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Research Paper

Spatially explicit modeling of the probability of land abandonment in the Spanish Pyrenees

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HIGHLIGHTS

- Spatial-explicit predictors enable high-resolution mapping of abandonment probability.
- Urban and socioeconomic development promote land abandonment.
- Tourism, population growth and accessibility drive the abandonment patterns.
- Water availability (SPEI) does not seem to influence the chance of abandonment.

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ABSTRACT

Many mountain regions in Europe have experienced massive migrations towards metropolitan areas, with far-reaching implications for societies and the environment, especially croplands and grasslands. In this work, we tailored a geospatial framework to envisage the probability of land abandonment in the Spanish Pyrenees at moderate spatial resolution. We predicted the likelihood of land abandonment combining machine learning algorithms, geospatial data and historical observations of land abandonment in the period 1980 to 2019. The model attained a high predictive performance (AUC = 0.85) at a moderate resolution (30 m), providing insights into the spatial behavior of the potential for both abandonment and its main driving forces. The highest rates of abandonment were found in rural settlements and towns in bottom valleys where tourism and recreational activities have proliferated over the years. Fast and comfortable connections between the main metropolitan areas (e.g. Barcelona and Zaragoza) and the mountain regions foster touristic activity and lead to the creation of new settlements. Ecotourism and mountain sports promote land abandonment as evidenced by the high probability predicted over the Central Pyrenees (from *Pallars Jussà* to *Alto Gállego* counties). Our results provide spatially explicit probability and uncertainty outputs, providing insights into site-specific abandonment potential and the influence of its drivers. These results can substantially assist land planners in decision-making, enabling assessments at local scale.

1. Introduction

Land abandonment is globally pervasive, though it occurs preferably in developed countries (Beilin et al., 2014). Industrialization and the resulting “rural exodus” that took place during the 20th century fostered changes in land use, promoting the abandonment of low-income agricultural lands (Pereira et al., 2010; Stoate et al., 2009) in what has been, to date, the largest land cover and use transformation over Europe (Estel et al., 2015; Lasanta et al., 2017; Terres et al., 2015). Vast areas of natural and semi-natural pastures in mountain systems in Europe were particularly prone to land abandonment (Gartzia et al., 2014; Gellrich and Zimmermann, 2007; Lasanta et al., 2017; MacDonald et al., 2000). These grassland-type communities are in fact cultural landscapes resulting from long-term human intervention (Dieterich and Van Der Straaten, 2004), maintained over centuries by extensive livestock grazing. They hold intrinsic natural and aesthetic features (Prados, 2008) and provide valued recreational, environmental and cultural services and goods (Serra et al., 2014). In the particular case of the

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Pyrenees massif, there is strong evidence of landscape and environmental degradation after land abandonment, including soil degradation, increased fire risk and reduction of river flows (Ameztegui et al., 2021, 2010; Cervera et al., 2019; Lasanta et al., 2017; Lasanta and Vicente-Serrano, 2007; Mottet et al., 2006; Nadal-Romero et al., 2011; Perpiña et al., 2020; Poyatos et al., 2003; Vacquie et al., 2015; Vidal-Macua et al., 2018).

Land abandonment fosters multiple impacts at different spatial and temporal scales. Woody encroachment, the advance of forest lands over former pastures and croplands, is perhaps the preeminent consequence in the Pyrenees (Gartzia et al., 2014) and is the main driver behind the upward displacements of the treeline. The treeline since the 1950′s has moved upwards approximately 40 m.a.s.l. from 2,111 m.a.s.a.l. (Ameztegui et al., 2016). The colonization by woody communities is often linked to ecological degradation and loss of biodiversity, both in terms of species richness and functional diversity (Jongman, 2002). Landscape features such as connectivity, patch size and patch diversity are also altered by land abandonment, triggering an important cultural heritage loss and diminishing its aesthetic properties (Ameztegui et al., 2021; Schirpke et al., 2019). Moreover, forest progression boosts wildfire hazard (increasing fire intensity and spread potential) by enabling fuel accumulation and intruding in the traditional mosaic of vegetation patches intermingling with croplands that was once a distinctive trait of the Mediterranean mountains (Pais et al., 2020). Soil erosion is boosted in lands where vegetation does not re-colonize abandoned plots; under extreme rainfall events, this process may accelerate soil degradation, losing organic matter content in the top-soil horizons (García-Ruiz and Lana-Renault, 2011).

Several endogenous (site-specific features) and exogenous drivers (socioeconomic and political context) are behind the abandonment of agricultural lands in the European mountainous areas (Lasanta et al., 2017; Terres et al., 2015). The low economic revenue of traditional agriculture due to poor mechanization potential, linked to the lack of subsidies for rainfed crops, promoted the consolidation of irrigated lands away from mountains (Nainggolan et al., 2012; van Leeuwen et al., 2019). The low income obtained by the primary sector triggered cascading effects like the rise of tourism and the subsequent development of second residential housing (Serra et al., 2014). This process was more noticeable in the vicinity of National Parks or Natural Protected areas (NPAs), giving rise to the term "*Naturbanization*" (Prados, 2008) which refers to the urbanization of rural and natural areas as second homes for leisure activities in the environment (hiking or winter sports, among others).

To date, there is extensive knowledge of the processes and factors favoring land abandonment, as evidenced by the numerous studies cited so far. Nonetheless, the process itself holds an intrinsic spatial nature, being often difficult to foresee it with the necessary spatial accuracy to adopt suitable measures to prevent or reverse its impacts. The existing research focused heavily on unravelling the role of the drivers (Corbelle-Rico et al., 2012; Garbarino et al., 2020; Vidal-Macua et al., 2018), but previous analyses providing a spatial representation of the phenomenon are scarce (Morán-Ordóñez et al., 2011); especially those conducted at a resolution sufficient to enable decision-making. The implementation of management initiatives to prevent and restore abandonment effects often takes place at the very local level (e.g., concentration of land ownership) but couples necessarily to region-wide initiatives (e.g., subsidize plans), thus requiring a spatial accuracy that enables assessments at multiple scales.

In this research, we analyzed the relationships of the factors from a regional perspective, obtaining a relative importance of each factor on the probability of land abandonment. Therefore, the greater or lesser presence of each factor can be associated with differences in the intensity of the phenomenon at the local level. Based on the existing literature that analyzes the drivers of land abandonment in other mountain regions in Europe, or in smaller areas of the Pyrenees, we hypothesized that socioeconomic drivers would be the main responsible of recent land abandonment. Moreover, touristic development is often negatively associated with traditional farming and livestock breeding, so we expected those variables related to tourism would be particularly important. Lastly, given that socioeconomic processes are not totally independent from topography and relief, variables such as elevation and aspect are also likely to play an important role in land abandonment. The method was calibrated and validated in the Pyrenees, one of the major remaining hot spots of natural and semi-natural grasslands in Europe (Ali et al., 2016). Our results can guide managers and decision-makers to explore and design preventive measures related to economic

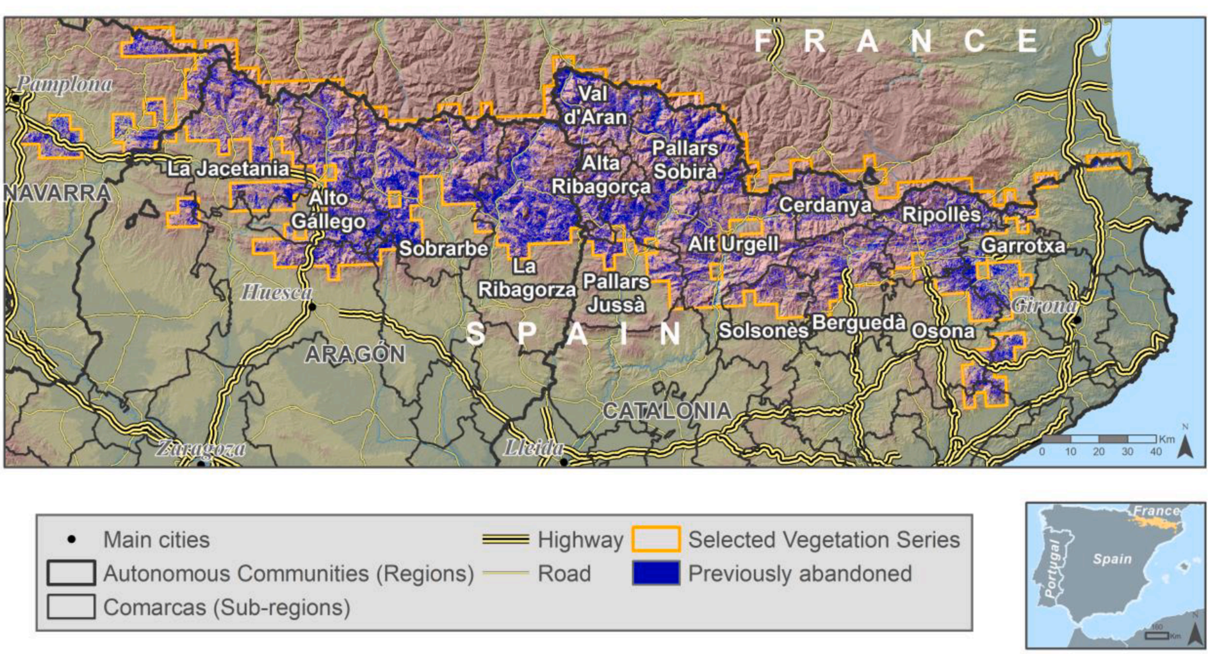

Fig. 1. Location of the study area and boundaries of the analysis. Previously abandoned areas (Gelabert et al., 2021) were highlighted in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

diversification and rural depopulation reduction, in order to preserve these valuable microenvironments and the cultural landscapes they are immersed in.

