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Mapping socio-environmental pressures to assess Portuguese soil vulnerability

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ABSTRACT

Soil degradation has concerning impacts on ecosystem functions and biodiversity, decreasing essential processes such as food production or sustaining water quality. We studied eight soil threats to assess degradation processes: hydrogeological risks, soil sealing, salinization, desertification, contamination, compaction, erosion and decline in soil organic matter. A knowledge-based methodology was used measure the importance of 15 anthropogenic and environmental variables, with top weights of water availability (0.11), rate of land use change (0.09) and agricultural practices (0.09). Variables were combined into one additive model per threat to assess its distribution in Portugal. Merged soil threat vulnerability maps provided a spatial representation of the distribution of aggregated soil vulnerability, to find a 58% of moderate vulnerable soils where multiple threats coexist and are key for future management changes, a 32% of low vulnerable soils with reduced levels of soil threats, where temperature and precipitation are the main drivers of soil degradation and a 10% of highly vulnerable soils, which encompasses populated urban areas and rural civil parishes, where contamination and high rates of land turnover are the main drivers. Our maps can be used to make informed decisions on soil management and establish strategic policies for a sustainable use of land.

1. Introduction

Soil is an essential component of terrestrial life that performs multiple key environmental, social and economic services and is largely a non-renewable resource at a human scale (Blum, 2005; Lal, 2015). Soil quality determines the capacity of ecosystems to perform vital functions related to plant productivity, water resources and storage, nutrient availability, or buffering of environmental changes (Robinson et al., 2012). The complex and diverse matrices in our soils also provide a great variety of microhabitats for a myriad of organisms, including microorganisms and soil fauna (FAO ITPSGSBISCBD & EC, 2020; Montanarella et al., 2015) also being essential to support vegetation and crops, both structurally and nutrient-wise (Bini, 2009).

Soil degradation is a significant global problem, as one third of the world's soil surface is affected by some form of decline in soil quality (Bini, 2009). A combination of environmental and socio-economic causes contribute to soil degradation. Some of these relate to natural processes such as water and wind erosion, particularly in extreme climate events, but degradation is primarily caused and exacerbated by human activities, being land use change a key driver of degradation (Blum, 2008). Factors that promote soil degradation, known as soil threats, can lead to strong feedbacks that accelerate soil degradation through declines in soil biodiversity and function (Krasilnikov et al., 2015; Lal, 2015; Zeiss et al., 2022). They include harmful agricultural practices such as pesticide usage or mineral fertilizers that acidify soils or conventional tillage that increases soil erosion and the loss of the

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fertile topsoil (Geissen et al., 2013), multiple types of contamination, land use change such as urbanization processes promoting soil sealing and habitat fragmentation, and indirect factors, such as population demographics and industrial development, can also compromise soil quality (Montanarella et al., 2015; Nelson, 2005).

Soil conservation is becoming an increasingly important concern for decision makers due to its impact on human health, soil functions, and ecosystem services that support the sustainability of modern societies. Despite the lack of environmental commitments or common legislation on soil management, soil functions are highly connected with the majority of the Sustainable Development Goals of the UN that every nation has to achieve by 2030 (Keesstra et al., 2016). The recent EU Biodiversity Strategy for 2030 explicitly considers soil restoration as one of their main commitments (European Commission, 2021) and according to the Mission on Soil Health and Food there is a goal to reach a healthy status in at least 75% of all European Soils by 2030 (European Commission, 2020), aligning with the aim to reach a soil legal status similar as the water and air in a future Soil Health Law (Köninger et al., 2022). Just recently in February 2023 the European Soil Data Centre launched the Soil Health Dashboard (EU Soil Observatory, 2023; Maréchal et al., 2022), a promising tool to assess soil health through 15 degradation processes and their cumulative impacts on European soils. However, their degree of coverage is not uniform, and some areas (including Portugal) are still not well covered for key degradation processes such as wind and tillage erosion. Likewise, this group of maps are not yet taking into account local conditions such as soil type and climate, that are key for assessing soil health.

