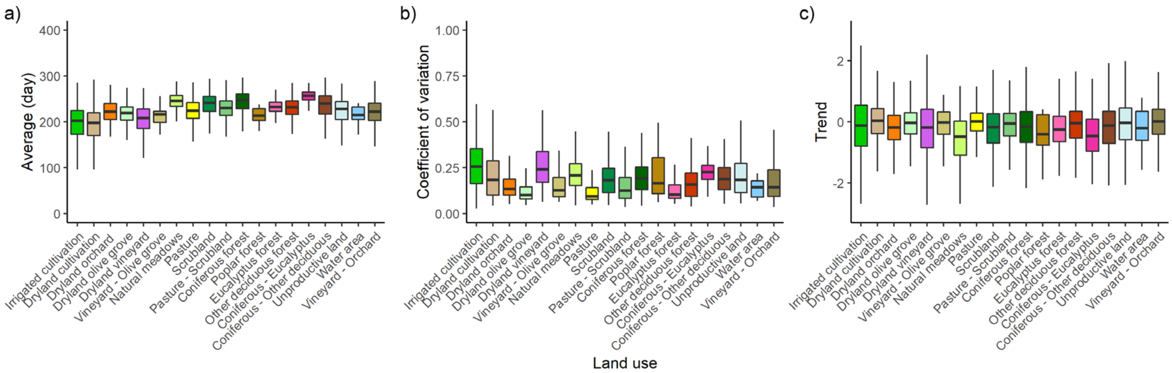

Figure S6. Season duration statistics throughout the series according to different types of land cover.

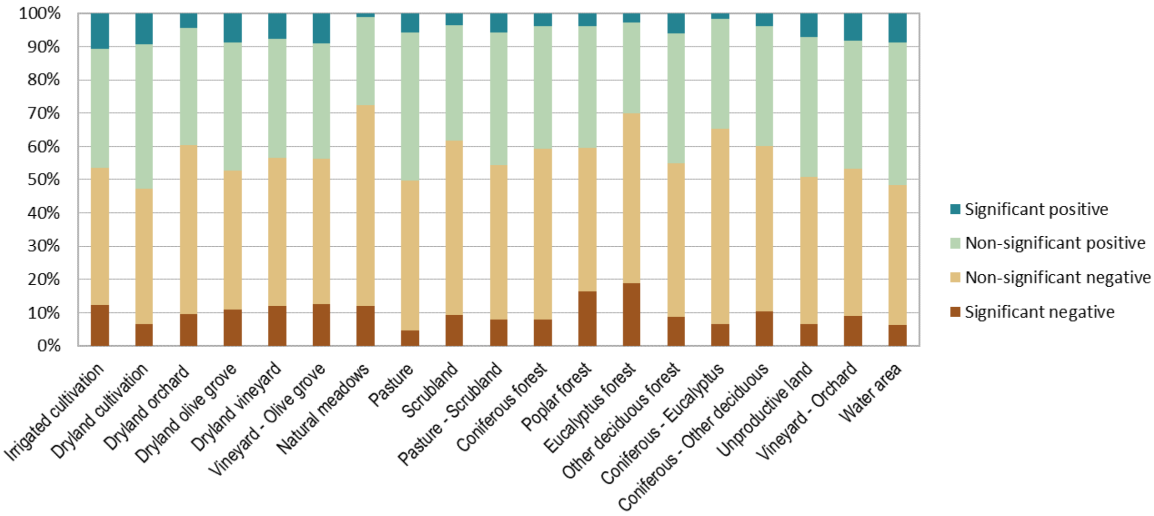

Figure S7. Changes in season duration by land use.

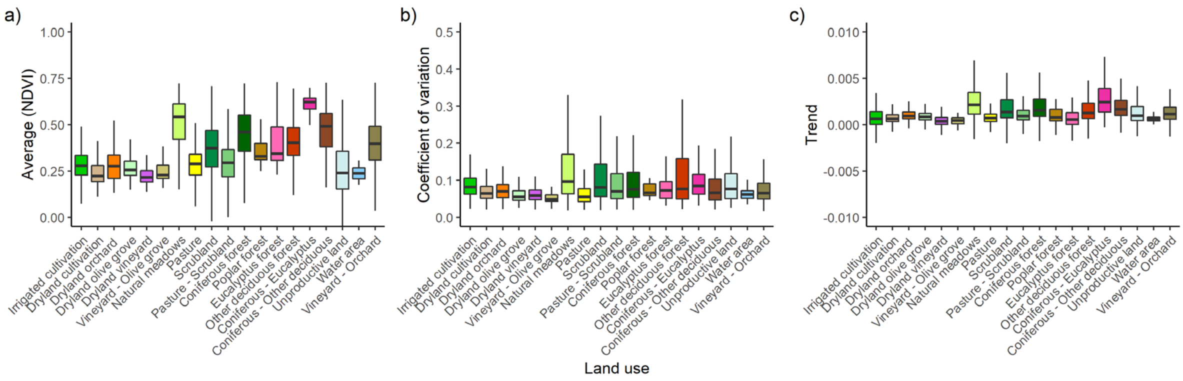

Figure S8. Base value statistics of the season throughout the series according to different types of land cover.

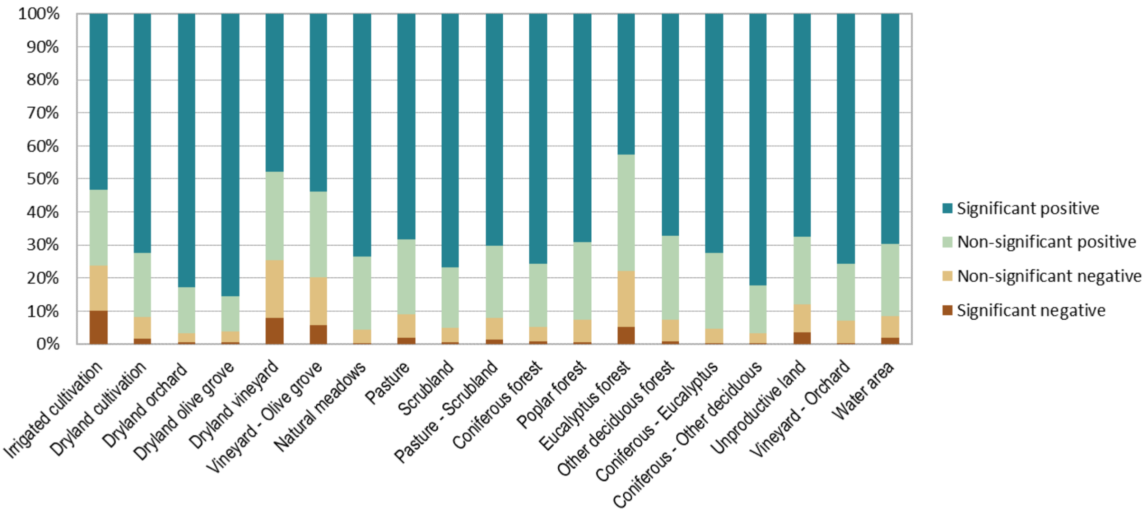

Figure S9. Changes in the base value of NDVI for the vegetative season by land use.

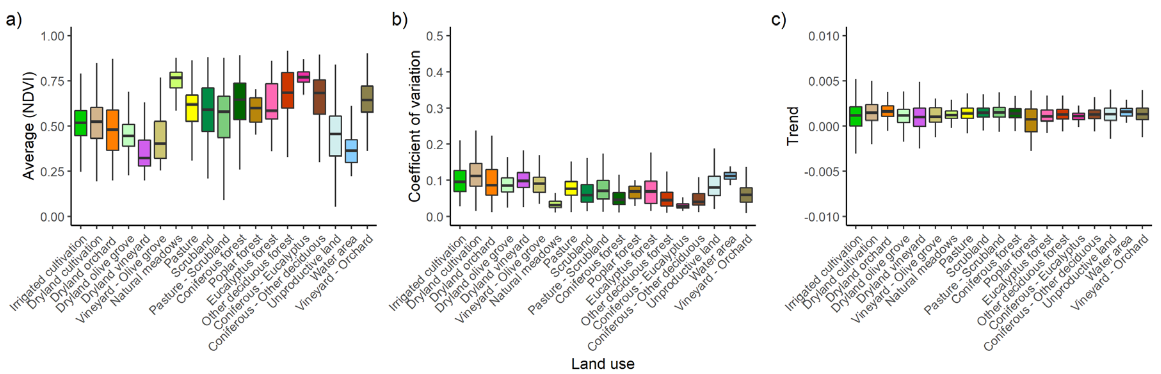

Figure S10. Maximum value statistics of the season throughout the series according to different types of land cover

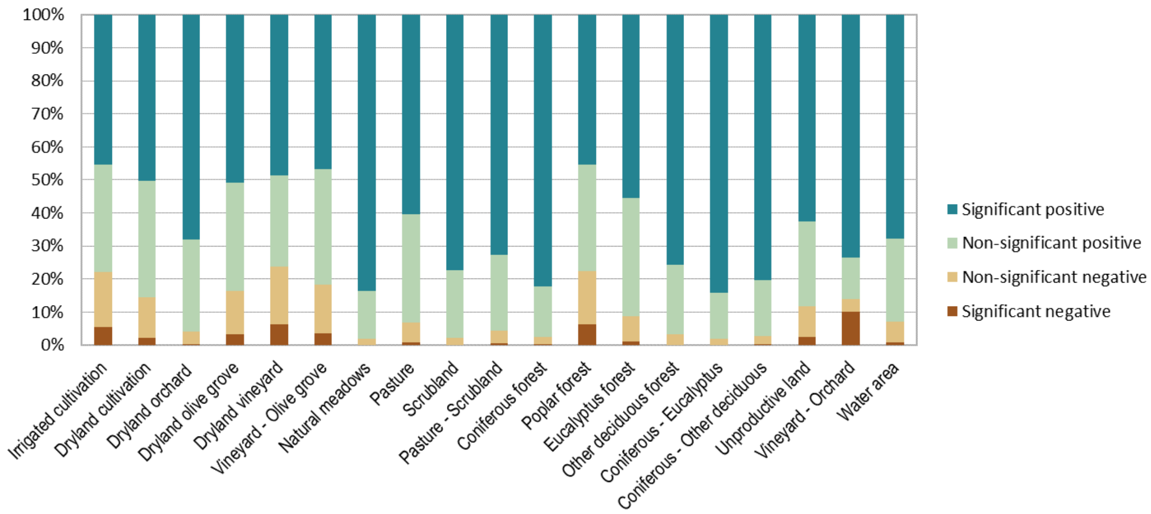

Figure S11. Changes in the maximum value of the season by land use.

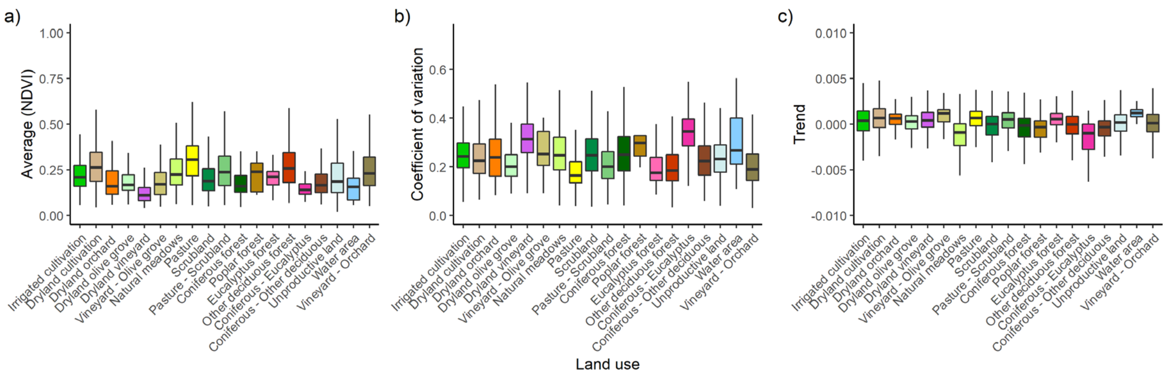

Figure S12. Season amplitude statistics throughout the series according to different types of land cover.

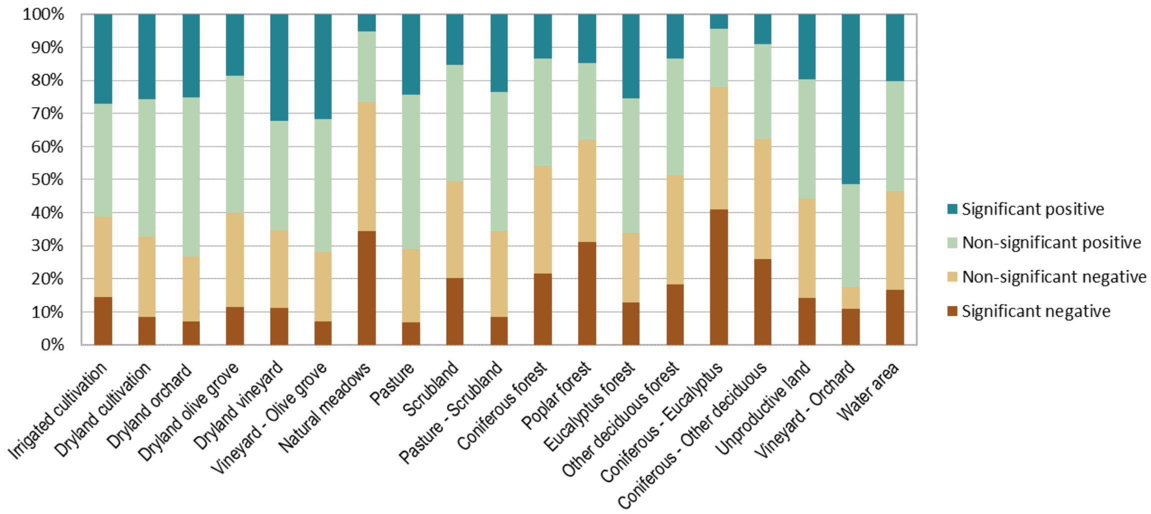

Figure S13. Changes in amplitude by land use.

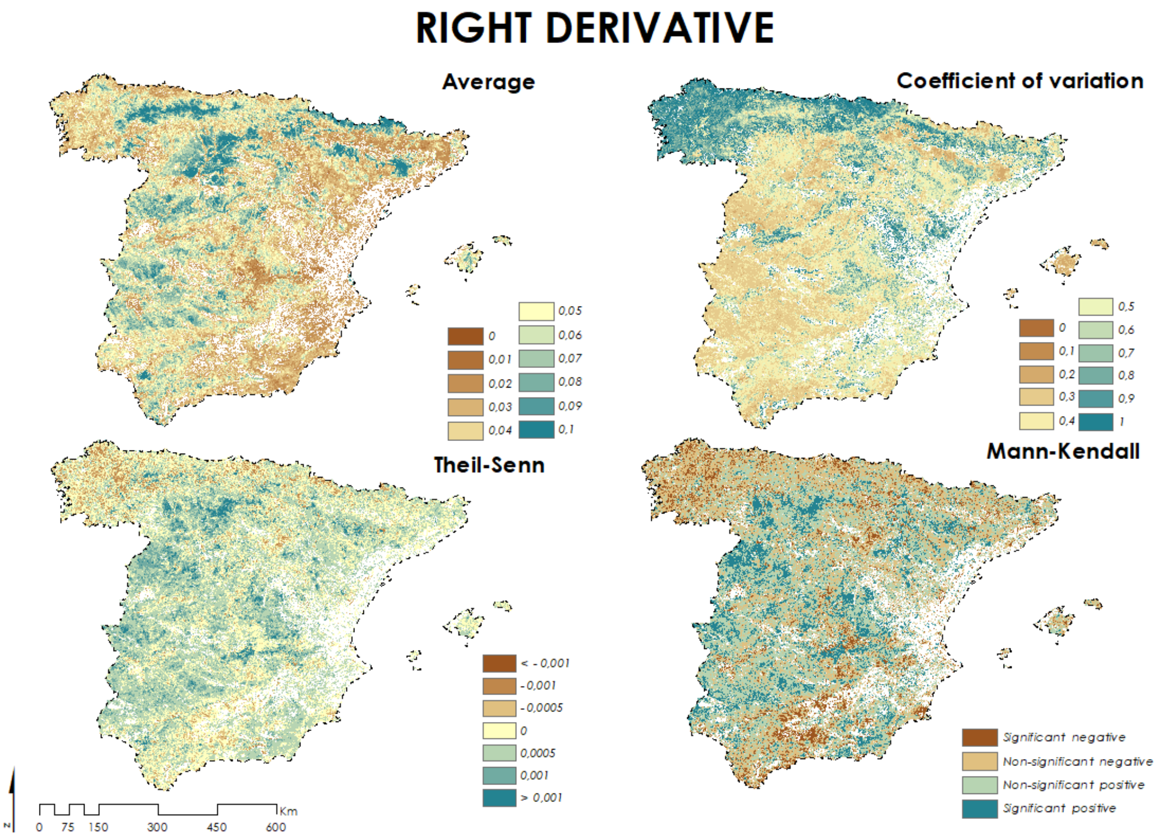

Figure S14. Maps of the statistics for the right derivative of the season.