2. Materials and methods

2.1. Study area

The Pyrenees are a mountain range located northeast of the Iberian Peninsula, a natural border between Spain and France. Climate is characterized by an altitudinal gradient (elevation ranges from 600 m to 3000 m), fostering increasing rainfall and decreasing temperatures as elevation is gained. The average annual precipitation stands around 1500 mm, equally distributed throughout the year, though it is slightly lower during the summer. Temperature in winter is cold (0–5 °C), mild during the summer season (10–12 °C). However, temperature peaks at W-E ends of the mountain range due to the sea influence and the lower elevations.

The elevation gradient governs land cover distribution and types, but the current treeline position (2,200–2,400 m.a.s.l.) and structure, the subalpine and montane pastures, and the predominance of a few tree species arise from historical landscape transformations (Ninot et al., 2007). The **basal** belt (600–900 m.a.s.l.) is dominated by sclerophyllous forests of *Quercus ilex* mixed with serial xerophilous garigues and shrubs (*Rosmarinus, Cistus*). The **submontane** belt (with upper limit at 1100–1300 m.a.s.l.) holds Submediterranean forests of marcescent oaks (*Q. pubescens, Q. faginea*) and pines (*Pinus nigra* or *P. sylvestris*). The **montane** belt (reaching 1,600 m.a.s.l.) is dominated by *Fagus sylvatica and Abies alba* in the humid sites, and by *Pinus sylvestris* in the Eastern, more Mediterranean regions. Above 1600 m.a.s.l., the main tree species is *Pinus uncinata,* which constitutes the treeline in most of the massif. The treeline position lies at 2,200–2,400 m.a.s.l., well below its climatic potential due to centuries of intense human activity, and the **subalpine** belt holds natural and managed grasslands/pastures (García Ruiz and Lasanta, 2018) produced by the "alpinization" of the *Pinus uncinata* forests. The **alpine** belt (up to 2,800 m.a.s.l.) is dominated by short grassland communities (e.g., *Oxytropido-Elynetum* pastures*, Hieracio-Festucetum supinae*, *Leontodonto-Caricetum curvulae, Festuca eskia, Festuca gautieri* grasslands), noteworthy in specific habitats for their species richness or the presence of endemic plants.

Forestry and agriculture shaped the region into cultural landscape mosaics, especially in the 600–1,600 m.a.s.l. altitudinal range. Historically, the primary sector was the economic "engine" of the Pyrenees, with cereal growing (wheat, vetch, barley, or oats) and livestock farming as main activities. Nowadays, herbaceous crops (swath meadow) devoted to forage production have replaced the cereal crops, and agriculture is being either abandoned or replaced by tertiary activities (tourism) linked to mountain sports (ski, hiking, etc.), promoting camping accommodations and second residences (Lasanta et al., 2013, 2007).

The study was framed in the Spanish Pyrenees side, encompassing the potential forest region as outlined by Rivas-Martinez (1987). We selected open areas (pastures, grasslands and croplands) that due to its bioclimatic conditions are suitable to hold forests, in the range between 600 and 2,400 m.a.s.l. (Fig. 1).

2.2. Methods

2.2.1. Response variable

Predicting the probability of land abandonment required a binary response variable observing the occurrence (1) or the absence (0) of past abandonment. Candidate locations comprised either abandoned locations that were formerly dominated by grasslands or crops now forested with a coverage greater than 50% in areas bigger than 1 ha (coded as 1) or non-abandoned grassland communities or crops that persisted over time also in areas bigger than 1 ha (coded as 0). The site selection was carried out by visual inspection of an ortophotographic series, using a regular 5x5km grid to stratify the sampling process. We collected all detectable sites under the aforementioned considerations and a balanced sample in number of abandoned plots. Candidate sites were subsequently converted into single point locations. In non-abandoned locations we used the centroid of the plot polygon. In abandoned plots the point was placed in the region with higher evidence of vegetation succession (Please see an example in Supplementary Fig. 1). We were able to identify a set of 477 "ground truth" locations composed of 250 non-abandoned sites (0) and 227 abandoned (1) at some point in the period 1982–2018. These samples have an average nearest neighbor distance of 2.85 km. We used all the available ortophotographies served by the Spanish Geographic Institute (IGN) from the PNOA (2019), OLISAT (1997/1998), and SIGPAC (1997/2003) programs (see Table 1 for further information).

Table 1
Description of the ortophotographies used to construct the response variable.

Extent	Server	Project/ Program	Scale	Resolution	Year
Spain	IGN	PNOA	1:15,000	0.25 m	2017–2019
Spain	IGN	OLISAT	1:30,000	0.50 m	1997 & 1999
Spain	IGN	SIGPAC	1:40,000	0.50 m	1997, 2002 & 2003
Catalonia	ICGC	–	1:5,000	0.50 m	1988
Navarra	IDENA	–	1:5,000	0.50 m	1982

2.3. Explanatory variables

The literature recognizes three main types of drivers of land abandonment: **ecological constraints**, such as topography or edaphology and climate, **socioeconomic drivers**, e.g. demographic variations, accessibility to markets and policies, and **land mismanagement**, e.g. overexploitation, floods or water contamination (García-Ruiz and Lana-Renault, 2011; Lasanta et al., 2017; Rey Benayas, 2007; Rey Benayas et al., 2007; Terres et al., 2015; Ustaoglu and Collier, 2018). Land abandonment is triggered by the combination of these three types of drivers, being often prevalent the socioeconomic factors (Sluiter and de Jong, 2007).

The explanatory covariates of land abandonment were selected based on an extensive literature review (e.g. MacDonald et al. 2000; Mottet et al. 2006; Zaragozí et al. 2012; Terres et al. 2015; Lasanta et al. 2017; Vidal-Macua et al. 2018; Schirpke et al. 2019) and we favored those available at detailed spatial resolution. Spatial proxies for each driver type were created at a 30 m resolution, as a trade-off solution between processing time and capturing the spatial variability with sufficient accuracy. To pair response locations and predictors, we overlay the candidate locations to each raster layer corresponding, extracting the value of the underlying pixel.

2.3.1. Topography and relief

The shape and arrangement of the relief influence the chance of abandonment mostly in relation to land productivity. In short, the more productive the land the less prone to abandonment (Gellrich and Zimmermann, 2007). The bottom of mountain valleys is usually more productive since mechanization is feasible. Slope and aspect also affect productivity, which tends to be higher in sunny and moderate slopes areas opposed to shady and steep areas (Vidal-Macua et al., 2018). We used a digital elevation model (DEM) at 25 m of resolution, obtained from the Spanish Geographical Institute (MDT25; IGN 2015) and resampled to 30 m using bilinear interpolation, to retrieve elevation (in m.a.s.l.) and standard relief features such as slope angle (in degrees), aspect, and curvature metrics by means of the topographic position index (TPI; Weiss 2001).

2.3.2. Climate-related drivers

The potential influence of climate conditions on abandonment was explored through the temporal evolution of drought spells over the region (Arnaez et al., 2011). We used the Standardized Precipitation Evapotranspiration Index (SPEI) as calculated in the Global Drought Monitor database (Vicente-Serrano et al., 2010). SPEI was calibrated using ERA-5 reanalysis data from 1961 to 2019 (from the Copernicus Climate Change Service, C3S) and spatialized at a $\sim 100\ km^2$ resolution. SPEI is a drought-related index that synthesizes the water balance anomaly accounting for both precipitation and temperature (the latter being involved in the calculation of the potential evapotranspiration). SPEI ranges from −3 to 3, with moist conditions occurring when SPEI is above 0.84 and dry spells below −0.84 (Vicente-Serrano et al., 2010). SPEI can be calculated at different temporal scales (from 1 up to 48 months). In this work, we retrieved the 12-month anomaly for December (SPEI12) on a yearly basis. We then calculated the Sen's slope of the SPEI12 (Sen, 1968), a trend detection procedure that summarizes the direction (increase or decline), magnitude (slope absolute value) and significance of a trend in a time series of data.

2.3.3. Ecological related drivers

Ecological constraints reduce competitiveness for farmers (Arnaez et al., 2011). Soil characteristics are key in crop productivity. Therefore, the first fields to be abandoned are those with poor soil quality, shallow and stony soils (Gellrich and Zimmermann, 2007). We indirectly estimated soil porosity by using soil bulk density (cg/cm^3) in the first 15 cm from SoilGrids 2.0 – 250 m (Poggio et al., 2021).

2.3.4. Socioeconomic and human-related drivers

The process of land abandonment relates heavily to the potential for agricultural revenue and impact of recreational activities (Lasanta et al., 2017; Schirpke et al., 2019). Overall, the former acts as an anchor for agriculture and grasslands whereas the latter promotes abandonment.