In order to contribute to these monitoring tools planned by the EU for the next decade, regional studies on the assessment of soil quality can both provide a good approach to build up our knowledge and allow future expansions of the monitoring. More importantly, we are especially lacking studies that combine the effects of multiple factors in soil functions and biodiversity (Rillig et al., 2019). For developing good and generalizable models it is essential to take into account multiple scales and environmental conditions, and Portugal has a great potential to be an excellent peripheric region to apply these models. Despite its relatively small size (89.015 km^2), continental Portugal is also a very diverse territory in terms of climate, vegetation and socioeconomic conditions, and thus can be used as an appropriate example to investigate socio-environmental pressures. It can be considered a mostly rural country predominantly occupied by semi-natural lands and forests (48.2%) and agricultural land uses (48%) (Freire & Caetano, 2005) and subjected to several threats including pollution (Figueira et al., 2002; Inácio et al., 1998), land management (Da Silva, J. M. et al., 2004a; De Almeida et al., 2018), biological invasions (De la Fuente & Beck, 2018; Nunes et al., 2019), urban expansion (Freire & Caetano, 2005; Rocha et al., 2021), environmental risks and disasters (Da Silva, E. F. et al., 2004b; Pereira et al., 2014), climate change (Carvalho et al., 2014; Costa et al., 2012), and resource exploitation threats. Despite mining installations having been closed in the last 50 years, environmental consequences of the continuous extraction of mineral resources (i.e., copper and, tin) for decades are still affecting Portuguese soils, as many of these areas are still left degraded or in recovery (Caetano & Marcelino, 2017). Contamination by agricultural nitrates is still affecting extensive areas, classified as vulnerable, in the northwest of Portugal (Freire & Caetano, 2005; Rodrigues et al., 2021). One of the main causes of soil degradation are the intense land use changes that have occurred in the last decades and are still ongoing. For example, in the last 15 years, there was an expansion of 42.1% in artificial surfaces with direct and indirect consequences related to an increase of soil erosion, soil sealing and pollution. In addition, rural land abandonment followed by an increase of pastures and shrublands may raise the risk of uncontrolled fires (Sil et al., 2019). In the last 50 years, Portuguese forests have also experienced profound changes, such as the expansion of non-native species as *Eucalyptus globulus* plantations that currently occupy a 26% of forestry surface (ICNF, 2019). Overall, land cover changes and associated threats can have significant impacts on the conditions of soils and on their ability to sustain biodiversity and key ecosystem services.

In line with the EU objectives to include soil management and conservation into policies and legislative instruments (Montanarella & Panagos, 2021), and Portuguese goals to increase environmental sustainability and improve the conservation of soils (Rodrigues et al., 2021), we here propose a novel approach for an integrated assessment of multiple threats, using Portugal as case-study, to develop existing knowledge on soil vulnerability with the goal to improve soil health (Rodrigues et al., 2021). This assessment of the condition of soils and the monitoring of its change is essential to make informed decisions on soil management and establish strategic policies for a sustainable use of land (Karlen et al., 2019; Tulloch et al., 2015). We aim to i) identify and evaluate the group of key factors that affect soil threats; ii) compile a comprehensive dataset encompassing soil, climate and anthropogenic variables; iii) create maps of distribution of soil threats and iv) combine them for assessing Portuguese soil vulnerability. To our knowledge, this is the first time that eight soil threats are evaluated for Portugal, and the methodology described can also be used as a roadmap for future soil assessments in other regions and at larger scales.

2. Material and methods

2.1. General soil threat approach

The soil threat approach allows us to study explicit degradation processes affected by multiple pressures at a time. For this, we considered the main soil threats identified by European and global assessments (Jones, A. et al., 2005; Stolte et al., 2016; European Commission, 2006) as follows: i) decline in soil organic matter, ii) hydrogeological risks (floods and landslides), iii) desertification, iv) soil compaction, v) contamination, vi) salinization, vii) erosion and vii) sealing, declines in soil biodiversity threat was not assessed due to the lack of potential biodiversity indicators (for definitions and summary of potential pressures see Table 1). The potential drivers of these environmental changes can operate directly on ecosystem processes, e.g. wind increasing erosion, or more diffusely, e.g socio-political changes like population growth promoting soil degradation processes as desertification through land use changes.

2.2. Evaluation of soil threats

2.2.1. Variable selection

Soil threats are complex and strongly interacting processes that operate at different scales (Stolte et al., 2016) by a combination of drivers or controlling variables. A group of variables that summarizes climatic, demographic, economic and environmental facets was selected with the following considerations: (i) keep a short list of variables, as the number of variables affects to the detriment of the consistency of the Analytic Hierarchy Process (AHP) methodology; (ii) select measurable variables either directly or through a combination of sub variables; (iii) obtain a balanced proportion between socio-economic and environmental pressures affecting soils and (iv) include variables that document change over time. In some cases, in the absence of available direct data, we used close proxies to assess the different threats, e.g., the use of "herbicides" to correspond to the difference between organic and total agriculture. Finally, we considered 15 variables covering a wide variety of drivers of soil degradation from abiotic factors, such as wind speed or water availability variables, to drivers more related to socio-economic aspects, such as population density or land management. Most of the variables used for the spatial representation of vulnerability to soil threats are composite, created by combining multiple subvariables (Table 2).

2.2.2. Data sources

The collection of subvariables was obtained from public datasets

Table 1
Summary table of our bibliographic review on the definition and impact of each soil threat. Threats selected and defined based on Lal, 2015, Montanarella et al., 2015; Stolte et al., 2016.