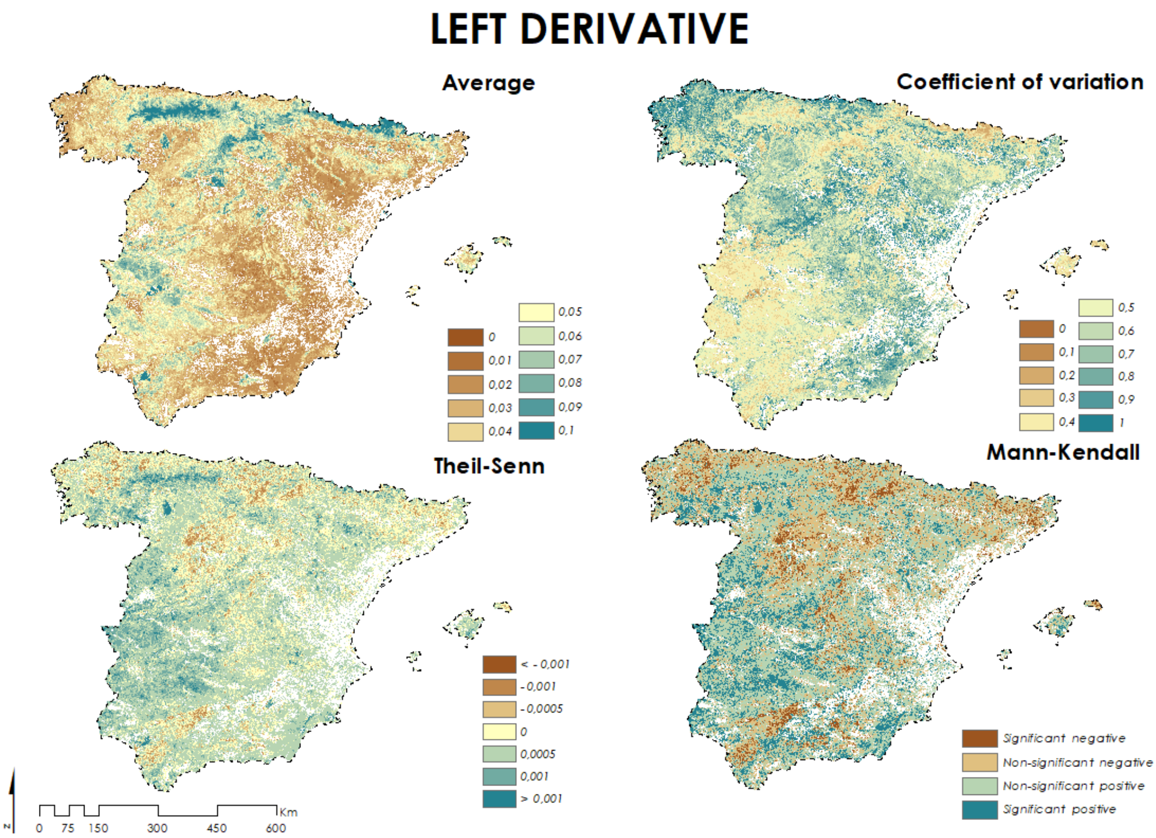

Figure S15. Maps of the statistics for the left derivative of the season

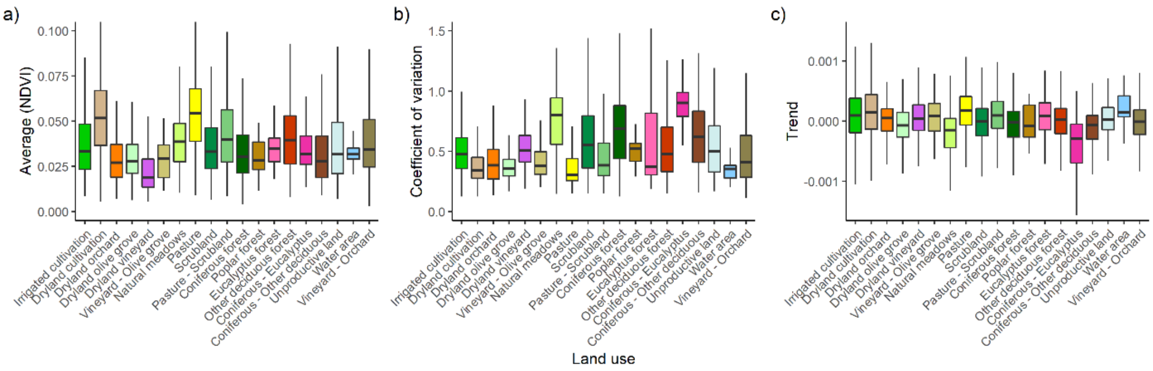

Figure S16. Right derivative statistics of the season throughout the series according to different types of land cover.

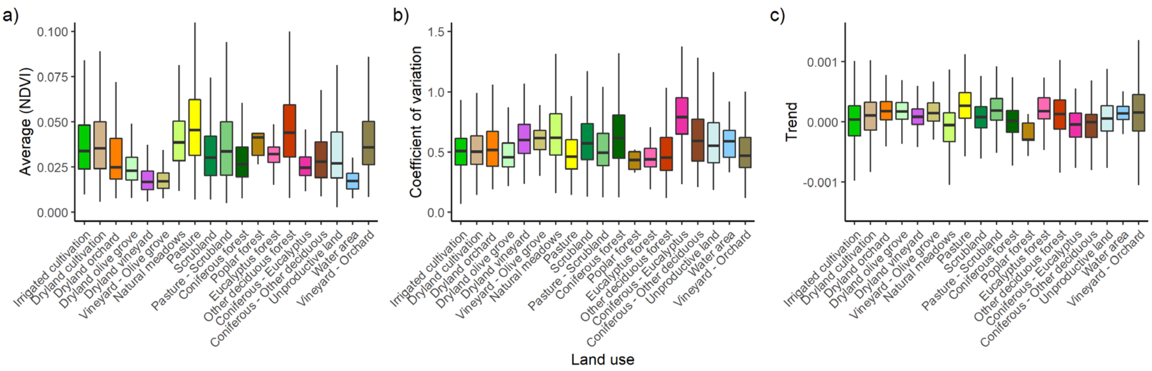

Figure S17. Left derivative statistics of the season throughout the series according to different types of land cover.

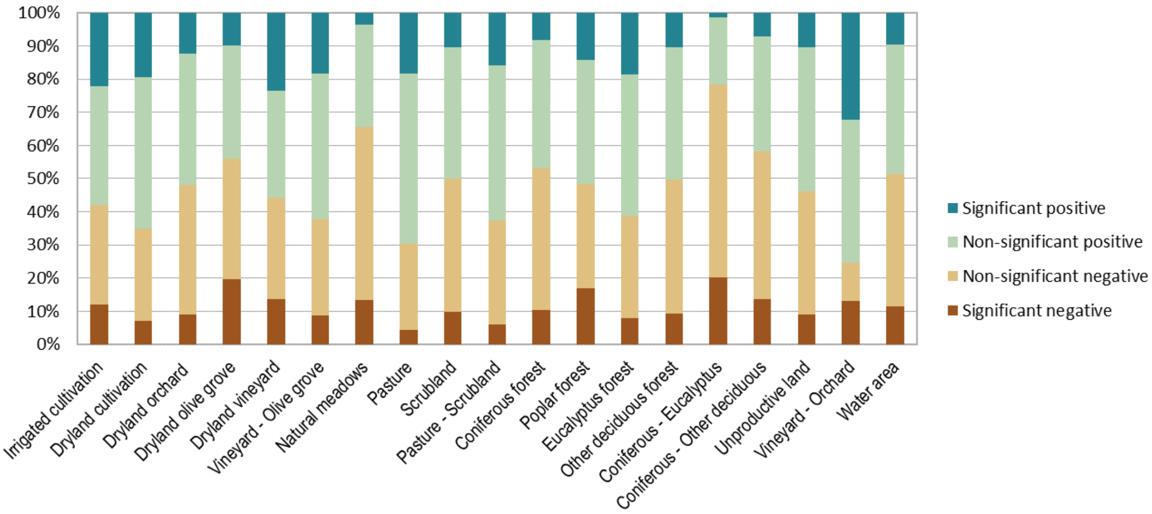

Figure S18. Changes in the right derivative by land use.

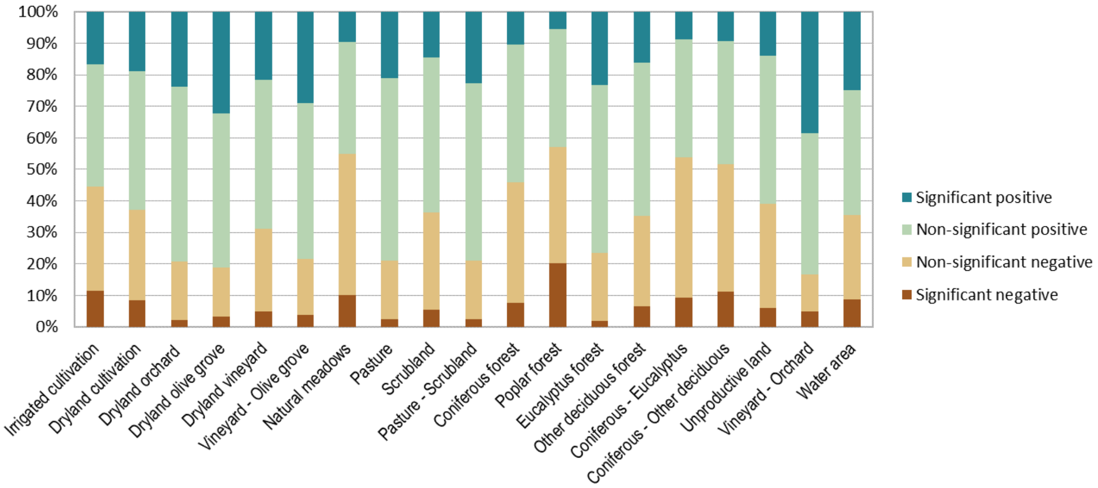

Figure S19. Changes in the left derivative by land use.

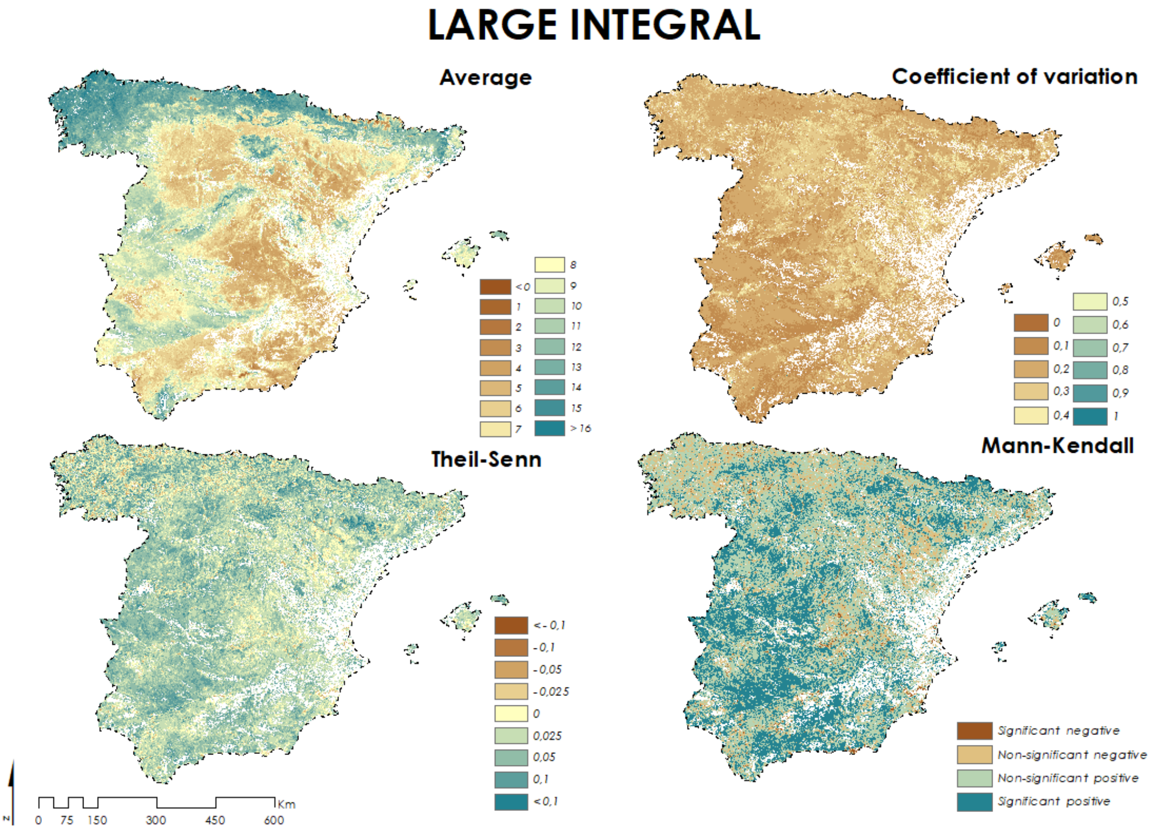

Figure S20. Maps of the statistics for the large integral of the season.

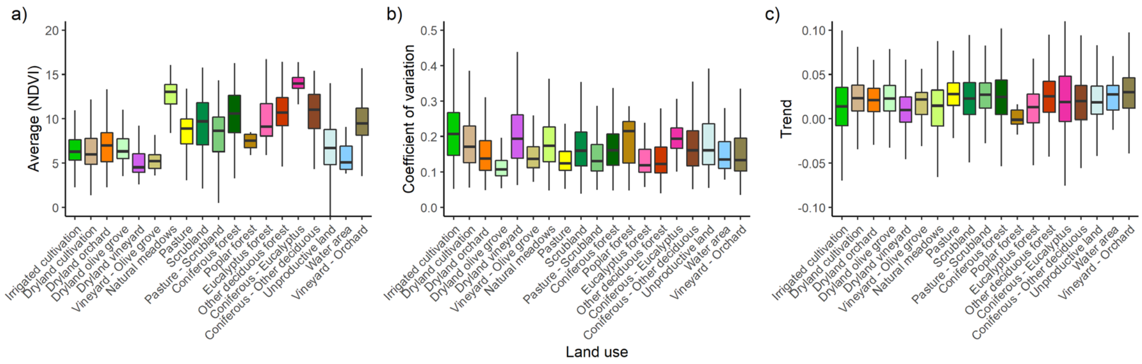

Figure S21. Large integral statistics of the season throughout the series according to different types of land cover.