Tourism is the main driving force of socioeconomic change and land transformation in the Pyrenees (Schirpke et al., 2019; Serra et al., 2014). Despite a wider tourism opportunity spectrum in recent years, ski, hiking, camping and resorts remain the predominant recreational activities (Lasanta et al., 2013, 2007). The spatial footprint of tourism was rated in terms of distance to stable tourism-related facilities, ski resorts and camping sites, as concentration points for visitors that engage in varied recreational activities (e.g., hiking). We obtained the spatial location of ski and camping sites from the 1:25.000 scale National Topographic Database (BTN25, IGN 2018). Then, we calculated the Euclidean distance (in meters) to the closest site.

Population dynamics are a key indicator of socioeconomic evolution (Collantes and Pinilla, 2004; Marín-Yaseli and Lasanta, 2003); loss of population due to either migration or aging is linked to economic decline (MacDonald et al., 2000). In turn, this promotes the abandonment of traditional agricultural activities and lands (Lasanta et al., 2017; Vidal-Macua et al., 2018). We retrieved yearly population density (inhabitats/km^2) records at municipality level in the period 1986 to 2019 from the municipal population registries ("*Padrón*") accessed through the Spanish Statistics Institute (INE). Again, we characterized population trends by synthesizing the change in the annual number of inhabitants using the Sen's Slope (Sen, 1968).

Plot structure also contribute to understand land abandonment (Renwick et al., 2013). To an extent, the size of agricultural plots relates to the productivity (Lasanta et al., 2017). Larger plots tend to attain higher productivity rates by allowing mechanization and monoculture, and they often belong to agricultural holdings with a single proprietor. Conversely, small plots are often arranged in complex mosaics, being the mechanization effort less profitable. We used plot size as a proxy for land structure and agricultural economic profitability. We calculated kernel density of polygon size (km^2) at 30 m spatial resolution, for each individual agricultural plot from the cadastral vector information (DGC, 2020).

Accessibility plays a crucial role in economic development (MacDonald et al., 2000; Terres et al., 2015). Proximity to population settlements or the road network facilitates the access to touristic infrastructures (Cervera et al., 2019; Lasanta et al., 2007), boosting the withdrawal of traditional activities and favoring the growth of the touristic and tertiary activities (Serra et al., 2014). We calculated the Euclidean distance (in meters) to roads from a set of vector layers outlining the road network (roads, paths, and forest tracks) all of them accessible by car, representing the full road network obtained from the 1:25.000 scale National Topographic Database (BTN 25,IGN 2018); Euclidean distance to villages was also obtained from the same source (BTN 25, IGN 2018).

2.4. Modeling land abandonment

We modeled the spatial distribution of land abandonment probability by means of presence-absence binomial classification models. We used Random Forest (RF), a popular non-parametric and stochastic tree-based algorithm (Breiman, 2001; Liaw and Wiener, 2002). This algorithm is sensible to correlation between variables, but in our case there were no high pair-wise correlations between variables (Supplementary Fig. 5). RF was calibrated, validated and tested using the *caret* R's package (Kuhn, 2008).

2.4.1. Model training and calibration

RF models require hyper-parameters tuning like the number of predictors to be used at each split on any given "tree" (*mtry*), the number of trees (*ntrees)* or the minimum number of observations at the end nodes (min *node size*). The split rule followed the Gini index and we used AUC as model validation metric. These parameters were optimized during the calibration stage using a 10-fold repeated cross-validation with 5 replications. To account for potential sensitivity to the locations that conform the response variable (see section 2.4) and prevent overfitting, we implemented an additional k-fold cross-validation ($k = 3$) to split the original sample into 3 training (66%) and test (33%) datasets. This procedure led to a set of 30 models that were later aggregated into a single final prediction. Each model produced an individual raster map corresponding to model predicted probabilities. The predictions were averaged as the median value of the 30 raster maps, and as a measure of uncertainty and reproducibility, the coefficient of variation was provided. Additionally, we tested for spatial autocorrelation in prediction residuals using the Moran's I index (Moran, 1950), to warrant the spatial coherence of the results.

We tested this previous calibration as a null model to account for spatial autocorrelation. We computed a semivariogram using the model residuals (Supplementary Figs. 3 & 4); the stabilization of semivariance (Range) was around 8 km. To control this effect in the model, we created a train subsample with a set minimum distance of 10 km. Additionally, to control for spatial bias in our phenomena we added coordinates X and Y to the model as explanatory variables.

2.4.2. Model testing and performance

Model performance was evaluated via the previous 3-fold (section 2.4.1) cross-validation procedure. At each step, we used test samples to estimate the predictive performance of the RF models. We calculated the area under the curve (AUC) (Hanley and McNeil, 1982) of the receiver operating characteristic (ROC), a threshold-independent measure of the goodness-of-fit of any classifier. AUC measures the relationship between the false-positive (sensitivity) and true-positive (specificity) rates. It ranges from 0.5 to 1 representing random outcome and perfect prediction, respectively. According to Zhou et al. (2011) AUC values greater than 0.7 are sufficiently accurate to trust predictions (Mandrekar, 2010).

2.4.3. Variable performance

Machine learning algorithms tend to "hide" information on how they reach predictions, largely due to the complexity of the algorithm itself.

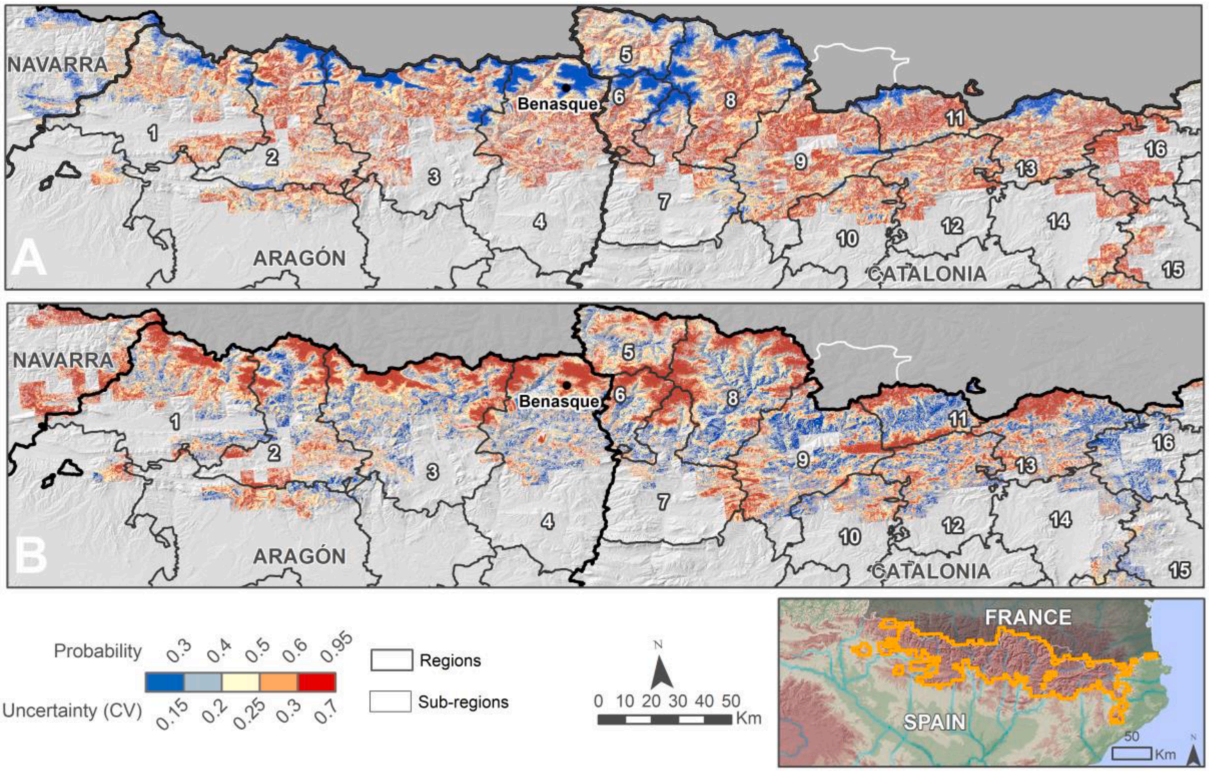

Fig. 2. Spatial distribution of land abandonment probability and uncertainty in the prediction. a) Probability of land abandonment and b) Uncertainty measured using the coefficient of variation of each of the 30 predictions. A shaded relief surface is used as backdrop. Previously abandoned areas (Gelabert et al., 2021) were masked in gray. Sub-regions labels: 1. La Jacetania, 2. Alto Gállego, 3. Sobrarbe, 4. La Ribagorza, 5. Val d'Aran, 6. Alta Ribagorça, 7. Pallars Jussà, 8. Pallars Sobirà, 9. Alt Urgell, 10. Solsonès, 11. La Cerdanya, 12. Berguedà, 13. Ripollès, 14. Osona, 15. Garrotxa, 16. Selva.

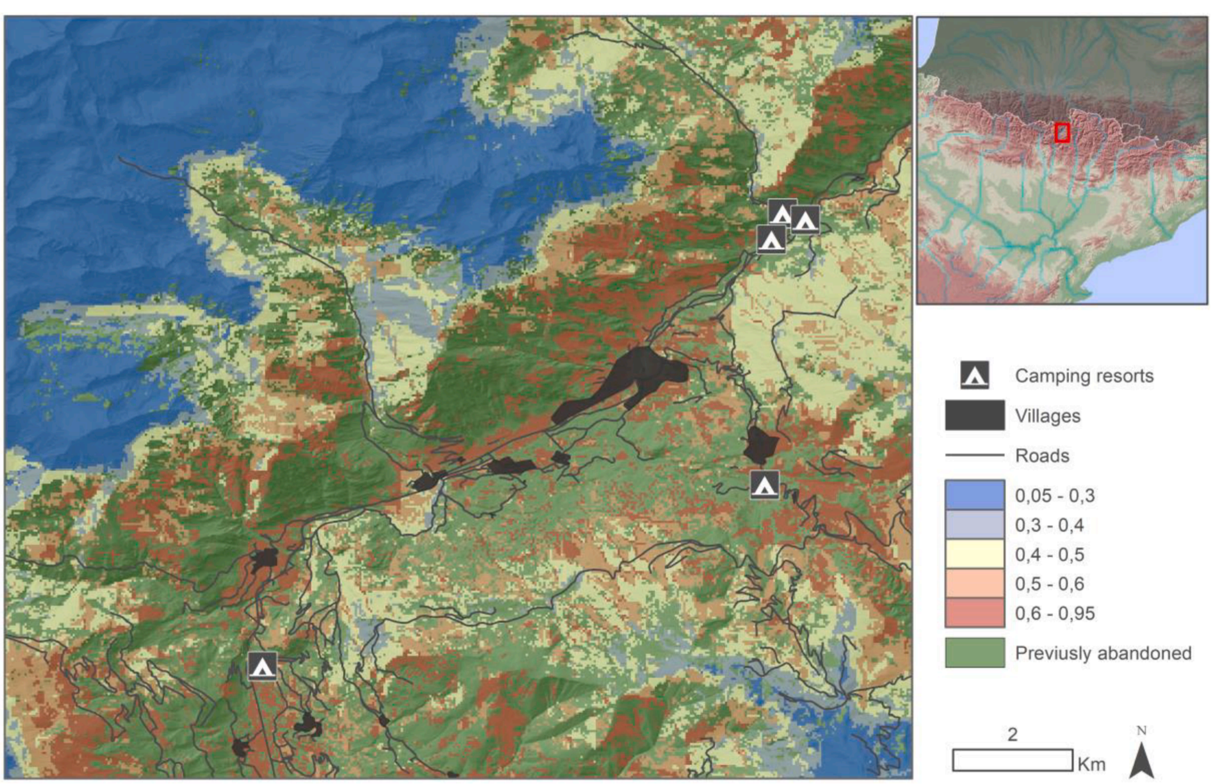

Fig. 3. Close-up view (1:100,000) of the Benasque valley. A shaded relief surface is used as backdrop.

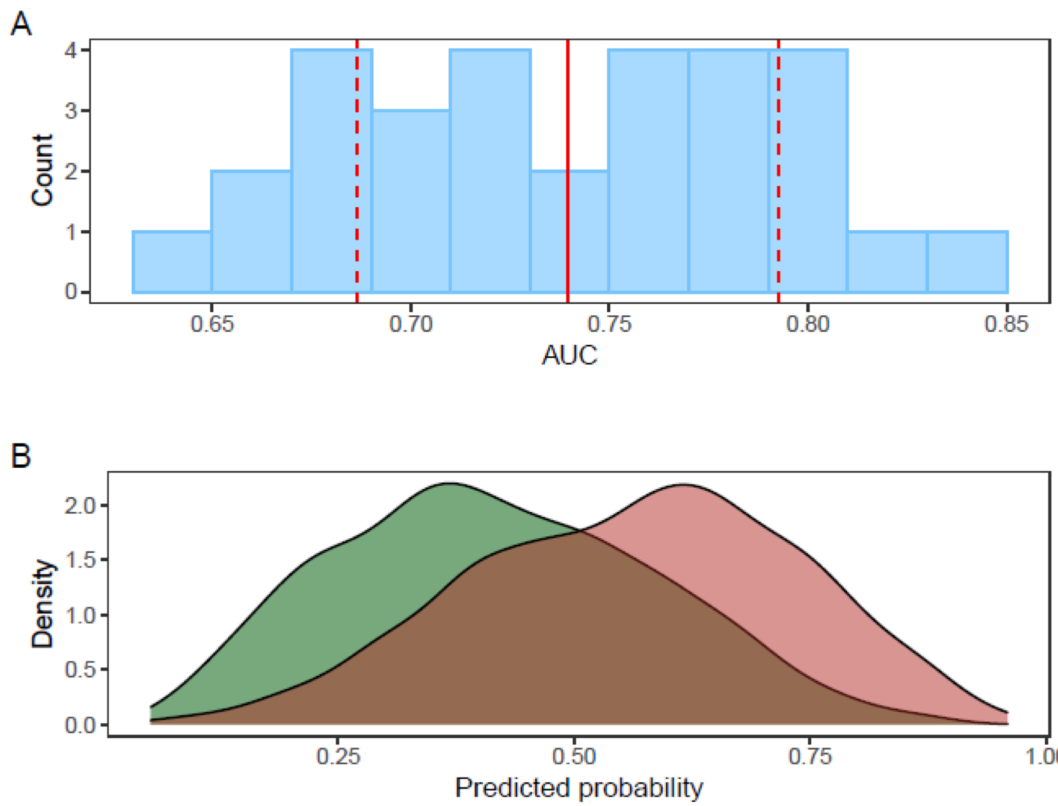

Fig. 4. A) Frequency values of AUC using RF. The solid line represents the mean AUC and dashed line ± 1 standard deviation. B) and density histograms of predicted probability classified as abandoned (red) non abandoned (green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

To deliver insights into the role of the involved covariates, we retrieved their relative importance for each model. We used the node impurity, which defines the optimal condition to split tree branches during the training process. Averaging the impurities of each predictor provides a measure of its importance to the forest and, thus, the prediction.

Moreover, we addressed the graphical representation of the explanatory sense of covariates using partial dependence plots (PDP; Friedman 2001). PDPs are a graphical way to represent the marginal effect one variable has on the machine learning model prediction. We built 2-dimensional PDPs using a LOESS function (Locally Weighted Scatterplot Smoothing), showing the marginal response of the model (y-axis) along the range of values of a given predictor (x-axis). PDPs were built using the *pdp* (Greenwell, 2017) and *ggplot2* (Wickham, 2016) packages.

3. Results

3.1. Spatial pattern of predicted land abandonment probability

The spatial distribution of abandonment probability portrayed clear differences between the eastern and western ends of the Pyrenees (Fig. 2). Abandonment was more likely in the east (Ripollès, Garrotxa, Osona and Selva counties), with many areas over the 0.8 probability threshold. This region has excellent road connectivity with the Metropolitan area of Barcelona, which has contributed to the spread of second homes and investment properties. Probability rates were consistently intermediate-high up to the central Pyrenees, roughly on the border between Aragon and Catalonia. The western half (extending from *Pallars Sobirà to La Jacetania*) was characterized by a mosaic of hot and cold probability spots. Very low probability values (below 0.3) were observed inside and around protected areas intermingling with higher probability (above 0.3) in locations specialized in rural tourism or skiing. Despite the presence of cold spots, values between 0.4 and 0.6 were predominant, with peaks above 0.6 in *Sobrarbe*, *Alto Gállego* and *Val d'Aran*. The uncertainty levels were consistently low throughout the study area, aside from some minor clusters of high variability in mountain summits and most protected areas in the central Pyrenees (Fig. 2B). A close-up view in Fig. 3 allows to best discern the effect of topography, accessibility, and proximity to touristic activities. Higher probability values were located in valley bottoms, close to cities and camping resorts. The probability of abandonment decreased with the altitudinal gradient. Furthermore, the inset view of the *Benasque* valley demonstrates the suitability of the model to address large-scale areas (1:100,000), identifying sharp transitions that enable the spatial characterization of the abandonment phenomenon.

3.2. Predictive performance of the RF models

The predictive performance of the models was satisfactory, with all RF models yielding a consistently high AUC ranging from 0.64 to 0.83 (mean AUC = 0.74, Fig. 4A). We observed a clear gap (Kruskal-Wallis test significant; $p < 0.05$) at 0.5 probability (Fig. 4B) that separates the predicted probability between abandoned and non-abandoned locations. The density plots corroborated the high contrast between categories (Fig. 4C). In non-abandoned locations, we found a frequency peak close to 0.3, after which the curve flattens. In abandoned locations probability peaked near 0.65, decreasing fast into low density values below the 0.5 threshold. Taken together, all diagnostics support the satisfactory performance of the models, thus endorsing our findings.