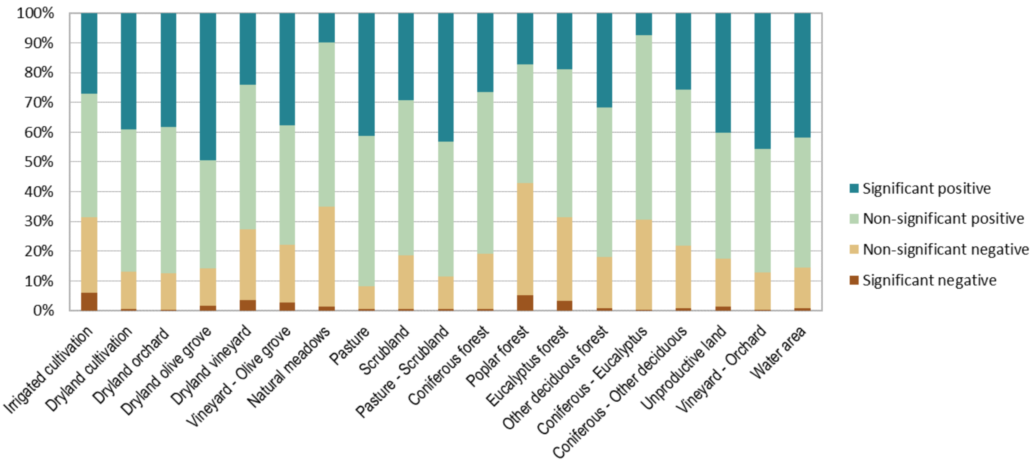

Figure S22. Changes in the large integral by land use.

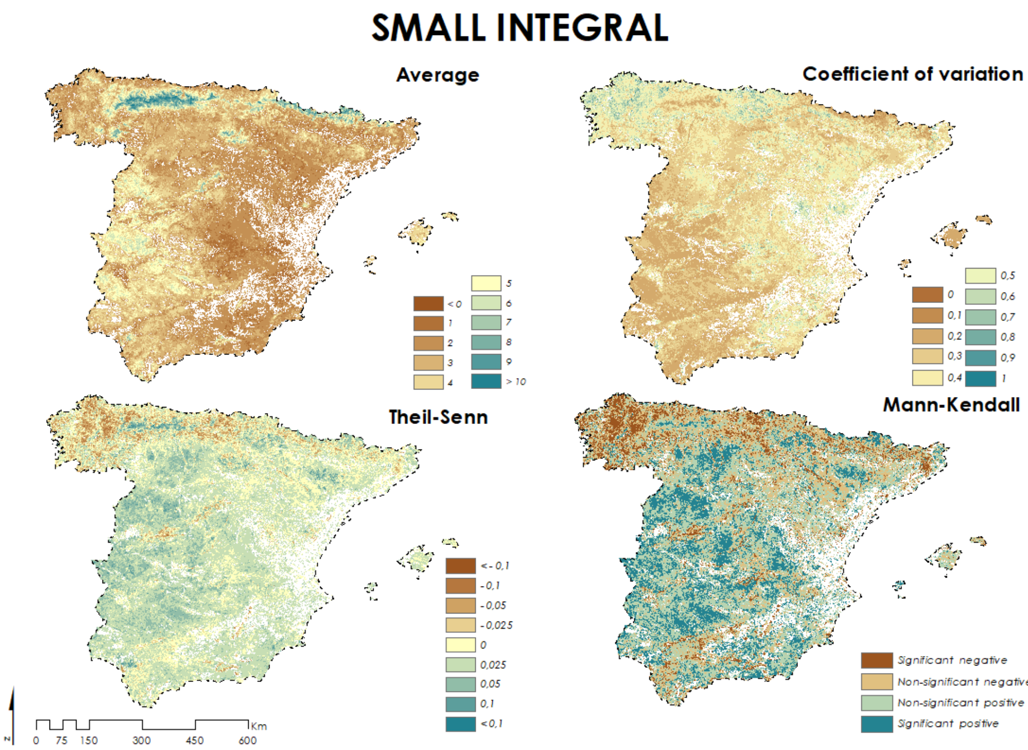

Figure S23. Maps of the statistics for the small integral of the season.

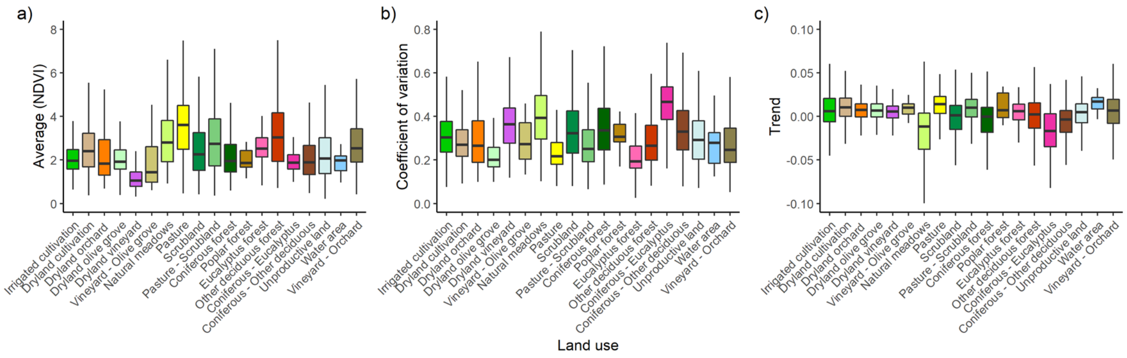

Figure S24. Small integral statistics of the season throughout the series according to different types of land cover.

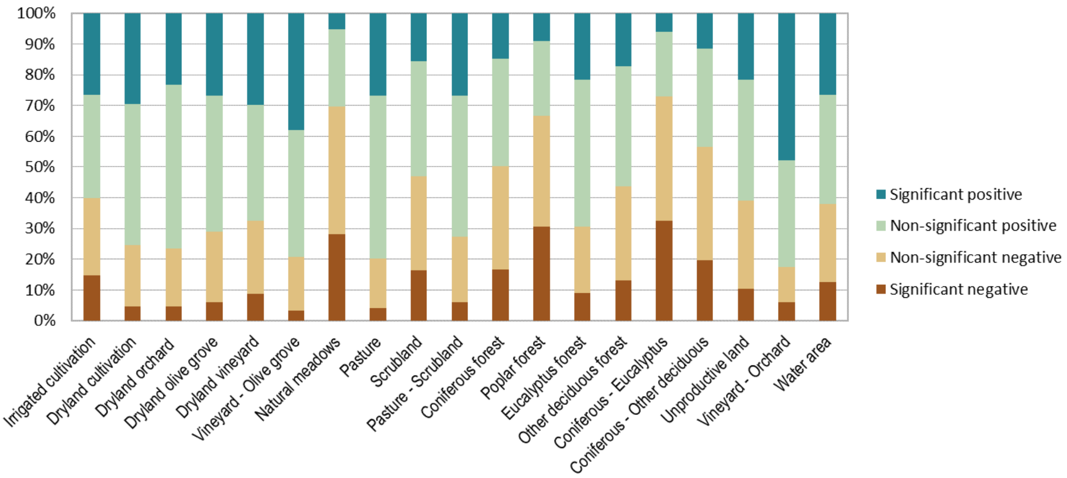

Figure S25. Changes in the small integral by land use.

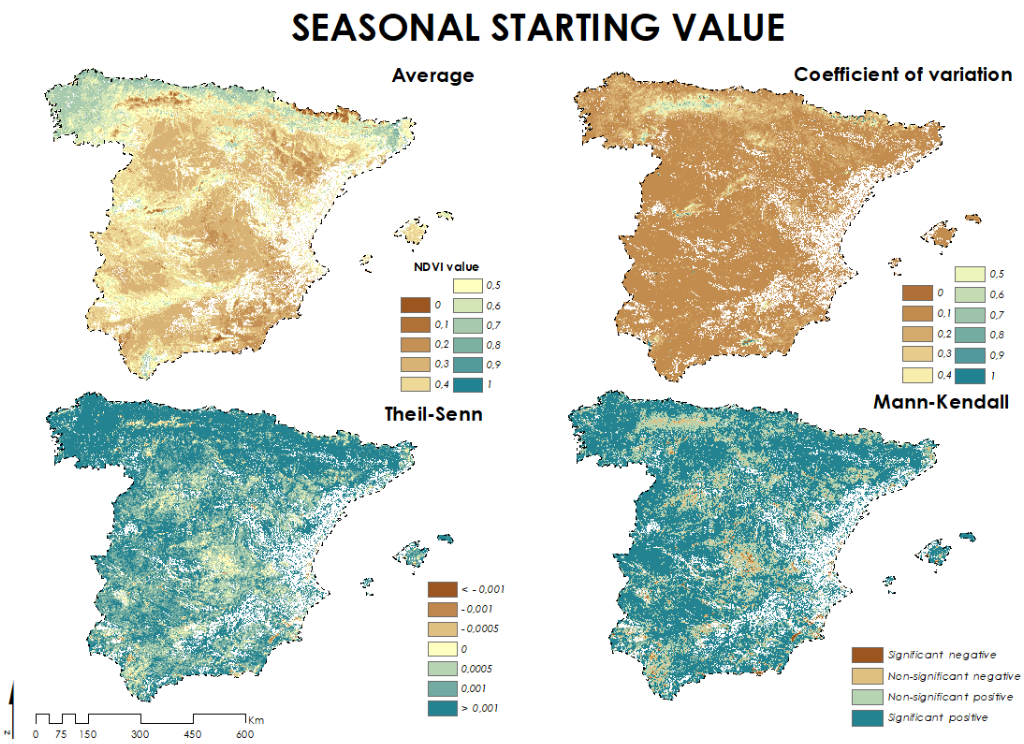

Figure S26. Maps of the statistics for the initial value of the season.

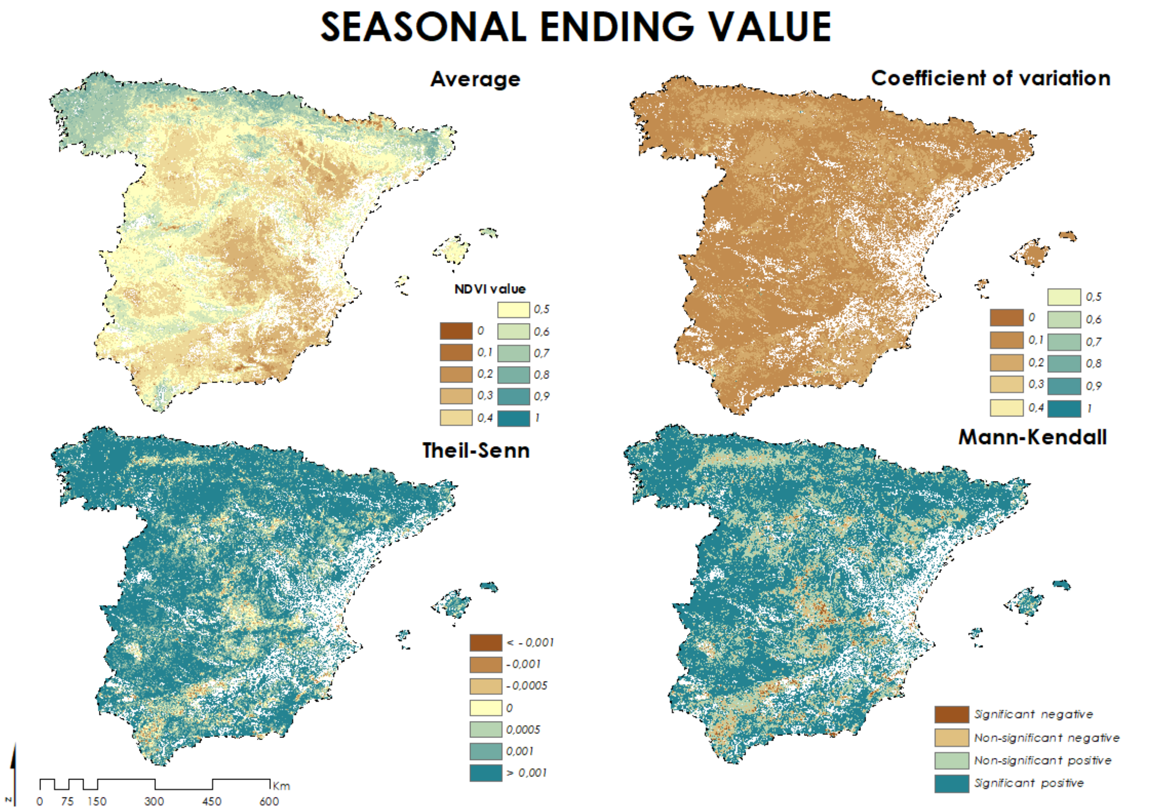

Figure S27. Maps of the statistics for the final value of the season.

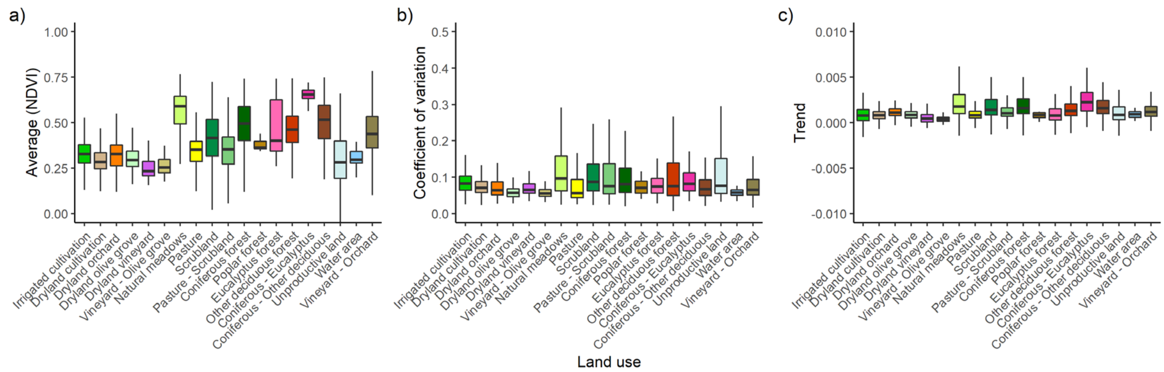

Figure S28. Start value statistics of the season throughout the series according to different types of land cover.

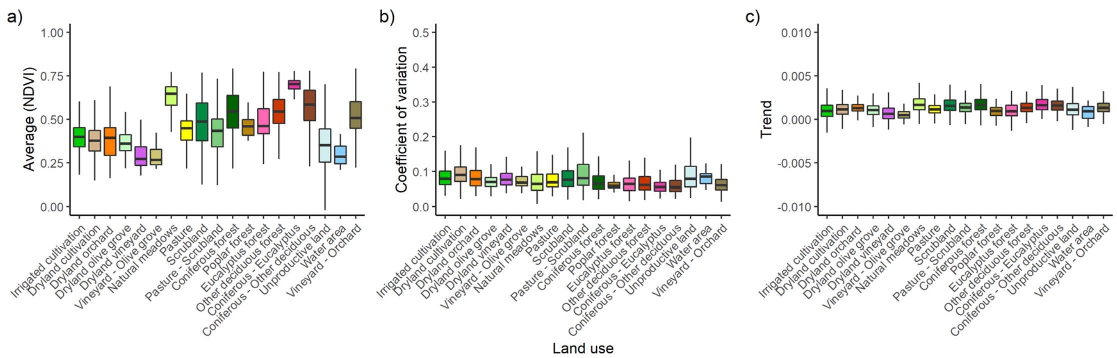

Figure S29. End value statistics of the season throughout the series according to different types of land cover.

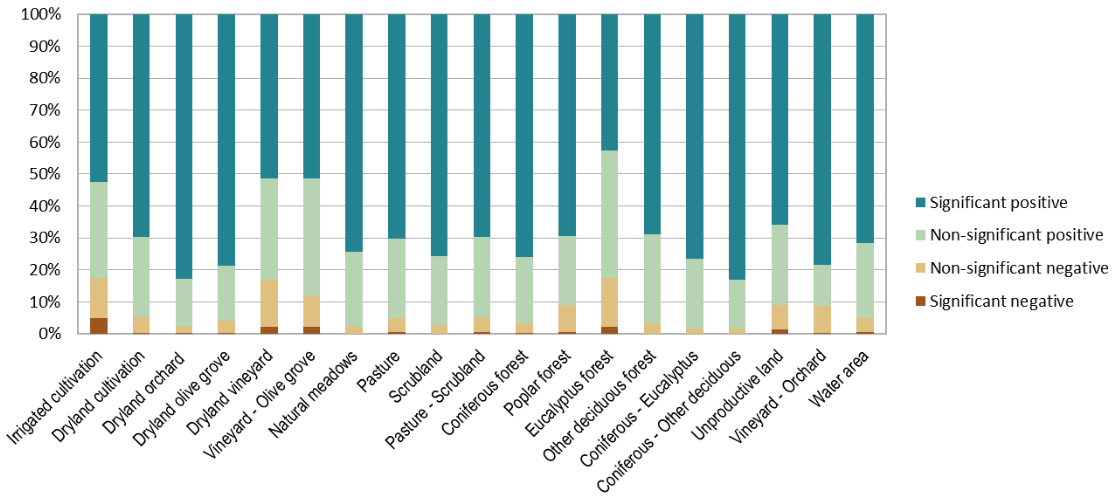

Figure S30. Changes in the start value of the season by land use.

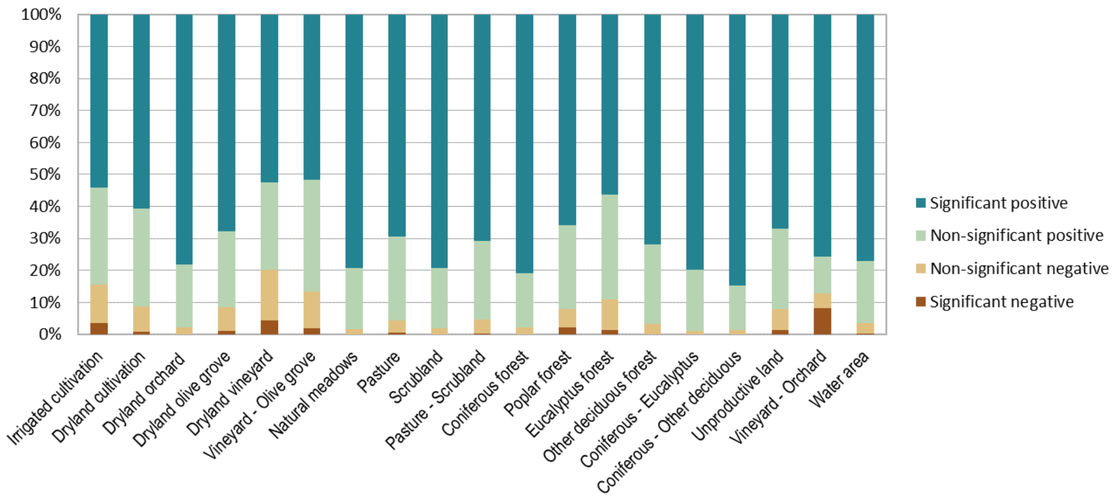

Figure S31. Changes in the end value of the season by land use.

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FRAGMENTATION, BIRDS, AND CONSERVATION OF THE *POLYLEPIS* FOREST IN SOUTHERN PERU

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ABSTRACT. In the southernmost Andean regions of Peru, Moquegua, and Tacna, close to Chile and Bolivia borders, large forest stands of *Polylepis* species are essential for the social, economic, and environmental functionality of six basins. However, the need for more knowledge about their ecology, limited conservation efforts, and insufficient technical capacities for territorial regulation could accelerate their structural and functioning deterioration. Using landscape ecology -interdisciplinary science shaped by geography and biology- we found that in four evaluated areas, the composition of birds (and therefore also the resources they use) is differentiated by the influence of landscape fragmentation. Only two protected areas were legally recognized in the region, but they were established to cover small and remote isolated territories, which makes it challenging to conserve them effectively. Due to the poverty conditions common among the local communities, extractive or pastoralist activities conducted in large areas can trigger higher forest fragmentation rates. Under these circumstances, the valuable ecosystem services in the study area would be permanently lost or maintained at high risk. Because of these risks, specific measures were proposed to improve the social-environmental management of the forest by implementing mechanisms aimed at generating sustainable economic benefits in a healthy environment and social peace.

Fragmentación, aves y conservación del bosque de Polylepis en el extremo sur de Perú

REUMEN. En los Andes del extremo sur peruano, Moquegua y Tacna, departamentos limítrofes con las Repúblicas de Chile y Bolivia, se distribuye un gran bosque de *Polylepis* importante para la funcionalidad social, económica y ambiental de seis cuencas hidrográficas. Sin embargo, su escaso conocimiento ecológico, los pocos esfuerzos para conservarlo y las insuficientes capacidades técnicas de regulación territorial podrían facilitar la degradación de su estructura y funcionamiento. Utilizando la ecología del paisaje -ciencia interdisciplinaria conformada por la geografía y la biología-, se ha demostrado que en cuatro zonas evaluadas la composición de aves (y por ende también de los recursos que ellas utilizan) es muy diferente por influencia directa de la fragmentación encontrada. Esta circunstancia se vuelve sumamente clave para lograr una adecuada conservación, ya que, si las actividades extractivas otorgadas en grandes extensiones o las comunidades campesinas, a causa de sus altos niveles de pobreza, fragmentaran el bosque, o peor aún, si se mantuvieran las dos áreas protegidas reconocidas de forma aislada y de tamaño insuficiente, la coyuntura sería crítica y los valiosos servicios ecosistémicos del área de estudio se encontrarían permanentemente en alto riesgo. Se proponen, pues, medidas para mejorar la gestión socioambiental del bosque implementando mecanismos orientados a generar beneficios económicos sostenibles en un entorno saludable y de paz social.

Keywords: Landscape ecology, protected areas, sustainable development, Moquegua, Tacna.

Palabras clave: Ecología del paisaje, áreas protegidas, desarrollo sostenible, Moquegua, Tacna.

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1. Introduction

Polylepis, a tree and shrub genus endemic to the South American Andes, is a unique entity. Its twenty-seven recorded species (Kessler and Schmidtlebuhn, 2006; Mendoza and Cano, 2011) form fragmented or relictual forests spanning Chile to Venezuela. These forests, found at altitudes ranging from 900 meters in Cordoba, Argentina, to over 5,000 meters in Sajama, Bolivia, and Tacna, Peru (Renison *et al.,* 2013; Franco *et al.,* 2021), boast the highest levels of diversification in Peru and Bolivia (CDC UNALM, 2006; Zutta and Rundel, 2017). However, due to their territorial overlap with diverse human populations, they have become one of the most threatened Andean ecosystems (Cuyckens *et al.,* 2016).

The southern Peruvian Andes tends towards aridity, corresponding to units 7, 8, and 9 of the regionalization of rainfall on the Pacific slopes with an accumulated annual rainfall below 400 mm according to the classification by Rau *et al.* (2017). These arid environments constitute the primary habitat for three of the nineteen identified at the national level (Mendoza and Cano, 2011). These are the more water-stress-resistant species belonging to the genus. Its mostly fragmented forests (Kessler, 2002 and Rada *et al.,* 2009) can play a significant water-regulation role within the basins declared in the water emergency from 2007 onwards, making them unique plant formations essential in the extreme southern Peruvian corridor (Moquegua and Tacna regions) bordering Chile and Bolivia. Regrettably, there are still gaps in information on its cultural, environmental, and economic values, as well as very few conservation efforts, reflecting weak environmental management and conservation regulations. That is particularly critical in a region that maintains high levels of extreme poverty, constituting a significant risk in implementing measures to ensure sustainable development.

Given the critical state of *Polylepis* forests and their potential impact on sustainable development, it is proposed to conduct a comprehensive evaluation. This evaluation will focus on the relationship between bird composition and *Polylepis* forest fragmentation, using the principles of landscape ecology. The study will be conducted in four different areas, and the state of conservation of these forests will be geographically evaluated. Public policies will be rigorously analyzed, and a series of changes will be proposed to ensure these ecosystems are properly managed and contribute to sustainable development.

2. Methodology

2.1. Delimitation of the study area

To delimit the study area, vector geographic layers were downloaded from various sources of information: i) the spatial coverage of the *Polylepis* forest (Franco *et al.,* 2021; MINAM, 2018; Pacheco *et al.,* 2019), ii) the cartographic representation of watersheds and human activity (Regional Government of Tacna, 2023), and iii) the polygons representing the boundaries of the Andean and Puna ecoregion of the departments of Moquegua and Tacna (CDC UNALN, 2006). All this information were all loaded and processed in the QGIS software (QGIS Development Team, 2023). With the cutting and editing tools, each fragment of the forest formed an evaluation zone, based on its geographical position and representation in one of the six watersheds or by its proximity to other larger fragments with which they could be interacting.

2.2. Calculation of fragmentation indices, bird composition and correlation

Each of the *Polylepis* forest zones, delimited within the study area, was individually subjected to the calculation of its fragmentation indices, using the Patch Analyst Tools v5.2 extension (Rempel *et al.,* 2012). This was initially programmed to perform the calculation at the level of each fragment and obtain the values of its areas, perimeters, shape indices (SI), perimeter-area ratio (PAR) and Fractal Dimension (FD), indicating their complexity and irregularity. With the results, a similarity analysis of each zone was performed using the R software (R Core Team, 2020).

Next, the Patch Analyst Tools were programmed to calculate the values of fifteen fragmentation indices at the landscape level (set of fragments that make up a delimited forest area). Of these, five indices represent the evaluation of the shape of the fragments: MSI (average of the shape index), MPAR (average of the perimeter-area ratio), MPFD (average of the Fractal Dimension), AWMSI (weighted average of the average of the mean of the shape) and AWMPFD (weighted average of the mean of the fractal dimension of the patches). Three are related to the edge: TE (total edge), ED (edge density), and MPE (average of the edge). Five are linked to size and density: MPS (mean fragment size), MedPS (median size), PScoV (coefficient of variation of fragment size), PSSD (standard deviation, fragment size). Finally, two indices are representative of the area: TLA (the index of the total area of the landscape) and CA (class area).

As a next step, it was necessary to determine the composition of birds in each of the delimited forest areas; for this, we used the ornithological sighting records, obtained in the field between 2018 and 2023, during the trips made by the research team. The technique of transects of at least one kilometer of walking per counting point and the corresponding photographic record were applied. At least five transects of ten (10) fixed counting points with a radius of 25 meters were used in each. All the birds observed in each area were recorded and with the help of a camera, tripod and binoculars, the respective geographical coordinates were also noted (Franco *et al.,* 2020). To complement the information on the ornithological composition, bird watching records were downloaded from the eBird platform and database between 2010 and 2022 (eBird, 2021). With the geographical coordinates of the records, they were uploaded together to the QGIS to be edited, cut, and grouped according to the forest area to which they correspond.

In order to evaluate the existence of a direct relationship between fragmentation and the ornithological composition of the forest, it was first necessary to analyze whether the fragmentation indices at the landscape scale have a statistically significant autocorrelation, by constructing a correlation graph with Pearson's values (Taiyun and Simko, 2021) using the R software (R Core Team, 2020). The result of this analysis allowed us to know and select those fragmentation indices that predominate in each delimited forest area. For this purpose, together with the results of their ornithological composition, a non-metric multidimensional scaling (NMDS) was carried out to represent in each forest area the proximity between its set of birds and the indices that influence them (Hothorn *et al.,* 2008; Oksanen *et al.,* 2022).

2.3. Assessment of the conservation situation of the Polylepis forest

To evaluate the situation of forest conservation, official geographic information was downloaded from various sources, mainly related to the current use of the territory: i) the cartography of protected areas and priority sites for conservation (SERNANP, n.d.) that indicated how much area is currently conserved and how much potential it has for the future; (ii) the mining and peasant community cadastre from the GEOCATMIN -Geological and Mining Cadastral Information System (Hanco, 2010)- with which it was possible to determine the forest territory that is involved in current and future mining operations and which peasant communities are the own large plots of land; and (iii) the Provincial and District Monetary Poverty Map 2018 (INEI, 2020), which has been an important and conditioning factor for the conservation of biodiversity (Fisher *et al.,* 2005). This cartography was subjected to a superposition process with that of the *Polylepis* forest using the QGIS software for calculations.

3. Results

The study area corresponding to the *Polylepis* forest of the departments of Moquegua and Tacna, in the extreme south of Peru, ecoregions of the central Andes and the puna, was delimited (Fig. 1a). Based on the geographical distribution of the six watersheds, four areas of *Polylepis* forest were delimited: the Tambo basin, the Ilo Moquegua basin, the Maure basin and, finally, an area formed by the grouping of forest fragments located in the three basins on the Pacific slope of the department of Tacna: Locumba, Sama and Caplina basins, called VPTCQ (Fig. 1b).

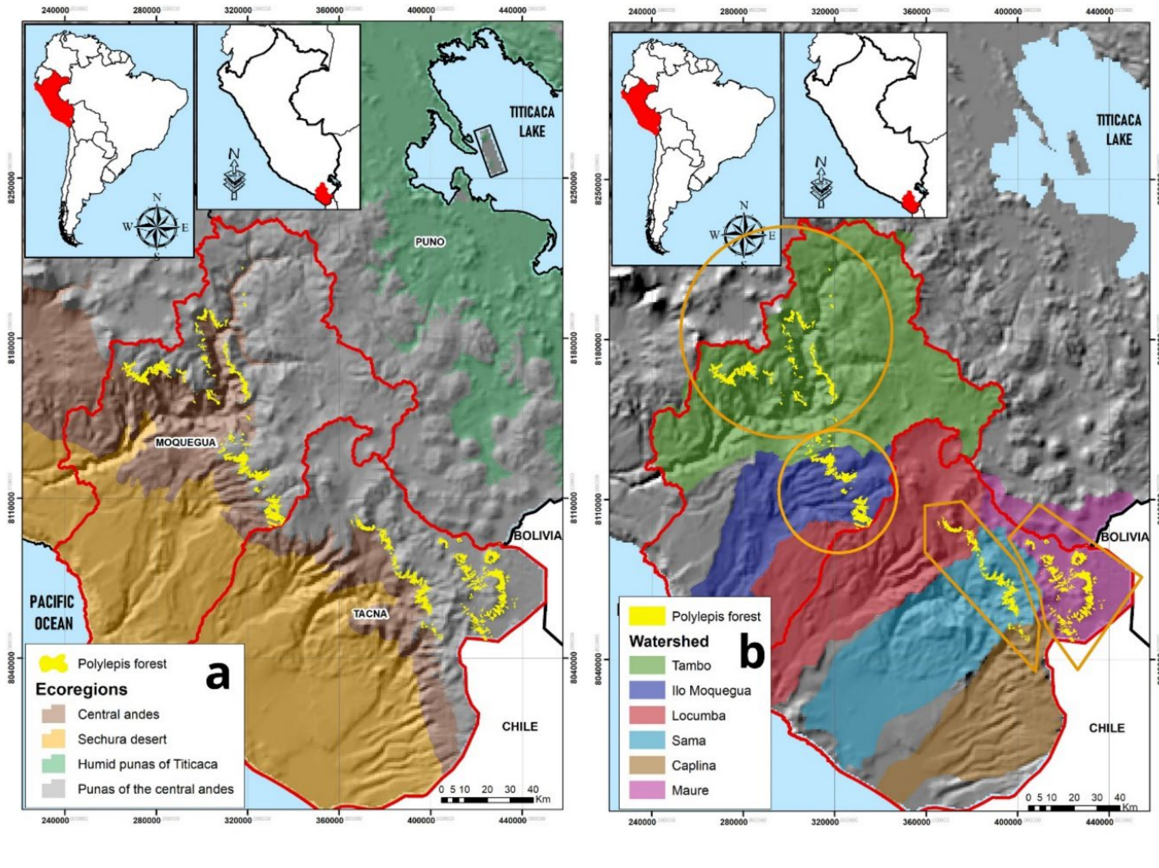

Figure 1. a) The yellow polygons represent the distribution of the Polylepis *forest in the Central Andes ecoregions and in its Punas; b) The large orange polygons show the four areas of* Polylepis *forest whose level of fragmentation and bird richness were determined in their respective watersheds (Source: CDC UNALM, 2006; El Peruano, 2013).*

Four indices (perimeter, PAR, SI and FD) were calculated for each of the forest fragments in their respective zone and the results of the statistical similarity analysis are presented in Figure 2, in which it is possible to observe that the area forest of the Tambo basin presents significant differences with the other areas studied in three of the four indices calculated: the perimeter (P) is larger, the shape index (SI) is larger, and the perimeter-to-area ratio (PAR) is similar to the others, indicating its fragments are larger and more irregular than the rest. However, at the level of fractal dimension (FD) (complexity) it is the fragments of the VPTCQ zone that show very significant differences: they are smaller than Tambo, similar to Ilo Moquegua and Maure, but with less complexity than all the others.