3.3. The role and performance of abandonment drivers

Fig. 5 ranks model covariates according to their relative importance in the predictions. Overall, distance to villages was the most influential

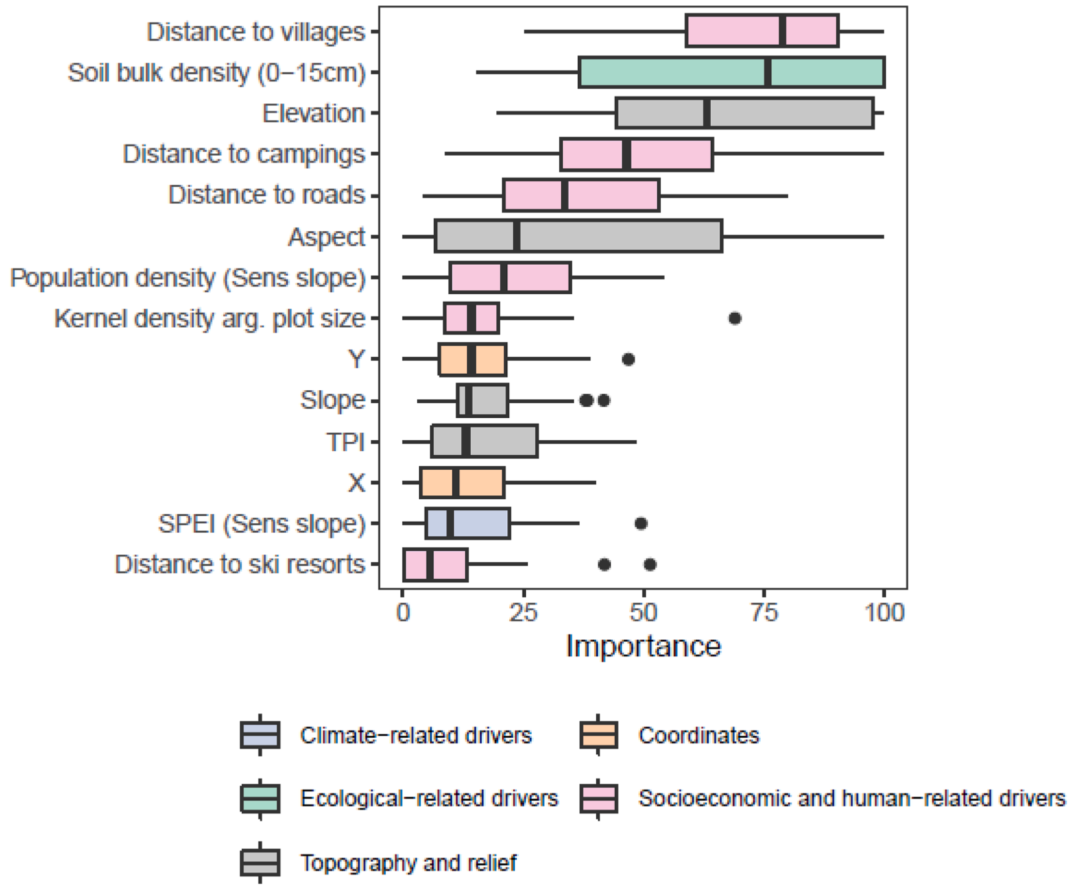

Fig. 5. Box-plots with variable performance in terms of node impurity. Boxes represent the distribution of increment in MSE across models. The boxes indicate the 1st/3rd quartiles, the whiskers indicate 10th/90th percentiles, the black line within the box is the median, and the dots indicate values below the 10th percentile or above the 90th percentile.

factor, but soil bulk density and elevation also had a strong influence on land abandonment. Distance to camping sites and roads were the main socioeconomic drivers, and exerted a considerable influence in the probability of land abandonment, especially when compared with the remaining topographic variables, which were consistently found as the least important. In a mid-tier position, we found aspect, followed closely by density population dynamics and agricultural plot size. Coordinates, slope and TPI were next in importance, and more influential than the remaining factors (SPEI, and distance to ski resorts).

Additionally, we analyzed the marginal effect in the predicted probability of abandonment of each covariate (Fig. 6). From this information, we extracted the characteristic traits of locations prone to land abandonment. The more likely locations were those (i) near to villages, (ii) in dense soils, (iii) in intermediate/high elevations (iii) with good accessibility (iv) but near to camping sites, (v) in south/east aspects (vi), where population density is increasing, (vii) preferably in large-size plots (viii) in steep slopes or (ix) bottom valleys and also (x) in zones with higher productivity (in bioclimatic terms).

4. Discussion

Land abandonment locations in the Iberian Pyrenees in 1982–2018 shared common characteristics that allowed to identify future areas likely to be affected by this environmental impact (Lasanta et al., 2017; Rey Benayas, 2007).

Previous work on the abandonment process and the role played by its drivers is relatively abundant in the literature. From a methodological standpoint, our analysis aligns with the work by Vidal-Macua et al. (2018) in the Pyrenees, Garbarino et al. (2020) in the Alps and Apennines, or Morán-Ordóñez et al. (2011) in *the Cantabrian mountains* (northwest Spain), relying on statistical or machine learning algorithms to model the probability of land abandonment from a set of driving factors. Our modeling results stand equal or above these works in terms of performance and in agreement with the overall behavior of the drivers.

One critical difference with previous studies laid in our use of continuous variables (as opposed to discrete in a spatial sense), allowing for mapping. The use of variables aggregated using administrative units provided explanatory insights to these authors, but precluded the detailed mapping of model outcomes (Thieken et al., 2006; Zandbergen and Ignizio, 2010). Excepting the study by Morán-Ordóñez et al. (2011), their focus was usually in the performance of the model or the explanatory significance of the drivers, but neither the spatial nature of the phenomena nor the spatial footprint of abandonment potential was fully addressed. As Morán-Ordóñez et al. (2011), we do supply spatial predictions. In fact, our outcomes in the Pyrenees complement and support their discoveries in *Cantabrian mountains*. We found that land abandonment in the Pyrenees not only was driven by similar factors but also depicted a similar spatial pattern. This suggests the existence of homogeneous causal relations for land abandonment in the northern Iberian Peninsula.

In the specific case of the Spanish Pyrenees, abandonment started in the early 2oth century (García-Ruiz et al., 2015) as a consequence of the industrialization process. During the second half of the century, the rural migrations towards main industrial cities and land abandonment reached their peak. Nowadays, the abandonment in the Pyrenees continues, though at a slower pace. The process is now linked to the raise of tertiary activities, mainly tourism and second residences in mountain

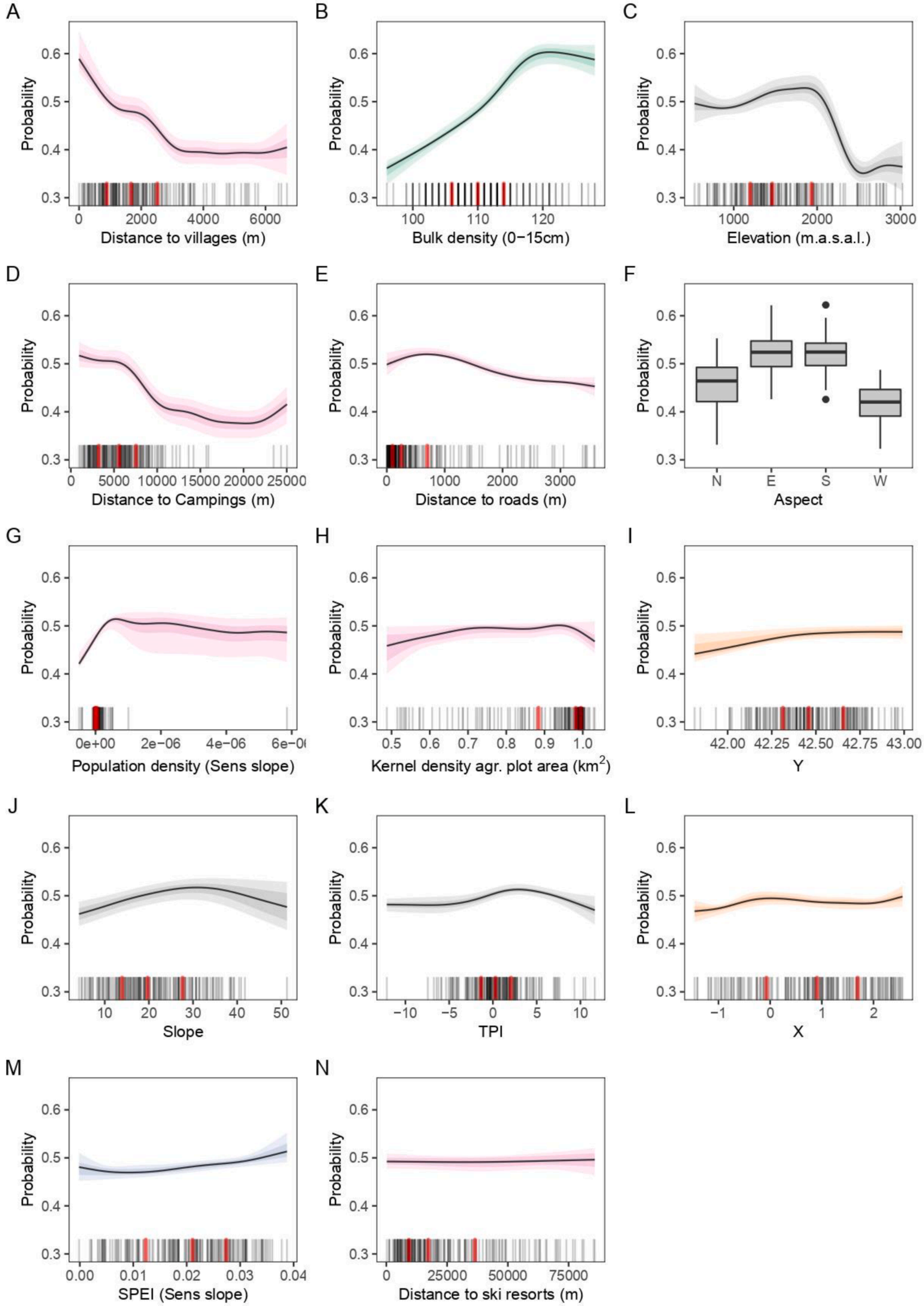

Fig. 6. Partial dependence plots of (A) distance to ski resorts, (B) distance to camping resorts, (C) distance to villages, (D) distance to roads, (E) Sen's slope statistic for population variation, (F) Plot structure, (G) Aspect, (H) Slope, (I) TPI, and (J) Elevation, and (K) Sen's slope statistic for SPEI variation. The x-axis represents the value of the covariate, and the y-axis represents the associated predicted probability. The solid line represents the averaged dependence whereas dark and light shaded areas represent 1st to 3rd quartile range and minimum and maximum range, respectively. Color represents driver domains: grey, physiography; pink, socioeconomic; and blue climate; green, ecological; orange, coordinates. The density of presence events is represented by vertical black lines above the x-axes, and overlaid red ticks depict the quartiles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