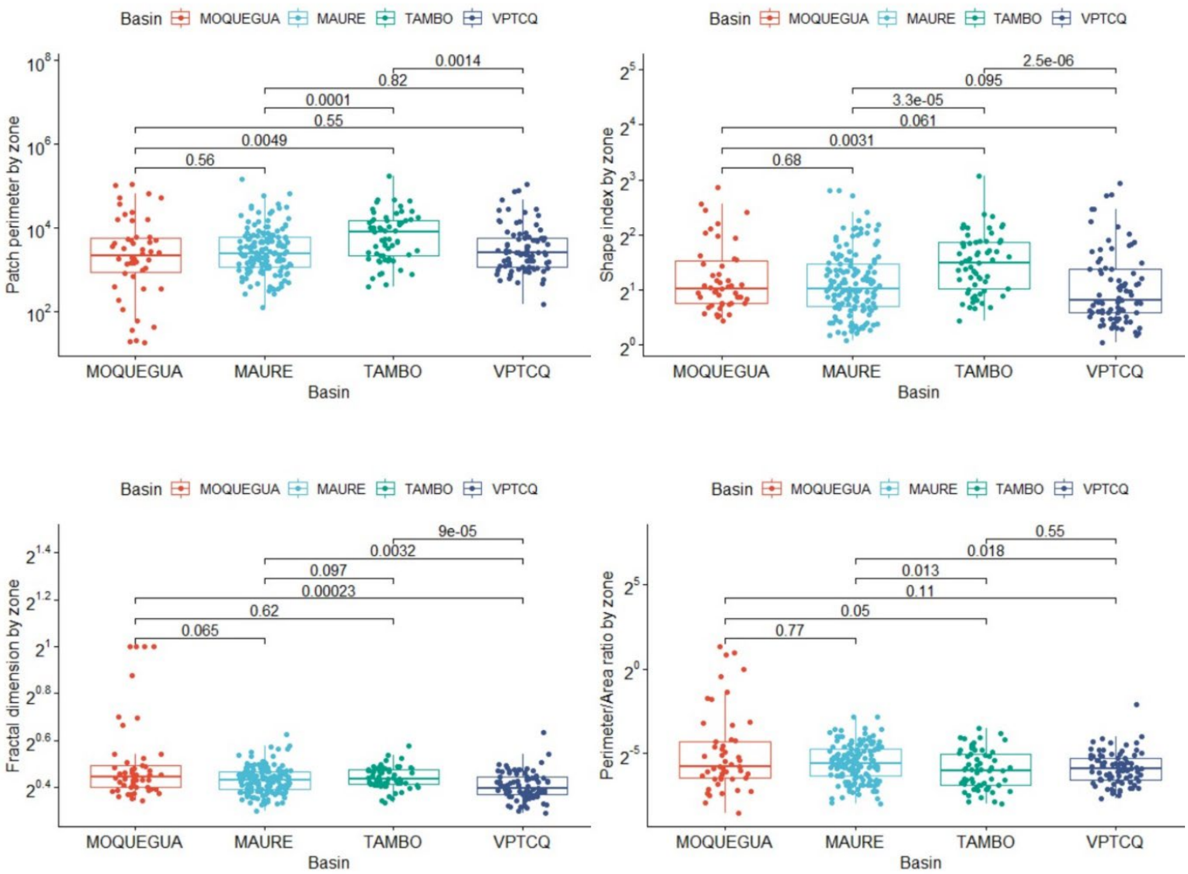

Figure 2. Statistical analysis of the shape of Polylepis *forest by each zone, comparing the existence of significant differences in the variables: Perimeter, Shape Index and Fractal Dimension.*

Table 1 also shows the values of the fifteen fragmentation indices calculated for each forest area, showing their differences and variations. These indices are multidimensional and lack the same unit of measurement but are related to the morphometric characteristics of the forest area studied.

Regarding the richness of bird species, according to Table 2, a total of 765 records were obtained, which were geographically distributed as follows: 432 records in the Ilo Moquegua basin, with 71 species, 64 records in the Tambo basin, with 33 species, 142 records in Maure, with 45 species, and 127 records in VPTCQ, with 50 species. Figure 3 presents the distribution map of bird species records within each *Polylepis* forest area, as well as some photographs of the most emblematic birds taken by the research team during field work.

Table 1. Landscape-level fragmentation indices of the four Polylepis *forest zones.*

TYPE	INDEX	PATCH			
		Tambo Basin	Ilo Moquegua Basin	Maure Basin	VPTCQ Basins
FORM	AWMSI	5.04	5.06	4.66	5.14
	MSI	2.99	2.53	2.38	2.30
	MPAR	218.71	2,008.77	281.53	225.09
	MPFD	1.36	1.43	1.35	1.33
	AWMPFD	1.35	1.35	1.35	1.36
EDGE	TEA	836,771.39	597,095.13	990,727.86	684,198.71
	ED	69.08	56.75	77.44	84.23
	MPE	13,717.56	11,941.90	6,880.05	8,446.90
DENSITY SIZE	MPS	198.59	210.42	88.84	100.28
	NumP	61.00	50.00	144.00	81.00
	MedPS	60.98	14.89	13.10	15.37
	PSCoV	240.91	264.32	378.66	261.10
	PSSD	478.42	556.17	336.41	261.82
AREA	TLA	12,113.83	10,520.79	12,793.29	8,122.61
	AC	12,113.83	10,520.79	12,793.29	8,122.61

Table 2. Official list of bird species recorded in the Polylepis *forest patches according to our own records from 2018 to 2023 and those obtained in EBIRD from 2010 to 2022.*

Number scientific	IUCN-2023	SPECIES	IUCN-2023	SPECIES	IUCN-2023
Aeronautes andecolus	LC	*Geranoaetus melanoleucus*	LC	*Phalcoboenus megalopterus*	LC
Agriornis albicauda	VU	*Geospizopsis plebejus*	LC	*Polioxolmis rufipennis*	LC
Agriornis montanus	LC	*Geospizopsis unicolor*	LC	*Phrygilus atriceps*	LC
Anairetes flavirostris	LC	*Leptasthenura aegithaloides*	LC	*Phrygilus punensis*	LC
Anairetes reguloides	LC	*Leptasthenura striata*	LC	*Psilopsiagon aurifrons*	LC
Asthenes dorbignyi	LC	*Lessonia oreas*	LC	*Pygochelidon cyanoleuca*	LC
Asthenes modesta	LC	*Metallura phoebe*	LC	*Rhea pennata*	VU
Asthenes pudibunda	LC	*Metriopelia aymara*	LC	*Rhopospina fruticeti*	LC
Attagis gayi	LC	*Metriopelia ceciliae*	LC	*Saltator aurantiirostris*	LC
Cathartes Aura	LC	*Metriopelia melanoptera*	LC	*Sicalis lutea*	LC
Catamenia analysis	LC	*Muscisaxicola albifrons*	LC	*Sicalis olivascens*	LC
Catamenia inornata	LC	*Muscisaxicola capistratus*	LC	*Sicalis uropygialis*	LC
Cinclodes albiventris	LC	*Muscisaxicola cinereus*	LC	*Spinus atratus*	LC
Cinclodes atacamensis	LC	*Muscisaxicola flavinucha*	LC	*Spinus crassirostris*	LC
Circus cinereus	LC	*Muscisaxicola frontalis*	LC	*Spinus magellanicus*	LC
Colaptes rupicola	LC	*Muscisaxicola juninensis*	LC	*Spinus uropygialis*	LC
Hummingbird coruscans	LC	*Muscisaxicola maclovianus*	LC	*Systellura longirostris*	LC
Conirostrum binghami	NT	*Muscisaxicola maculirostris*	LC	*Thinocorus orbignyianus*	LC
Conirostrum cinereum	LC	*Muscisaxicola rufivertex*	LC	*Tinamotis pentlandii*	LC
Conirostrum tamarugense	LC	*Nothoprocta ornata*	LC	*Troglodytes aedon*	LC
Diglossa brunneiventris	LC	*Ochetorhynchus ruficaudus*	LC	*Turdus chiguanco*	LC
Falco femoralis	LC	*Ochthoeca leucophrys*	LC	*Upucerthia albigula*	LC
Falco peregrinus	LC	*Ochthoeca oenanthoides*	LC	*Upucerthia validirostris*	LC
Falco sparverius	LC	*Oreotrochilus estella*	LC	*Vultur gryphus*	VU
Geositta cunicularia	LC	*Orochelidon andecola*	LC	*Zenaida auriculata*	LC
Geositta punensis	LC	*Passer domesticus*	LC	*Zonotrichia capensis*	LC
Geositta tenuirostris	LC	*Patagioenas maculosa*	LC		
Geranoaetus polyosoma	LC	*Patagonian gigas*	LC		

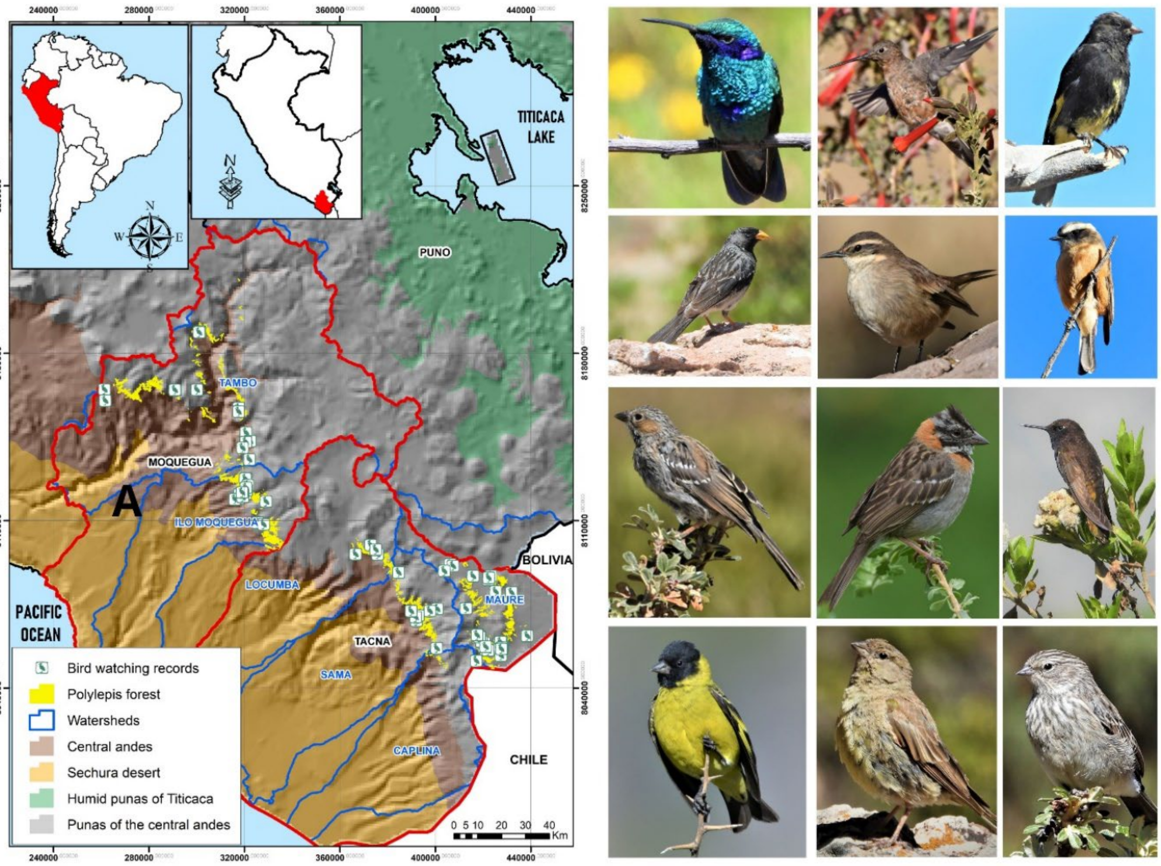

Figure 3. Geographic distribution of bird composition in the four evaluated areas of the Polylepis *forest in the extreme south of Peru. On the right, you can see emblematic birds photographed during the research team's excursions.*

The correlogram in Figure 4 represents the autocorrelation that exists between the fourteen fragmentation indices calculated for each zone, clarifying that in this analysis the CA or area class was not considered, because the research is based on a single vegetation class. The number of asterisks represents the level of correlation (high or low) and the intensity of the color, the sense of color, positive or negative values, which allowed us to select the MSI, MPAR, AWMPFD, TE, ED, MPS, NumP and MedMPS as the most representative.

With all these data, the bidirectional NMDS of Figure 5 was elaborated, in which the black dots and text represent the four evaluated forest areas, the green text indicates the most representative bird species of their composition, and the blue arrows and letters represent the intensity of the influence that the fragmentation indices have on the bird composition. This statistical distribution indicates differences in the composition in the four forest zones, with the Ilo Moquegua and VPTCQ (or VP Tacna) basins being similar to each other, with species that are repeated in their respective records, unlike Maure which has a different composition, where a single species, *Rhea pennata*, predominates, as well as Tambo, where *Circus cinereus* predominates. It is also possible to observe that the blue arrows represent the intensity of the influence of the fragmentation indices on the composition, whose numerical values are presented in Table 3. It is observed that one of the shape indicators, the MPAR, greatly influences the composition of birds in the forest of the Ilo Moquegua basin, while the AWMPFD is important in the basins of the Pacific slope of Tacna or VPTCQ. In the forest of the Maure basin, one of the indicators of fragment density, NumP, mainly influences bird composition, but it also shares with Tambo an important influence of the TE or total edge indicator. In Tambo, the influence of four indices is observed, but of different types: in the shape by the MSI, in the size by the MedMPS and the MPS, and partially in the border with the TE.

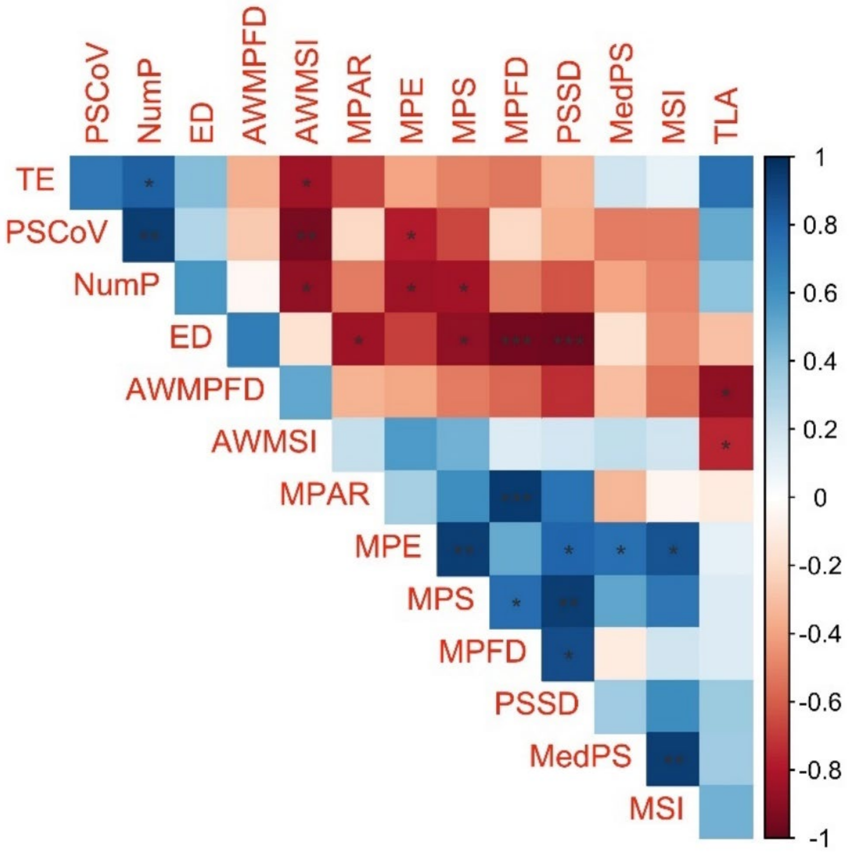

Figure 4. Correlogram developed to determine the autocorrelation of the fragmentation indices calculated for each forest area. The number of asterisks represents the correlation level that exists between the indices (high or low) and the color intensity characterizes the sense of correlation (positive or negative).

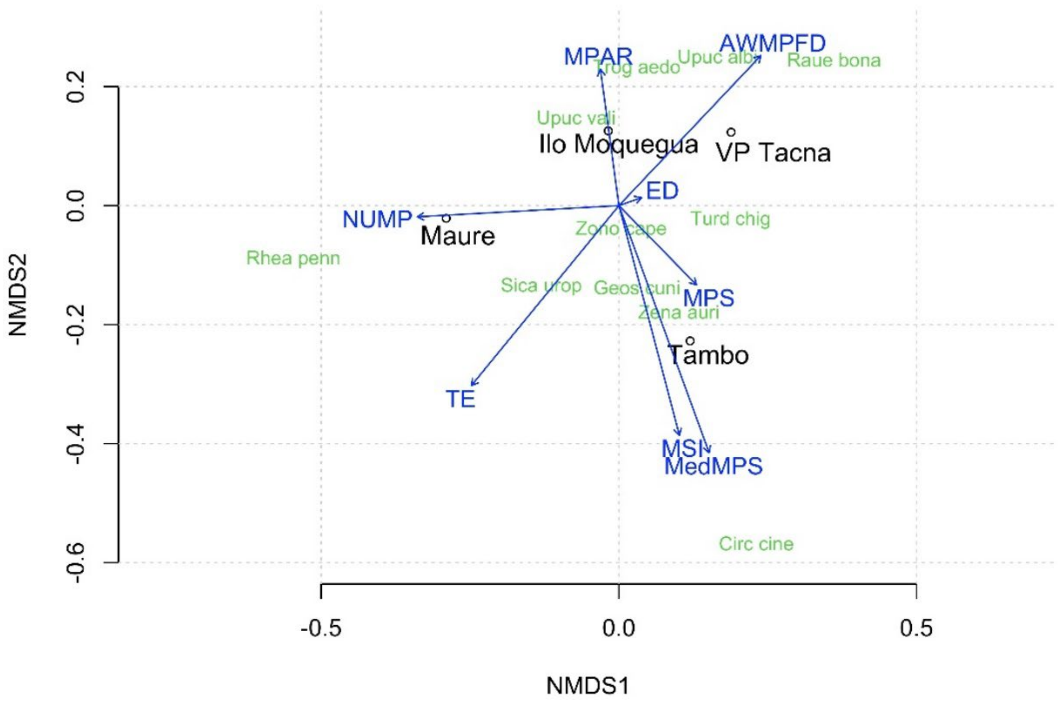

Figure 5. Bidirectional NMDS analysis regarding the influence of fragmentation indices (blue) on bird composition (green) by forest area assessed (black).

Table 3. Fragmentation indices together with the level of influence on bird composition in the Polylepis *forest.*

FRAGMENTATION INDEX	NMDS1	NMDS2
MSI	0.2547	-0.9670
MPAR	-0.1344	0.9909
AWMPFD	0.6872	0.7265
TEA	-0.6339	-0.7734
ED	0.9437	0.3308
MPS	0.6995	-0.7146
NUMP	-0.9985	-0.0556
MedMPS	0.3429	-0.9394

Table 4 shows how the *Polylepis* forest area in the extreme south of Peru has been occupied, clearly observing that only 3.09% is within a protected area administered by the governing body, SERNANP, through the Salinas and Aguada Blanca National Reserve and its buffer zone located in the Tambo basin. 10.88% is located within a Regional Conservation Area administered by the Regional Government of Tacna in the Maure basin. Thus, the preserved areas add up to approximately 14% of the total *Polylepis* forest. The remaining 86% corresponds to non-conserved territories with different types of use and tenure, as shown in Figure 6.

Table 4. Diagnosis of the current use of the territory of the Polylepis *forest.*

CONDITION	TYPE OF USE	OWNERSHIP	SURFACE (Km^2)	%
Not Preserved	Mining Operation Units	Public Land	1.62	0.37
		Land of Peasant Communities	1.55	0.36
	Livestock Activity	Of Peasant Communities	239.58	55.01
	Barren Lands	Public Land (no other vested rights have been assessed)	131.91	30.29
Preserved	ACR	Public and Peasant Communities	47.40	10.88
	ANP	Public and Peasant Communities	13.45	3.09
TOTAL			435.51	100.00

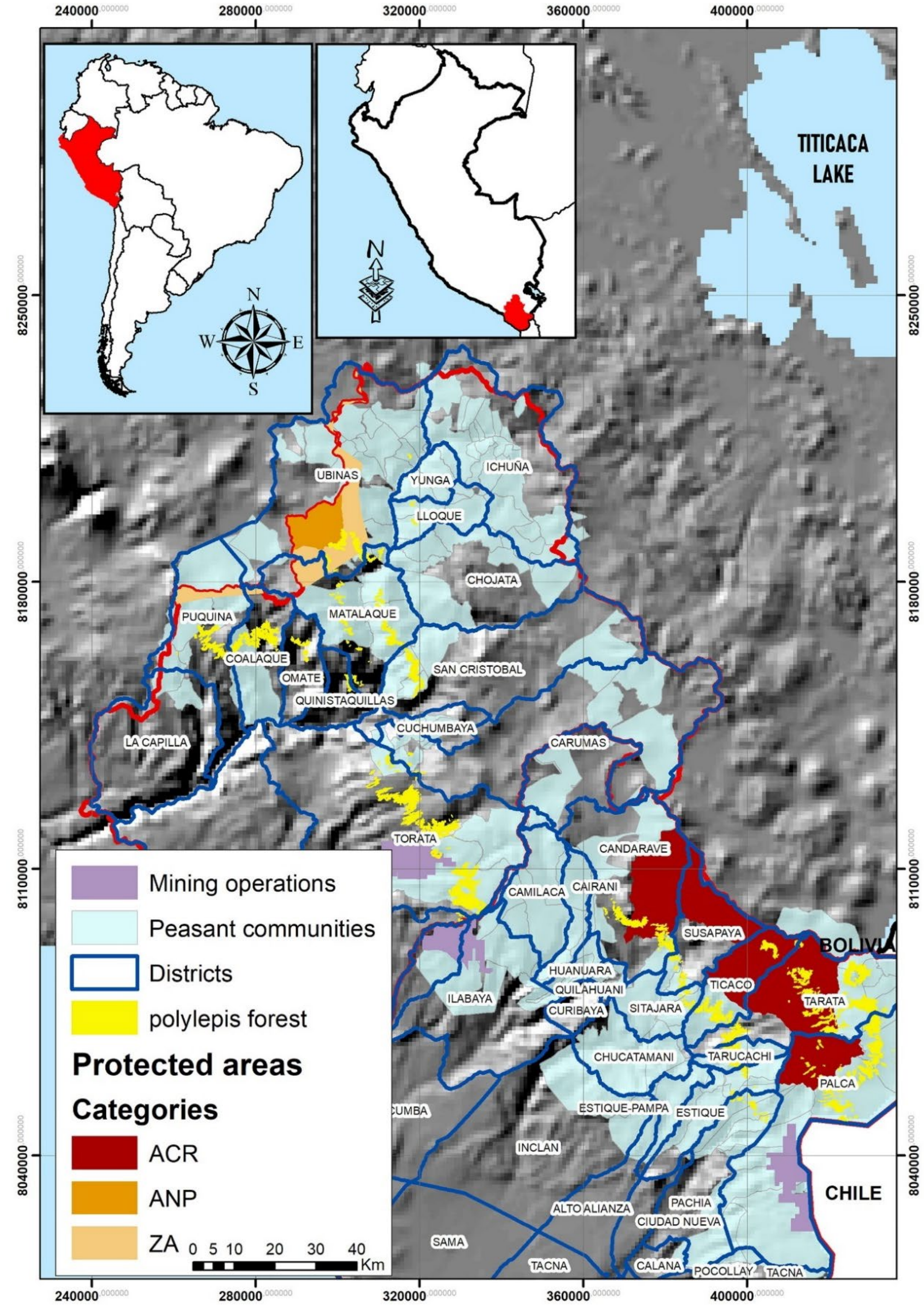

Figure 6. Geographical distribution of the Polylepis forest at the district level, peasant communities, mining operations and protected areas of different categories (national or regional).

Likewise, using the graphic base of the priority sites for conservation (SPC) of the regions of Moquegua and Tacna, represented in Figure 7, it is observed that there are eight large polygons (represented in fuchsia), which have been studied, delimited, and recognized -by its authorities and in their maximum territorial planning documents- as future protected areas. However, the technical processes for establishing an effective conservation modality have not been initiated for more than ten years. In these polygons, there are 192.53 km^2 of *Polylepis* forest, with enormous potential to be conserved and adequately managed, which would increase its surface within protected areas by more than 40%, as presented in Table 5.

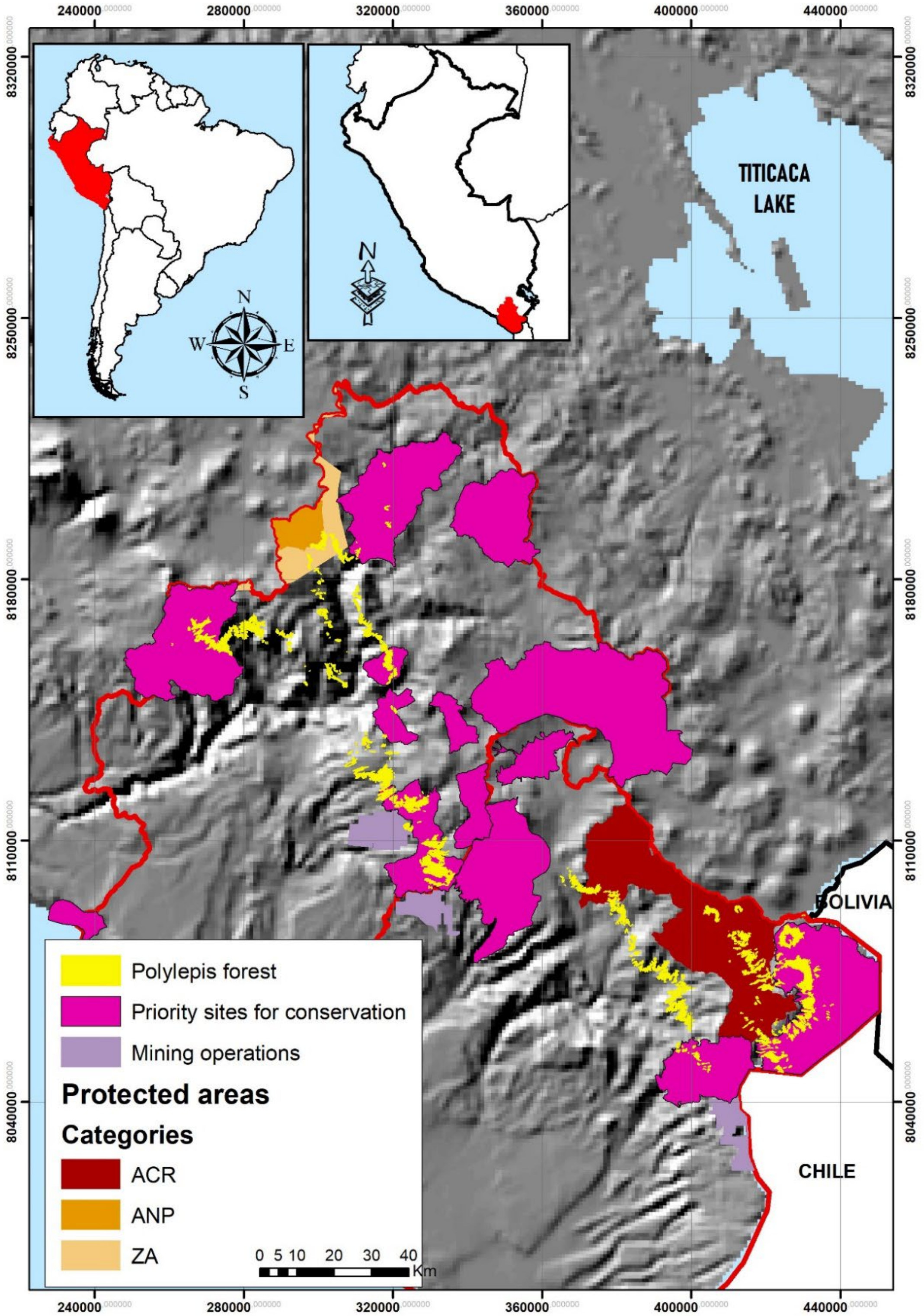

Figure 7. Distribution of priority sites for conservation projected and recognized by the regional governments of Moquegua and Tacna since 2013, but without technical processes initiated.

Table 5. Surface area and stakeholders that would be linked through future conservation modalities through the diagnosis of the Priority Sites for conservation recognized by the Regional Governments of Moquegua and Tacna since 2013.

Department	**Priority Site for Conservation**	**Actors**				**Area (Km²)**	**% Conservation Potential**
		Interior of Mining Operations	Close to mining operations	Peasant communities	State		
Moquegua	Queñual de Muylaque	No	0.00	11.47	0.04	11.51	2.64
Moquegua	Chilata	No	0.00	4.35	17.52	21.87	5.02
Moquegua	Ticsani Valley	No	0.00	1.03	0.07	1.10	0.25
Moquegua	Upper Tambo Valley	No	0.00	2.29	0.00	2.29	0.53
Moquegua	Queñoal de Arondaya and Cuellar	Yes	1.68	38.38	25.66	65.72	15.09
Tacna	Upper Caplina Basin	Yes	0.00	4.35	0.00	4.35	1.00
Tacna	Bajo Candarave	Yes	0.00	0.02	0.00	0.02	0.01
Tacna	Upper Peru Tripartite	Yes	0.00	85.28	0.37	85.65	19.67
TOTAL			1.68	147.18	43.67	192.53	44.21

Finally, it was determined that the geographical distribution of human poverty is sectorized and extends to all the Andean and high Andean districts of the departments of Moquegua and Tacna, with a maximum percentage of 54.7% as shown in Figure 8. Overlapping with the areas of the *Polylepis* forest, high poverty values are obtained, such as those included in Table 6, making it clear that this natural wealth is found in the poorest districts of both departments, especially in the forests of the Maure basin. The same occurs in the other areas evaluated as illustrated in Figure 9.

Table 6. Status of human poverty and forest area of Polylepis for each area studied.