regions (Prados, 2008; Serra et al., 2014). Tourism is thus the main element promoting socioeconomic change in the Pyrenees in recent decades (Lasanta and Vicente-Serrano, 2007). Primary activities, such as agriculture and livestock farming, have been abandoned in favor of activities linked to tourist facilities, or at least complemented with part-time dedication to tertiary activities aimed to provide an outflow of agricultural products with greater added value (Cánoves et al., 2004; Petrou et al., 2007; Vidal-Macua et al., 2018). In addition, side effects from the Common Agricultural Policy (Cazcarro et al., 2015) and other subsidies funded by the European Union such as the LEADER program – aimed at stabilizing and promoting repopulation – and INTERREG – designated to fund transnational initiatives – ended up in investments that favored the development of tertiary activities (Lasanta and Marín-Yaseli, 2007).

While in agreement with these drivers and causal relations, we found strong regional and local differences in the potential for land abandonment within the Pyrenees. The observed spatial pattern responds to site-specific combinations of certain drivers operating at different levels. The higher land abandonment potential occurs in the eastern end of the massif, in the sub-regions of *Osona, Garrotxa, Ripollès, Cerdanya* and the north of *Berguedà,* all of them belonging to Catalonia (Badía et al., 2004; Vilà-Cabrera et al., 2017). We believe this cluster responds to the growth of second residential housing encouraged by good accessibility (Fig. 6 A & E). Their relative position to the main road network (*C-17* and *C-16* speedways) connecting with the metropolitan area of Barcelona (the largest in the region) has favored the sprawl of leisure housing and other forms of accommodation, such as campings and hotels (Fig. 6D). In Aragon, a similar pattern is observed along the corridors around the *A-23, A-21* and *N-350*, *N-240* roads, all of them linking with Zaragoza. A different role is played by type of road, with high abandonment rates in locations connected to main roads (Vidal-Macua et al., 2018), but low around secondary and local roads (Fig. 6E). The presence of skiing and winter sports exerted a contrasting influence associated to local conditions. Lasanta, Beltran, and Vaccaro (2013) noted that ski resorts in Aragon are close to villages whereas in Catalonia they locate farther away. Accordingly, the predicted probability of abandonment near ski facilities is higher in Aragon than in Catalonia, suggesting that the ski resorts do not foster abandonment by themselves (Fig. 6 N) but rather for their complementary recreational offer to villages and towns. The behavior of population dynamics further evidenced that regions experiencing increased number of inhabitants were more prone to abandonment and vice versa. In other words, regions with greater tourism tradition – L*a Jacetania, Alto Gállego, Sobrarbe, Pallars Sobirà and Val d'Aran* – grew due to opportunities derived from the touristic activity abandoning primary activities (Fig. 6G) (García-Ruiz et al., 2015). In this line, LEADER and other programs fund actions in the tourism sector (rural tourism modalities and ecotourism) to anchor population (Lasanta and Marín-Yaseli, 2007). Our findings support that the growth in population and accessibility by road related to the development of tourist resorts increases the probability of land abandonment (Cervera et al., 2019; Lange et al., 2013). Likewise, the increasing number of inhabitants –and housing- is often associated to new job opportunities in the service sector (Ameztegui et al., 2010; Gellrich and Zimmermann, 2007; Lasanta et al., 2017, 2013, 2007; MacDonald et al., 2000).

Topographical features operate on a local level. The complex reliefs of mountainous areas for mechanization, coupled with the low mobility of an aged population, demote economic competitiveness (Corbelle-Rico et al., 2012; García-Ruiz and Lana-Renault, 2011; Lasanta et al., 2017; MacDonald et al., 2000; Terres et al., 2015). The chance of abandonment increases as we gain elevation reaching the maximum around 2000 m (Ameztegui et al., 2010). Also, abandonment seems to be more likely on south and east facing steep slopes which attain higher productivity potential (Fig. 6F&J) and in bottom valleys (Fig. 6 K). In Pyrenees agricultural plots are relatively large, around 1 km^2 between 1st and 3rd percentile (0.9 and 1.1 km2). In agreement with Renwick et al. (2013), we found smaller plots more prone to abandonment than medium-size one. Nonetheless, large plots, even though not abundant, were also linked to increased chance of abandonment (Fig. 6H); probably the higher abandonment incidence in small plots is be due to their location in valley bottoms.

Finally, results from SPEI Sen's slope analysis surprisingly concluded that the abandonment is currently taking place in areas where productivity is higher (in bioclimatic terms), suggesting a greater influence of socioeconomic factors in land dynamics (Fig. 6M). Gehrig-Fasel, Guisan, and Zimmermann (2007) and Ameztegui et al. (2010) found that in the Pyrenees forest advance responds to land abandonment rather than climate. It may happen that climate change is warming mountain regions, rendering climate relationships more difficult to assess (López-Moreno et al., 2008). Soil properties also attain high importance in land abandonment probability. Fig. 6B shows that in areas where abandonment has occurred the soil bulk density is higher than in cultivated areas (Koulouri and Giourga, 2007).

Overall, we found land abandonment favors areas with an accumulation of activities, infrastructure and population related to the tourism sector. In particular, easy access to high-capacity road infrastructures, far from contributing to the fixation of rural population in the territory, favors the sprawl of touristic resorts and leisure housing eventually leading to land abandonment. Relying economically only on tourism has proven risky, whereas diversification promotes resilient economies. The recovery of traditional agricultural practices, or reinvented ones based in the introduction of new bio-economy ventures, and their integration with recreational activities and new tourism modalities is thus necessary to avert the abandonment process and to prevent ecological and cultural degradation. Rural economic development is very sensitive to economic crises and extraordinary events such as the COVID-19 outbreak (Gössling et al., 2020). Consequently, both socioeconomic diversification and control of land abandonment in our mountain landscapes are crucial. Predicting and mapping the abandonment hot spots in the Spanish Pyrenees provides a much-needed basis for implementation of land management alternatives.

5. Conclusions

The identification of strategic locations where land abandonment will be more likely in the future is critical to design effective policies to prevent and reverse the process and its associated impacts. In this work, we present an approach based on highly accurate geospatial information to map the probability of land abandonment. Our results provide spatially explicit probability and uncertainty outputs, providing insights into site-specific abandonment potential and the influence of its drivers.

Our modeling approach captures both linear and nonlinear relationships between abandonment probability and its driving forces. We found that land abandonment in the Spanish Pyrenees is more likely to occur in areas, near to villages, with high touristic activity, with good road connectivity, and in plots with dense soil bulk density. Targeting hot spots for control of land abandonment allows restoring valuable ecosystem services generated by Pyrenean cultural landscapes as well as generating more resilient economies. Our outputs allow planners to make decisions at multiple scales, from local land management plans to region-wide policy programs.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2022.104487.

References

Ali, I., Cawkwell, F., Dwyer, E., Barrett, B., & Green, S. (2016). Satellite remote sensing of grasslands: From observation to management. *Journal of Plant Ecology, 9*, 649–671. https://doi.org/10.1093/jpe/rtw005

Ameztegui, A., Brotons, L., & Coll, L. (2010). Land-use changes as major drivers of mountain pine (Pinus uncinata Ram.) expansion in the Pyrenees. *Global Ecology and Biogeography, 19*, 632–641. https://doi.org/10.1111/j.1466-8238.2010.00550.x

Ameztegui, A., Coll, L., Brotons, L., & Ninot, J. M. (2016). Land-use legacies rather than climate change are driving the recent upward shift of the mountain tree line in the Pyrenees. *Global Ecology and Biogeography, 25*, 263–273. https://doi.org/10.1111/geb.12407

Ameztegui, A., Morán-Ordóñez, A., Márquez, A., Blázquez-Casado, Á., Pla, M., Villero, D., … Coll, L. (2021). Forest expansion in mountain protected areas: Trends and consequences for the landscape. *Landscape and Urban Planning, 216*, Article 104240. https://doi.org/10.1016/j.landurbplan.2021.104240

Arnaez, J., Lasanta, T., Errea, M. P., & Ortigosa, L. (2011). Land abandonment, landscape evolution, and soil erosion in a Spanish Mediterranean mountain region: The case of Camero Viejo. *Land Degradation and Development, 22*, 537–550. https://doi.org/10.1002/ldr.1032

Badía, A., Pèlachs, A., Vera, A., Tulla, A. F., & Soriano, J. M. (2004). Cambios en los usos y cubiertas del suelo y los efectos en la vulnerabilidad en las comarcas de montaña de Cataluña. Del rol del fuego como herramienta de gestión a los incendios como amenaza. *Pirineos, 169*.