Maure		**Shelter**		**VPTCQ**		**ILO MOQ**	
% Poverty	Km²	% Poverty	Km²	% Poverty	Km²	% Poverty	Km²
44.1	6.94	17.3	4.64	32.1	3.85	8.3	2.29
37.7	54.39	11.1	4.91	20.4	4.34	8.1	0.15
43.8	66.61	23.6	51.06	33.8	18.78	11.2	5.08
		31.2	17.35	36.3	3.72	31.7	97.48
		35.3	1.17	37.7	15.93	35.3	0.21
		44	27.76	38.9	24.12		
		54.7	14.24	43.8	10.48		

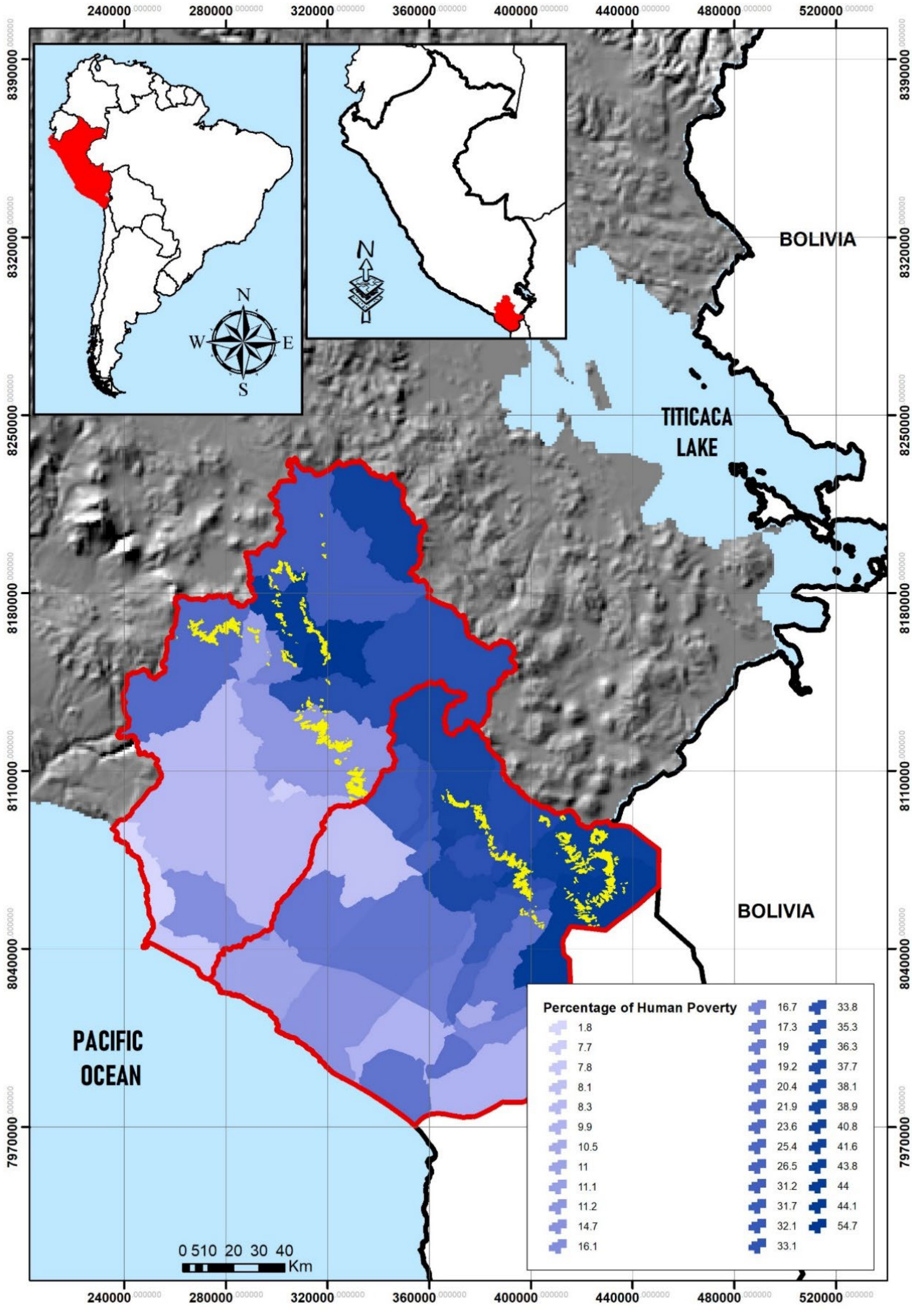

Figure 8. Map of the percentage distribution of human poverty by district and its overlap with the Polylepis *forest.*

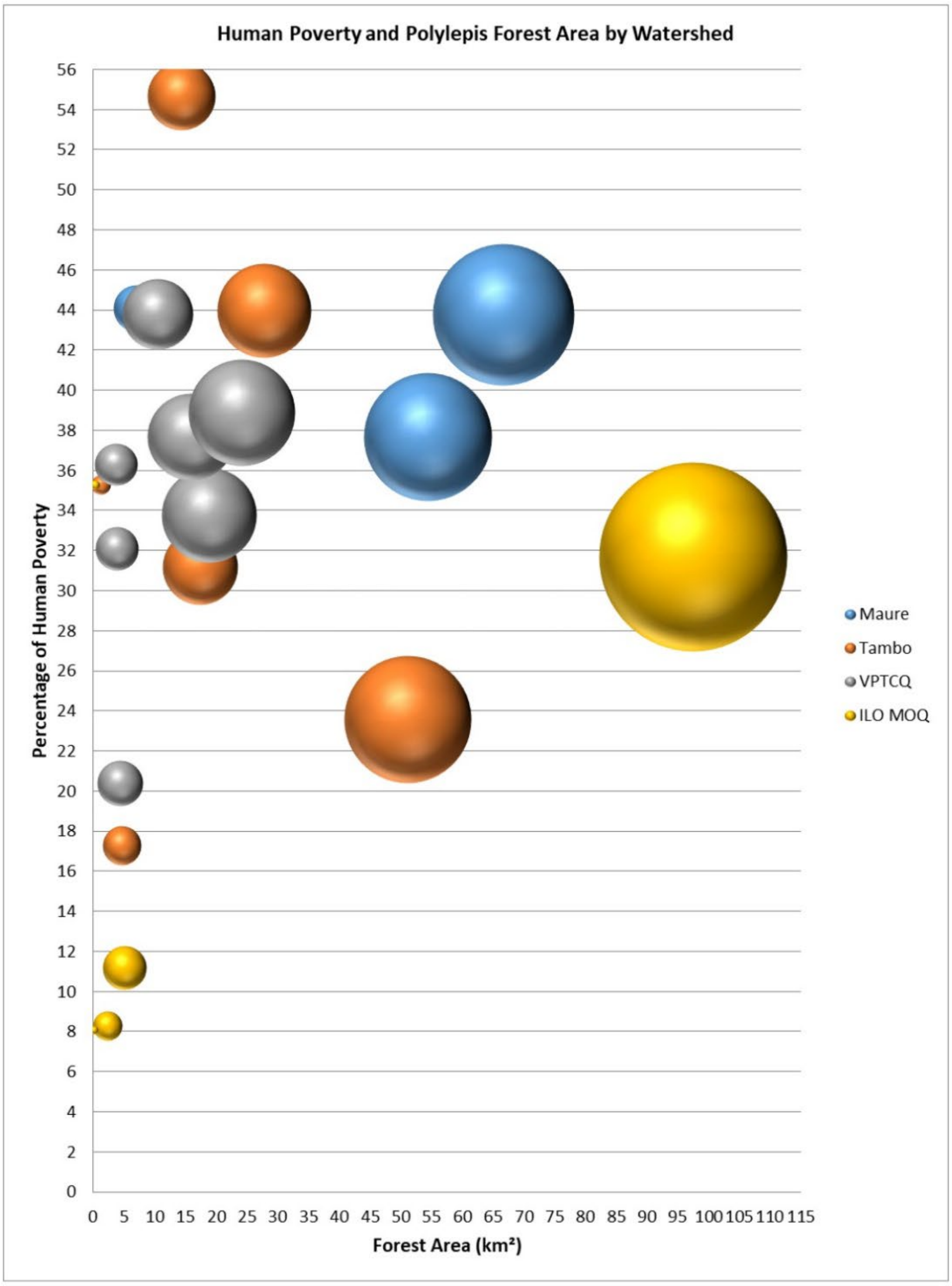

Figure 9. Distribution of the Polylepis forest according to the percentage of poverty in the evaluated areas, where the radii of the colored bubbles represent the area (km^2) of the Polylepis forest.

4. Discussion

At a global level, fragmentation is associated with processes that generate a negative impact on the natural vegetation cover and severe modifications in the structure of the landscape since it separates ecological units that have functioned efficiently for years and that become increasingly smaller and isolated with the transformation of their shape, edge, and areas (Fahrig, 2003; McGarigal and Cushman, 2002; Navarro *et al.,* 2021; Rodríguez-Etcheverry and Leiton, 2021; Shooshtari *et al,* 2018). The effects on ecosystems are adverse by endangering the normal development of the matter and energy flow, hydrological regimes, ecological processes, and abundant resources, among others (Uezu *et al.,* 2005; Kattan and Murcia, 2003). At the Latin American level, several researchers in native, dry, or tropical forests (Strap *et al.,* 2012; Lozano *et al.,* 2011; Mas and Correa, 2000) agree on the negative impact that fragmentation has had on their studied landscapes. However, fragmentation is an intrinsic condition for

Polylepis forests, also known as a relict, due to their natural dispersal (Simpson, 1979; Gareca *et al.,* 2010). Indeed, this will not be the same level for all *Polylepis* species and their corresponding forest formations. Where greater climatic and ecological stability have been generated over long periods, endemic and highly specialized species have developed, such as birds (Fjeldsa *et al.,* 2012).

Previous studies have considered these forests in Peru as a relict since, in most cases, the sizes of their fragments reach 0.02-0.03 km^2. Only in the central zone of Peru do they reach 0.5 km^2 (Simpson, 1986). The PSSD indicates that, in this part of the Peruvian territory, in the extreme south, bordering Chile and Bolivia, the smallest fragments are found, corresponding to the basins of the Pacific slope of Tacna. VPTCQ has a size of 261 m^2, the Maure basin 378 m^2, Tambo 478 m^2, and Ilo Moquegua 556 m^2. It is important to note that topographic relief plays a fundamental role in this type of distribution.

Despite the size of the forest fragments, each area evaluated has an essential and particular composition of birds that, as demonstrated by the statistical analysis, is influenced by forest fragmentation, especially by the eight indices presented in Table 3. Santos and Telleria (2006) also consider four fundamental factors in determining, calculating, or representing the fragmentation of natural ecosystems: MPS, NumP, ED, and TE. They also consider CA or class area, but this index has been removed from our analysis because the research has been based on evaluating a single vegetation class, the *Polylepis* forest.

This agrees with what was described by Valente and Betts (2019), who concluded that the composition of bird communities changes with a smaller fragment size. However, it cannot be generalized for the entire *Polylepis* forest analyzed. There are three marked compositions of birds in the four areas evaluated. The first is the forest area of the Ilo Moquegua basin and the VPTCQ basins, influenced by the shape indices of the fragments, representing regularity and complexity. The second composition is found in the forest of the Maure basin, influenced by the density indices of the fragments and partially by the edge indices. A third composition of birds is observed in the Tambo basin, influenced by size and shape indicators and moderately by edge indicators. For this reason, the forests of the extreme south of Peru are very particular, and their bird composition is based on the size of the fragments and the shape and edges.

These latter researchers recommend as a priority conserving the large forest fragments, which, applied to this study, should be those corresponding to the Tambo Ilo and Moquegua basins, as indicated in Figure 2. However, small and complex fragments, such as those of VPTCQ, should also be prioritized with conservation measures due to their particular ornithological composition or endemism (Fjeldsa, 2002; Renison *et al.,* 2018). The aim is to make its importance visible and improve its conservation level, as Sevillano et al. (2019) presented.

Therefore, it is essential to link geographical and statistical knowledge with the conservation of the biodiversity of the *Polylepis* forest in the extreme south of Peru. It is worrying that these forests are minimally represented within the Peruvian conservation system and that they contribute minimal territorial area to the total managed as protected natural areas (17%) and to the fulfillment of Aichi goal 11 by 2030, represented mainly by Amazon ecoregions (SERNANP, s.f.). As shown in Figure 5, the only two protected areas in our study area need to be increased. They are territorially isolated, not ecologically connected, and poorly articulated administratively, which would not guarantee efficient and effective conservation (Chassé *et al.,* 2021; Wiersma and Nudds, 2009). Furthermore, there is always the risk that anthropogenic activity can generate profound and irreversible impacts, for example, by constructing roads or highways that can increase their fragmentation and generate a biodiversity crisis (Rosselló and Lorenzo, 2017).

The need to implement innovative conservation management for the *Polylepis* forest is evident, with territorial connectivity between its areas through conservation corridors under different modalities (SERNANP, 2013), with different administrators, and with the political decision of its departmental authorities. The Regional Governments have not yet taken any decision or action in this regard despite having technical files of the priority sites for conservation that were prepared between 2011 and 2013 (Fig. 7). This could increase the conserved area by more than 40% and implement a decentralized, efficient, transparent, and sustainable conservation system (Azfar *et al.,* 2009).

Likewise, fragmentation must become a binding indicator in the management of *Polylepis* forests, which allows for regulating the environmental impact generated by constructing too linear or straight infrastructures. This modifies the MSI and other shape indices, causing the fragments to become more regular and harming biodiversity. Likewise, in forest areas where the composition of birds is primarily influenced by the size of the fragments, as is the case of the forest of the Tambo and Ilo and Moquegua basins, any work or infrastructure to be built must establish connectivity mechanisms to avoid ecological separation of the fragments and maintain their functioning as a single unit (Grilo *et al.,* 2011; Ministry of Agriculture, Food and Environment, 2015; Ministry of Environment and Rural and Marine Affairs, 2010). In short, these approaches establish essential ideas for the environmental management assumed by the Peruvian State and which are included in the current national legislation that regulates the evaluation of environmental impact based on qualitative study methods and which refer to fragmentation using as an indicator tangible the number of fragments or NumP (MINAM, 2011) and ignoring the other relevant indicators.

Paradoxically, in recent times, when essential territories are proposed to be declared protected areas, it is still a widespread practice to exclude areas under concession for mining and oil activities (with very linear forms) to avoid dialogue, authorizations, and consents between the sectors of the State. As a result, there are protected areas of linear polygons, very regular and with minimum sizes that, at first glance, could be more useful for adequate conservation management (Andrade, 2007). It is therefore necessary to change focus and adopt new concepts such as sustainable mining or productive extractive activities linked to conservation (ECLAC, 2019). It is also essential to question the technical information used to delimit current protected areas, such as the National Maps of Vegetation Cover and Ecosystems of Peru (MINAM, 2018; MINAM, 2015), which are not suitable for management at specific scales (Norgués, 2013).

Fragmentation not only limits forest conservation. The high poverty of the human populations that inhabit them (Fig. 7 and 8) also makes conservation options difficult (Fisher *et al.,* 2005). Therefore, Opportunities are required to develop their livelihoods and to transform the *Polylepis* forest into an effective tool for sustainable development, promoting close coordination between the multiple actors in the territory (Table 4). It is about achieving and replicating successful experiences (Álvarez and Shany, 2012; Amaya, 2020; Hernández *et al.,* 2018; Rivera *et al.,* 2008) through effective conservation mechanisms based on economic benefits, fragmentation, biodiversity, and ecosystem services. (Andrade, 2020, Secretariat of the Convention on Biological Diversity, 2004) with development opportunities for all public and private actors.

Therefore, within these innovative mechanisms, the establishment of modalities for using and conserving forest resources through concessions stands out (Law No. 29763, 2011). These will improve the forest conservation area and boost socio-economic development in the Andes and the Puna (Bergmann *et al.,* 2021; Saravia and Aguirre, 2019). However, some erroneous paradigms still need to allow us to understand the multifunctionality of forest heritage (Macdicken *et al.,* 2015). Forest zoning (ZF) is detained in the offices of the regional governments of the two departments. With it, it is still possible to grant forestry, conservation, ecotourism, and local municipal administration forest titles, among others. Likewise, the regional processes of identification and recognition of fragile ecosystems - other methods of ecosystem management that would help conserve the *Polylepis* forests of the extreme south of Peru - still need to be completed, paralyzed, or slowly managed.

5. Conclusions

The *Polylepis* forests in the departments of Moquegua and Tacna are essential to supporting the water stress of its six hydrographic basins caused by extreme climatic and geographical conditions. Although close to each other, the different areas of the forest present unequal fragmentation and avian composition. Inadequate conservation planning and management, added to extreme human poverty, are the main limitations that expose these forests to different pressures, threats, and permanent risks.