Beilin, R., Lindborg, R., Stenseke, M., Pereira, H. M., Llausàs, A., Slätmo, E., … Queiroz, C. (2014). Analysing how drivers of agricultural land abandonment affect biodiversity and cultural landscapes using case studies from Scandinavia, Iberia and Oceania. *Land Use Policy, 36*, 60–72. https://doi.org/10.1016/j.landusepol.2013.07.003

Breiman, L. (2001). Random forests. *Machine Learning, 45*, 5–32. https://doi.org/10.1201/9780429469275-8

Cánoves, G., Villarino, M., Priestley, G. K., & Blanco, A. (2004). Rural tourism in Spain: An analysis of recent evolution. *Geoforum, Themed section on "Material Geographies", 35*, 755–769. https://doi.org/10.1016/j.geoforum.2004.03.005

Cazcarro, I., Duarte, R., Martín-Retortillo, M., Pinilla, V., Serrano, A., 2015. Water scarcity and agricultural growth in Spain: from curse to blessing?, in: Natural Resources and Economic Growth.

Cervera, T., Pino, J., Marull, J., Padró, R., & Tello, E. (2019). Understanding the long-term dynamics of forest transition: From deforestation to afforestation in a Mediterranean landscape (Catalonia, 1868–2005). *Land Use Policy*. https://doi.org/10.1016/j.landusepol.2016.10.006

Collantes, F., & Pinilla, V. (2004). Extreme Depopulation in the Spanish Rural Mountain Areas: A Case Study of Aragon in the Nineteenth and Twentieth Centuries. *Rural History, 15*, 149–166. https://doi.org/10.1017/S0956793304001219

Corbelle-Rico, E., Crecente-Maseda, R., & Santé-Riveira, I. (2012). Multi-scale assessment and spatial modelling of agricultural land abandonment in a European peripheral region: Galicia (Spain), 1956–2004. *Land Use Policy, 29*, 493–501. https://doi.org/10.1016/j.landusepol.2011.08.008

DGC, 2020. Cadastral data. Inst. Nac. Estad.

Dieterich, M., & Van Der Straaten, J. (2004). *Cultural Landscapes and Land Use*. Springer.

Estel, S., Kuemmerle, T., Alcántara, C., Levers, C., Prishchepov, A., & Hostert, P. (2015). Mapping farmland abandonment and recultivation across Europe using MODIS NDVI time series. *Remote Sensing of Environment, 163*, 312–325. https://doi.org/10.1016/j.rse.2015.03.028

Friedman, J. H. (2001). Greedy function approximation: A gradient boosting machine. *Annals of Statistics, 29*, 44. https://doi.org/10.1214/aos/1013203451

Garbarino, M., Morresi, D., Urbinati, C., Malandra, F., Motta, R., Sibona, E. M., … Weisberg, P. J. (2020). Contrasting land use legacy effects on forest landscape dynamics in the Italian Alps and the Apennines. *Landscape Ecology*. https://doi.org/10.1007/s10980-020-01013-9

García Ruiz, J. M., & Lasanta, T. (2018). El Pirineo Aragonés como paisaje cultural. *Pirineos*. https://doi.org/10.3989/pirineos.2018.173005

García-Ruiz, J. M., & Lana-Renault, N. (2011). Hydrological and erosive consequences of farmland abandonment in Europe, with special reference to the Mediterranean region - A review. *Agriculture Ecosystems and Environment, 140*, 317–338. https://doi.org/10.1016/j.agee.2011.01.003

García-Ruiz, J. M., López-Moreno, J. I., Lasanta, T., Vicente-Serrano, S. M., González-Sampériz, P., Valero-Garcés, B. L., … Gómez-Villar, A. (2015). Los efectos geoecológicos del cambio global en el pirineo central español: Una revisión a distintas escalas espaciales y temporales. *Pirineos, 170*. https://doi.org/10.3989/Pirineos.2015.170005

Gartzia, M., Alados, C. L., & Pérez-Cabello, F. (2014). Assessment of the effects of biophysical and anthropogenic factors on woody plant encroachment in dense and sparse mountain grasslands based on remote sensing data. *Progress in Physical Geography: Earth and Environment, 38*, 201–217. https://doi.org/10.1177/0309133314524429

Gehrig-Fasel, J., Guisan, A., & Zimmermann, N. E. (2007). Tree line shifts in the Swiss Alps: Climate change or land abandonment? *Journal of Vegetation Science, 18*, 571–582. https://doi.org/10.1111/j.1654-1103.2007.tb02571.x

Gelabert, P. J., Rodrigues, M., de la Riva, J., Ameztegui, A., Sebastià, M. T., & Vega-Garcia, C. (2021). LandTrendr smoothed spectral profiles enhance woody encroachment monitoring. *Remote Sensing of Environment, 262*, Article 112521. https://doi.org/10.1016/j.rse.2021.112521

Gellrich, M., & Zimmermann, N. E. (2007). Investigating the regional-scale pattern of agricultural land abandonment in the Swiss mountains: A spatial statistical modelling approach. *Landscape and Urban Planning, 79*, 65–76. https://doi.org/10.1016/j.landurbplan.2006.03.004

Gössling, S., Scott, D., & Hall, C. M. (2020). Pandemics, tourism and global change: A rapid assessment of COVID-19. *Journal of Sustainable Tourism*, 1–20. https://doi.org/10.1080/09669582.2020.1758708

Greenwell, B. M. (2017). pdp: An R Package for Constructing Partial Dependence Plots. *R J., 9*, 421–436.

Hanley, J. A., & McNeil, B. J. (1982). The meaning and use of the area under a receiver operating characteristic (ROC) curve. *Radiology*. https://doi.org/10.1148/radiology.143.1.7063747

IGN, 2018. Mapas vectoriales y bases cartográficas y topográficas a escala 1:25,000 para explotación y consulta mediante sistemas de información geográfica. Inst. Geográfico Nac. Gob. Esp.

IGN, 2015. MDT25. Inst. Geográfico Nac. Gob. Esp.

Jongman, R. H. G. (2002). Homogenisation and fragmentation of the European landscape: Ecological consequences and solutions. *Landscape and Urban Planning, Fragmentation and Land Use Planning: Analysis and beyond?, 58*, 211–221. https://doi.org/10.1016/S0169-2046(01)00222-5

Koulouri, M., & Giourga, C. (2007). Land abandonment and slope gradient as key factors of soil erosion in Mediterranean terraced lands. *CATENA, 69*, 274–281. https://doi.org/10.1016/j.catena.2006.07.001

Kuhn, M. (2008). Building predictive models in R using the caret package. *Journal of Statistical Software, 28*, 1–26.

Lange, A., Piorr, A., Siebert, R., Zasada, I., 2013. Spatial differentiation of farm diversification: How rural attractiveness and vicinity to cities determine farm households' response to the CAP. Land Use Policy, Themed Issue 1-Guest Editor Romy GreinerThemed Issue 2- Guest Editor Davide Viaggi 31, 136–144. Doi: 10.1016/j.landusepol.2012.02.010.

Lasanta, T., Arnáez, J., Pascual, N., Ruiz-Flaño, P., Errea, M. P., & Lana-Renault, N. (2017). Space–time process and drivers of land abandonment in Europe. *Catena, 149*, 810–823. https://doi.org/10.1016/j.catena.2016.02.024

Lasanta, T., Beltran, O., & Vaccaro, I. (2013). Socioeconomic and territorial impact of the ski industry in the spanish pyrenees: Mountain development and leisure induced urbanization. *Pirineos, 168*, 103–128. https://doi.org/10.3989/Pirineos.2013.168006

Lasanta, T., Laguna, M., & Vicente-Serrano, S. M. (2007). Do tourism-based ski resorts contribute to the homogeneous development of the Mediterranean mountains? A case study in the Central Spanish Pyrenees. *Tourism and Management, 28*, 1326–1339. https://doi.org/10.1016/j.tourman.2007.01.003

Lasanta, T., & Marín-Yaseli, M. L. (2007). Effects of European Common Agricultural Policy and Regional Policy on the Socioeconomic Development of the Central Pyrenees, Spain. *Mountain Research and Development (MRD), 27*, 130–137. https://doi.org/10.1659/mrd.0840

Lasanta, T., & Vicente-Serrano, S. M. (2007). Cambios en la cubierta vegetal en el pirineo aragonés en los últimos 50 años. *Pirineos, 125–154*. https://doi.org/10.3989/pirineos.2007.v162.16

Liaw, A., & Wiener, M. (2002). Classification and regression by randomForest. *R News, 2*, 18–22.

López-Moreno, J. I., Goyette, S., & Beniston, M. (2008). Climate change prediction over complex areas: Spatial variability of uncertainties and predictions over the Pyrenees from a set of regional climate models. *International Journal of Climatology, 28*, 1535–1550. https://doi.org/10.1002/joc.1645

MacDonald, D., Crabtree, J. R., Wiesinger, G., Dax, T., Stamou, N., Fleury, P., … Gibon, A. (2000). Agricultural abandonment in mountain areas of Europe: Environmental consequences and policy response. *Journal of Environment Management, 59*, 47–69. https://doi.org/10.1006/jema.1999.0335

Mandrekar, J. N. (2010). Receiver Operating Characteristic Curve in Diagnostic Test Assessment. *Journal of Thoracic Oncology, 5*, 1315–1316. https://doi.org/10.1097/JTO.0b013e3181ec173d

Marín-Yaseli, M. L., & Lasanta, T. (2003). Competing for Meadows. *Mountain Research and Development (MRD), 23*, 169–176. https://doi.org/10.1659/0276-4741(2003)023[0169:CFM]2.0.CO;2

Moran, P. A. P. (1950). Notes on continuous stochastic phenomena. *Biometrika, 37*, 17–23.