To guarantee forest conservation, increasing the surface area of protected areas is necessary, breaking with some erroneous paradigms that limit sustainable development and promoting new concepts and innovations that balance economic development and people's quality of life. In Chile, they achieved this by integrating betting activities into a healthy and protected natural environment. They built knowledge, concepts, and legal, technological, and social tools aimed at developing, for example, sustainable mining, achieving an articulated work of all productive sectors in favor of conservation.

In Peru, urgent regulatory changes and inter-institutional actions are required, but it is necessary to integrate conservation standards with mining procedures. Exploration and exploitation tasks must consider environmental management in their respective concession area. Many mining companies may oppose this because they need to gain experience in conservation. However, they can link up with specialized entities or associate with peasant communities that are already developing effective ecosystem conservation practices.

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BOOK REVIEW

José M. García-Ruiz, José Arnáez, Teodoro Lasanta, Estela Nadal-Romero, Juan Ignacio López-Moreno, 2024. *Mountain Environments: Changes and Impacts. Natural Landscapes and Human Adaptations to Diversity*. Earth and Environmental Sciences Library Series, Springer Verlag, Springer Nature Switzerland. ISBN 978-3-03-151954-3, 978-3-03-151955-0. https://doi.org/10.1007/978-3-031-51955-0

Las montañas han atraído a los naturalistas desde el siglo XVIII, ya que son unos excelentes lugares para la investigación y unos completos laboratorios de campo para encontrar respuestas al funcionamiento de los sistemas naturales. En las montañas nacen los grandes ríos de la Tierra, se extienden las superficies forestales y los prados, y desde las áreas más elevadas -sin prácticamente vegetación- descienden los glaciares remodelando los relieves y asombrando a todo aquel que los contempla. En las montañas hay vigorosas fuerzas que condicionan a quienes las habitan de forma permanente, a aquellos que las han recorrido, e incluso a los que ocupan sectores más favorables de laderas medias o fondos de valle.

Los paisajes de montaña cambian con la altitud, a medida que se asciende, y cambian con la diversidad topográfica, climática y geológica. La alta energía que impone la gravedad favorece la movilidad e intensidad de los flujos de agua y sedimentos que descienden ladera abajo. Toda esta complejidad ha condicionado la ocupación humana de las montañas y ha obligado a una compleja adaptación. La montaña alberga a los últimos paisajes naturales, con predominio de sistemas abióticos y bióticos, y a unos paisajes culturales únicos consecuencia del ajuste de los humanos a un medio hostil y difícilmente domable.

La Geografía ha abordado el estudio de las montañas con importantes contribuciones, principalmente a partir del siglo XIX. Es un magnífico escenario redescubierto en el siglo XVIII al que se acercaron escaladores, exploradores y científicos en busca de aventuras y conocimiento a medida que se fue perdiendo el miedo a la montaña. El libro “Mountain Environments: Changes and Impacts. Natural Landscapes and Human Adaptations to Diversity”, escrito por un grupo de geógrafos liderados por J.M. García-Ruiz, incorpora todo lo comentado hasta ahora. Todos los autores del libro cuentan con una dilatada experiencia y han centrado sus investigaciones en las montañas desde diferentes perspectivas, pero siempre con una visión integradora de sus diferentes elementos y múltiples relaciones. Su pasión por la geografía y las montañas se pone de manifiesto en el prefacio firmado por J. M. García-Ruiz, pero también a través de todo el libro. Formando parte del personal investigador del Instituto Pirenaico de Ecología (CSIC) y de la Universidad de La Rioja, han estudiado las montañas de la península ibérica, con especial dedicación a los Pirineos, y algunas otras montañas del mundo, alcanzando una visión especial y original perseguida por los naturalistas y geógrafos que han trabajado en las montañas desde hace más de 200 años. El libro nos propone una moderna, actualizada y profunda visión sobre los ambientes de montaña, la presencia humana en estos ambientes y los cambios recientes que están dejando profundas huellas en los sistemas naturales.

Los autores abordan un amplio número de temas relacionados con la geografía de la montaña que organizan en 14 capítulos. En concreto, explican el clima, la nieve, los glaciares, la hidrología, la geomorfología, la cubierta vegetal, las actividades humanas, la organización del territorio y los usos del suelo. Finalmente, incluyen una reflexión sobre la conservación de las montañas.

El libro comienza planteando qué es una montaña. Una discusión clásica de la geografía, esbozada por numerosos autores, que anticipa la temática que nos vamos a encontrar a lo largo de las páginas del libro. Se propone una amplia y al mismo tiempo precisa definición que incluye la rugosidad del terreno, la altitud, la diversidad de climas, y los pisos de vegetación. La singularidad de los ambientes de montaña radica en la zonación altitudinal de los climas, la vegetación y los procesos geomorfológicos en algunos casos afectados por los usos del suelo. Los autores definen las montañas por dos atributos básicos y clásicos de la geoecología: la heterogeneidad y la inestabilidad. Esto ya sugiere a los lectores el enfoque de este libro.

Un segundo capítulo aborda los cambios a largo plazo -desde un punto de vista geológico y climático- que explican la génesis de las montañas y sus estructuras, así como los procesos que las han configurado y remodelado. El capítulo se centra en las formas estructurales construidas hace más de 50 millones de años y en algunos casos todavía activas y en los elementos estructurales que el clima ha modelado desde las cimas a los fondos de valle a lo largo del Cuaternario. El libro proporciona una síntesis actualizada de los principales periodos glaciares, principalmente desde el Último Máximo Glacial (LGM) y los periodos de deglaciación posteriores, un proceso no lineal, deteniéndose con especial referencia en el Dryas Antiguo y Dryas Reciente.

El tercer capítulo se centra en el descubrimiento de las montañas y su percepción cultural desde la antigüedad hasta los tiempos modernos, en un gran salto temporal que va desde considerar a las montañas como entornos marginales y hostiles a la atracción, a incluso la exaltación en el romanticismo. El capítulo dedica una extensión considerable a discutir cómo las sociedades prehistóricas se acercaron a la montaña en función de la localización de los yacimientos arqueológicos. Los autores concluyen que tanto los neandertales como *Homo sapiens* frecuentaron las montañas y aprovecharon su diversidad para establecer estrategias de caza, a pesar del esfuerzo que suponía atravesar las montañas y también a pesar de las grandes dificultades climáticas a las que se tenían que enfrentar. Se presta especial atención a las transformaciones que tuvieron lugar durante el Neolítico y la Edad de Bronce, cuando los humanos se instalaron en asentamientos permanentes desde los que trasladaban el ganado en busca de los pastos estivales en los pisos alpino y subalpino. Los siguientes apartados constituyen una aproximación cultural acerca del conocimiento geográfico de las montañas y su percepción por parte de dos estudiosos e intelectuales de épocas muy distintas: Herodoto, a partir de sus experiencias y viajes, y A. Humboldt. Es este último quien, a través de sus estudios directos sobre la montaña, expone las claves físicas y cambia los paradigmas del conocimiento de la montaña, con conceptos innovadores como la altitud, las isotermas, los cambios climáticos, los límites de las nieves perpetuas y, sobre todo, los pisos de vegetación. Se esboza una interesante discusión sobre la posible influencia de Humboldt en los naturalistas posteriores basada en los exagerados vínculos expuestos por Andrea Wulf. Sin embargo, pasa por alto la cadena de naturalistas europeos que descubrieron el mundo de las montañas a partir de los Alpes, en particular Horace Benedict de Saussurre y Ramond de Carbonniéres. Numerosos naturalistas que estudiaron las plantas, el clima o los glaciares desafiaron la perspectiva, hasta entonces oscura, de las montañas y facilitaron nuevos enfoques como los aportados por Alexander von Humboldt, descubridor de la complejidad del paisaje y de una visión integradora de la montaña, tal y como destacan los autores.

Los siguientes capítulos están dedicados a presentar las características del clima de montaña, la nieve y el hielo (incluidos los glaciares) con claridad y rigor, como corresponde a unos autores con gran experiencia en estos temas. Lo más interesante es que los autores realizan conexiones continuamente con otros aspectos de la montaña. Este planteamiento es una constante en el conjunto del libro. El capítulo del clima se centra en las principales características de las temperaturas y las precipitaciones, su organización altitudinal, el viento y el funcionamiento de los monzones tan influyentes en el clima de Asia central y oriental. Se explican también los topoclimas que son muy útiles para comprender la diversidad de las montañas. Se presentan ejemplos de todo el mundo, varios de ellos de las montañas de la península ibérica, lo que aporta una perspectiva planetaria que hace más atractivo el capítulo. Todo el texto dedicado a la nieve es muy completo e innovador, resaltando las relaciones entre la nieve, el clima, la hidrología, los procesos geomorfológicos, el impacto en los ecosistemas, así como los efectos del bosque en la acumulación y el deshielo de la nieve. Se trata de un capítulo muy sintético que muestra también los métodos y técnicas de medición, así como los riesgos asociados a la nieve.

El capítulo 7 está enfocado al estudio del hielo y los glaciares. Quizás estos últimos son los principales atractivos para aquellos que se acercan por primera vez a la alta montaña. Se expone la extensión y distribución de los glaciares de montaña, así como su importancia en los ecosistemas de la montaña y de las tierras bajas. Se incluyen también dos subcapítulos sobre la evolución de los glaciares durante el Holoceno y, especialmente, desde el final de la Pequeña Edad del Hielo. Al final del capítulo se abre otro subapartado para estudiar las características y evolución reciente del permafrost de montaña, un tema de gran interés y que no suele aparecer en otros libros sobre la geografía de las montañas. No se hace referencia, en cambio, a las contribuciones realizadas sobre el permafrost por parte de la escuela suiza de W. Haeberli.

En el capítulo 8, sobre las características de la vegetación de montaña y su organización altitudinal, los autores se centran en la existencia de adaptaciones ecofisiológicas que facilitan la supervivencia de las plantas en un ambiente cada vez más hostil hacia la cumbre; el comportamiento de las montañas como islas que favorecen la aparición de endemismos; la importancia de la acumulación y fusión de la nieve en la distribución de la vegetación; o la importancia de los bosques en las áreas de montaña, y, particularmente de las coníferas, sobre todo en la zona templada. Pero quizás el aspecto que más ha llamado la atención de los geógrafos es la organización altitudinal de los pisos de vegetación y la existencia de la gran frontera de la *treeline-timberline*.

En el capítulo 9, los autores tratan sobre los aspectos hidrológicos de las montañas, tan importantes para las tierras bajas. Tal como indicó Michelet ya en el siglo XIX, las montañas son “torres de agua” puesto que en ellas se genera gran parte de los caudales que fluyen en la Tierra. Se explica a continuación la complejidad de los regímenes fluviales, la importancia de la vegetación para explicar la evolución del caudal de algunos ríos y el papel que desempeñan los embalses en el régimen fluvial. El capítulo finaliza con el estudio de la transferencia de sedimento por los ríos y su morfología.

Las formas de relieve y los procesos geomorfológicos son los protagonistas del capítulo 10. El punto de vista geoecológico comienza con un análisis escalar que integra factores geológicos, geomorfológicos, climáticos, biogeográficos, edáficos y de usos del suelo para explicar la distribución, el funcionamiento y la dinámica de las formas de relieve. El enfoque sobre la organización altitudinal a partir de los cambios que esta última introduce en las características de los suelos, el bosque y el hielo es correcto. Todo ello permite una organización espacial que funciona como un sistema en cascada desde las cumbres a los fondos de valle. En las partes bajas se insiste en la conexión entre actividades humanas, actuales e históricas, y procesos geomorfológicos.

Los capítulos 11 hasta el 14, con el que finaliza el libro, ocupan casi el 40% del texto, con un total de 156 páginas. En ellos los autores se centran más en los aspectos humanos de las montañas y en sus consecuencias ambientales. Así, el capítulo 11 es una presentación sintética de la lenta transformación de los paisajes de montaña, mediante un esfuerzo colectivo de la población rural. Este esfuerzo en muchos casos se remonta hasta el Neolítico, entremezclando funcionalidad, ética y cultura. Esto ha dado lugar a una organización muy especial de los paisajes de montaña y, en muchas ocasiones, a una estética armoniosa que favorece su estabilidad. Los autores insisten en que todavía se conoce poco acerca de la evolución de esos paisajes, y en la importancia de factores tales como la densidad demográfica, los rasgos ambientales, los acontecimientos históricos y el mercado como transformador de los usos del suelo.

El capítulo 12 es fundamental para entender la diversidad de usos del suelo en las montañas, tanto agrícolas como ganaderos. Se informa sobre la población en las montañas y sobre la teoría de la degradación ambiental del Himalaya. Este capítulo dedica una notable extensión a la agricultura de montaña, los diferentes tipos de campos, el colapso de los paisajes culturales y las repercusiones del abandono de tierras y de la emigración, las laderas aterrazadas y su evolución, con tendencias diferentes según el nivel de desarrollo de las regiones de montaña, con clara tendencia al abandono de la agricultura y ganadería y a la expansión de actividades turísticas en las de los países ricos, y superpoblación, bajos niveles de ingresos y escasez de infraestructuras en las de los países pobres. Se alude también a los diferentes patrones de la explotación ganadera y, sobre todo, a la gran importancia de los regímenes trashumantes y trasterminantes. En cambio, es más breve la referencia a otras actividades, algunas de ellas muy importantes (turismo, producción hidroeléctrica y minería), con insistencia en el papel de las montañas como reservas naturales.

El cambio global y el cambio climático son también objeto de atención en este libro en el capítulo 13, definiendo al primero como "el conjunto de cambios que introducen las actividades humanas en el funcionamiento de los sistemas naturales" y resaltando su importancia en las montañas. Los autores señalan varios factores decisivos en los cambios que ocurren actualmente en las montañas: las tendencias climáticas y la reducción de la acumulación de nieve; el retroceso de los glaciares y de los suelos helados; la evolución demográfica determinada por el grado de desarrollo de las montañas; y los consiguientes cambios de uso del suelo. Finalizan con un análisis sobre el llamado asilvestramiento o renaturalización *(rewilding)* de los ambientes abandonados, el más importante de los cuales es la homogeneización de los paisajes y sus consecuencias hidrológicas. Es un capítulo muy interesante que no podemos describir aquí más ampliamente y que debe llevar al lector a la obligada consulta de este libro.

El libro finaliza en el capítulo 14 con preguntas acerca de por qué las montañas son tan necesarias y por qué son tan especiales, indicando cuestiones muy variadas que van desde su contribución en recursos hídricos hasta la existencia de una organización social muy compleja que, allí donde todavía se mantiene, garantiza la estabilidad de laderas y de la producción intensiva, incluso en condiciones muy adversas. Los autores plantean problemas y soluciones y muestran su optimismo y, sobre todo, su admiración y emoción por los ambientes de montaña, insistiendo en que son "el mejor regalo de la Tierra" (p. 459).

El libro constituye un trabajo sólido, apoyado por una amplia bibliografía entre la que aparecen los propios autores. Los gráficos son muy expresivos y las fotografías, de las principales montañas del mundo, están ampliamente comentadas, dando lugar a un conjunto muy coherente, atractivo e interesante para el lector. Es muy notable el esfuerzo de síntesis realizado por los autores, apoyado en su conocimiento y experiencia, muy amplios en todos los casos, y su capacidad para ofrecer una perspectiva comprensiva de la geografía de las montañas. El libro es indudablemente más que un manual, abarcando una temática muy amplia que puede interesar a lectores muy variados con diferentes objetivos, ya que incluye mucha información acompañada de una gran contribución bibliográfica. El libro es un gran apoyo para geógrafos, geólogos, ambientalistas, ecólogos, sociólogos, gestores del territorio y universitarios implicados en la investigación relacionada con las montañas.

En resumen, la visión analítica e integradora de los elementos que explican la complejidad de los ambientes de montaña hace de este libro una herramienta indispensable para aquellos que se inician en su conocimiento y para aquellos más experimentados que quieran actualizar sus puntos de vista, una visión renovada de los problemas actuales que afectan a las montañas, del impacto humano sobre el medio ambiente y de las múltiples relaciones entre la humanidad y la naturaleza en las montañas de la Tierra a diferentes escalas.

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