Morán-Ordóñez, A., Suárez-Seoane, S., Calvo, L., & de Luis, E. (2011). Using predictive models as a spatially explicit support tool for managing cultural landscapes. *Applied Geography, 31*, 839–848. https://doi.org/10.1016/j.apgeog.2010.09.002

Mottet, A., Ladet, S., Coqué, N., & Gibon, A. (2006). Agricultural land-use change and its drivers in mountain landscapes: A case study in the Pyrenees. *Agriculture Ecosystems and Environment*. https://doi.org/10.1016/j.agee.2005.11.017

Nadal-Romero, E., Lasanta, T., Regüés, D., Lana-Renault, N., Cerdà, A., 2011. Hydrological response and sediment production under different land cover in abandoned farmland fields in a mediterranean mountain environment. Boletin Asoc. Geogr. Espanoles.

Nainggolan, D., de Vente, J., Boix-Fayos, C., Termansen, M., Hubacek, K., & Reed, M. S. (2012). Afforestation, agricultural abandonment and intensification: Competing trajectories in semi-arid Mediterranean agro-ecosystems. *Agriculture Ecosystems and Environment, 159*, 90–104. https://doi.org/10.1016/j.agee.2012.06.023

Ninot, J. M., Carrillo, E., Font, X., Carreras, J., Ferré, A., Masalles, R. M., … Vigo, J. (2007). Altitude zonation in the Pyrenees. *A geobotanic interpretation. Phytocoenologia, 37*, 371–398. https://doi.org/10.1127/0340-269X/2007/0037-0371

Pais, S., Aquilué, N., Campos, J., Sil, Â., Marcos, B., Martínez-Freiría, F., … Regos, A. (2020). Mountain farmland protection and fire-smart management jointly reduce fire hazard and enhance biodiversity and carbon sequestration. *Ecosystem Services, 44*, Article 101143. https://doi.org/10.1016/j.ecoser.2020.101143

Pereira, H. M., Leadley, P. W., Proença, V., Alkemade, R., Scharlemann, J. P. W., Fernandez-Manjarrés, J. F., … Walpole, M. (2010). Scenarios for Global Biodiversity in the 21st Century. *Science, 330*, 1496–1501. https://doi.org/10.1126/science.1196624

Perpiña, C., Coll, E., Lavalle, C., & Martínez, J. C. (2020). An Assessment and Spatial Modelling of Agricultural Land Abandonment in Spain (2015–2030). *Sustainability, 12*, 560. https://doi.org/10.3390/su12020560

Petrou, A., Pantziou, E. F., Dimara, E., & Skuras, D. (2007). Resources and Activities Complementarities: The Role of Business Networks in the Provision of Integrated Rural Tourism. *Tourism and Geography, 9*, 421–440. https://doi.org/10.1080/14616680701647634

Poggio, L., de Sousa, L. M., Batjes, N. H., Heuvelink, G. B. M., Kempen, B., Ribeiro, E., & Rossiter, D. (2021). SoilGrids 2.0: Producing soil information for the globe with quantified spatial uncertainty. *SOIL, 7*, 217–240. https://doi.org/10.5194/soil-7-217-2021

Poyatos, R., Latron, J., Llorens, P., 2003. Land use and land cover change after agricultural abandonment: The case of a Mediterranean Mountain area (Catalan Pre-Pyrenees). Mountain Research and Development (MRD) https://doi.org/10.1659/0276-4741(2003)023[0362:LUALCC]2.0.CO;2.

Prados, M. J. (2008). Naturbanization: New identities and processes for rural-natural areas [WWW Document]. *Naturbanization*. https://doi.org/10.1201/9780203881149-5

Renwick, A., Jansson, T., Verburg, P. H., Revoredo-Giha, C., Britz, W., Gocht, A., & McCracken, D. (2013). Policy reform and agricultural land abandonment in the EU. *Land Use Policy, 30*, 446–457. https://doi.org/10.1016/j.landusepol.2012.04.005

Rey Benayas, J. (2007). Abandonment of agricultural land: An overview of drivers and consequences. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources., 2*. https://doi.org/10.1079/PAVSNNR20072057

Rey Benayas, J. M., Martins, A., Nicolau, J. M., & Schulz, J. J. (2007). Abandonment of agricultural land: An overview of drivers and consequences. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources, 2*. https://doi.org/10.1079/PAVSNNR20072057

Rivas-Martinez, S., 1987. Memoria del mapa de series de vegetación de España. ICONA. Ministerio de Agricultura, Pesca y Alimentación, Madrid.

Schirpke, U., Altzinger, A., Leitinger, G., & Tasser, E. (2019). Change from agricultural to touristic use: Effects on the aesthetic value of landscapes over the last 150 years. *Landscape and Urban Planning., 187*, 23–35. https://doi.org/10.1016/j.landurbplan.2019.03.004

Sen, P. K. (1968). Estimates of the Regression Coefficient Based on Kendall's Tau. *Journal of American Statistical Association, 63*. https://doi.org/10.2307/2285891

Serra, P., Vera, A., Tulla, A. F., & Salvati, L. (2014). Beyond urban–rural dichotomy: Exploring socioeconomic and land-use processes of change in Spain (1991–2011). *Applied Geography, 55*, 71–81. https://doi.org/10.1016/j.apgeog.2014.09.005

Sluiter, R., & de Jong, S. M. (2007). Spatial patterns of Mediterranean land abandonment and related land cover transitions. *Landscape and Ecology, 22*, 559–576. https://doi.org/10.1007/s10980-006-9049-3

Stoate, C., Báldi, A., Beja, P., Boatman, N. D., Herzon, I., van Doorn, A., … Ramwell, C. (2009). Ecological impacts of early 21st century agricultural change in Europe – A review. *Journal of Environment Management, 91*, 22–46. https://doi.org/10.1016/j.jenvman.2009.07.005

Terres, J.-M., Scacchiafichi, L. N., Wania, A., Ambar, M., Anguiano, E., Buckwell, A., … Zobena, A. (2015). Farmland abandonment in Europe: Identification of drivers and indicators, and development of a composite indicator of risk. *Land Use Policy, 49*, 20–34. https://doi.org/10.1016/j.landusepol.2015.06.009

Thieken, A. H., Müller, M., Kleist, L., Seifert, I., Borst, D., & Werner, U. (2006). Regionalisation of asset values for risk analyses. *Natural Hazards and Earth System Sciences, 6*, 167–178. https://doi.org/10.5194/nhess-6-167-2006

Ustaoglu, E., & Collier, M. J. (2018). Farmland abandonment in Europe: An overview of drivers, consequences, and assessment of the sustainability implications. *Environmental Reviews, 26*, 396–416. https://doi.org/10.1139/er-2018-0001

Vacquie, L., Houet, T., Sohl, T., Reker, R., & Sayler, K. (2015). Modelling Regional Land Change Scenarios to Assess Land Abandonment and Reforestation Dynamics in the Pyrenees (France). *Journal of Mountain Science, 12*, 905–920.

van Leeuwen, C. C. E., Cammeraat, E. L. H., de Vente, J., & Boix-Fayos, C. (2019). The evolution of soil conservation policies targeting land abandonment and soil erosion in Spain: A review. *Land Use Policy, 83*, 174–186. https://doi.org/10.1016/j.landusepol.2019.01.018

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. *Journal of Climate, 23*, 1696–1718. https://doi.org/10.1175/2009JCLI2909.1

Vidal-Macua, J. J., Ninyerola, M., Zabala, A., Domingo-Marimon, C., Gonzalez-Guerrero, O., & Pons, X. (2018). Environmental and socioeconomic factors of abandonment of rainfed and irrigated crops in northeast Spain. *Applied Geography, 90*, 155–174. https://doi.org/10.1016/j.apgeog.2017.12.005

Vilà-Cabrera, A., Espelta, J. M., Vayreda, J., & Pino, J. (2017). "New Forests" from the Twentieth Century are a Relevant Contribution for C Storage in the Iberian Peninsula. *Ecosystems, 20*, 130–143. https://doi.org/10.1007/s10021-016-0019-6

Weiss, A.D., 2001. Topographic Position and Landforms Analysis, in: ESRI International User Conference,. ESRI, San Diego.

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. New York: Springer-Verlag.

Zandbergen, P. A., & Ignizio, D. A. (2010). Comparison of Dasymetric Mapping Techniques for Small-Area Population Estimates. *Cartography and Geographic Information Science, 37*, 199–214. https://doi.org/10.1559/152304010792194985

Zaragozí, B., Rabasa, A., Rodríguez-Sala, J. J., Navarro, J. T., Belda, A., & Ramón, A. (2012). Modelling farmland abandonment: A study combining GIS and data mining techniques. *Agriculture Ecosystems and Environment, 155*, 124–132. https://doi.org/10.1016/j.agee.2012.03.019

Zhou, X. H., Obuchowski, N. A., & McClish, D. K. (2011). Statistical Methods in Diagnostic Medicine. *Statistical Methods in Diagnostic Medicine*. https://doi.org/10.1002/9780470906514