Threats	Drivers
Decline in Soil Organic Matter (DOM): Decline in organic compounds containing (C, H, O, N, S, P) that range from undecomposed plant and animal tissues to humus.	Initial input of organic matter (OM) and its rate of decomposition-oxidation, soil texture (e.g. clay stabilizes OM) and climate (humidity and temperature). Farming system (manure application, crop rotation, fertilizers, tillage frequency, intensity) affects the amount of OM and its decomposition rates (Gmach et al., 2019; Johnston et al., 2009; Liu et al., 2006).
Erosion (ERO): Displacement of the upper layer of soil by different agents. Depending on the origin it can be divided by water and wind erosion.	Rainfall and wind erosion through detachment of soil particles, surface runoff and transport of eroded materials. Land cover change is an important factor affecting soil erosion as vegetation cover affects infiltration and water storage capacity. Agricultural practices with heavy machinery or inadequate logging in forests, construction of infrastructures and buildings that imply soil movements and mining. Wildfires also contribute to hydrological and erosional changes in soils. (García-Ruiz, 2010; García-Ruiz & Lana-Renault, 2011; Pimentel et al., 1995; Prats et al., 2014; Shakesby, 2011).
Compaction (COM): Heavy compression of soil by human-related forces that alters soil properties leading to a decrease in soil permeability to air, water and roots. It can be very persistent in the subsoil.	Wheels and heavy machinery from agricultural and forest land use (e.g. tillage or wood extraction) and to a lesser extent livestock or other animal hooves. Severe soil compaction is associated with industrial activities such as mineral extraction. (Batey, 2009; Hamza & Anderson, 2005; Nawaz et al., 2012).
Contamination (CONT): Diffuse or localized pollution caused by human-made chemicals. It is reflected by high concentrations of acidifying contaminants (e.g. SO_2, NOx), metals, metalloids such as arsenic, and organic compounds. Over time, it can lead to soil acidification, a decrease in soil pH.	Population density and proximity to populated areas. Industrial production, agricultural chemicals and the improper disposal of waste. Soil acidification is related to industrial pollution in the form of acidic rain through the deposition of acidifying gases or particles. It occurs especially in humid climatic conditions where rainfall exceeds evapotranspiration (Bolan et al., 1991; Feng et al., 2019; Goulding, 2016; Panagos et al., 2013; Van Straalen, 2002).
Desertification (DES): Land degradation caused by a combination of excessive human exploitation and the inherent fragility of drylands: with low water resources, plant cover, productivity and organic matter, variable rainfall, drought and little soil development.	Increase in population and human needs, socio-economic pressures (land use changes from rural to urban), farmland expansion and water use. Overcultivation and overgrazing (Kassas, 1995; Reynolds et al., 2007).
Salinization (SALI): Accumulation of salts in soils that compromises water resources and soil productivity. It reduces productivity of crops, as most vegetable crops have low tolerance to soil salinity and salinization is a major cause of desertification.	Agricultural practices: excessive use of groundwater (especially close to the sea), intense use of irrigation and low quality of water irrigation systems. Population growth and economic development increases demands for energy, food and water. It is worsened by climate change (Machado & Serralheiro, 2017; Nachshon, 2018).
Sealing (SEAL): Covering of the soil surface with an impervious material or impermeabilization of soils that become no longer able to perform their associated range of functions.	Human infrastructures: buildings, industrial development, roads and communications. Indirectly related to human socio-economic development (Burghardt, 2006; Tobias et al., 2018).
Hydrogeological Risks (HR) Flooding: Overflow of water from water bodies, or drainage water over areas normally not submerged. Landslide: movement of a mass of soil or rock down a slope under the force of gravity.	Precipitation, slope, vegetation, soil properties and soil depth. Land use changes, e.g. reducing forest/vegetation cover decreases soil cohesion by roots and thus promotes soil losses, opening of roads and other constructions that create instability on hills. Forest fires, land abandonment in terraced slopes (Arnáez et al., 2015; Pattison & Lane, 2012; Poesen & Hooke, 1997).

related to governmental and non-governmental agencies through direct download or following information request processes. Most physical and chemical soil properties are available from the LUCAS (Land Use/Cover Area frame statistical Survey Soil') Soil EU monitoring scheme from the European Soil Data Centre (Ballabio et al., 2016, 2019) which is an extensive and regular topsoil survey that is carried out across the European Union to derive policy-relevant statistics on the effect of land management on soil characteristics (Orgiazzi et al., 2018). Climate variables were taken from products of the European satellite ESA Copernicus Sentinel-5P (Karger et al., 2017) and most anthropogenic data was obtained from the website of the Portuguese national statistics office, Instituto Nacional de Estatística (INE, *ine.pt*) (see Supplementary Table 1 for a thorough list of the spatially explicit variables, data sources and characteristics). Depending on the soil threat, each variable has a positive, negative or neutral effect (Table 2). The direction of the effects between variables and soil threats is particularly important for subsequent analyses combining effect sizes of all variables studied for each soil threat.

2.2.3. *Variable scoring*

A multi-criteria approach was chosen to evaluate the degree of influence of each of the 15 variables on soil threats using Analytic Hierarchy Process (AHP) (Guerra et al., 2013). The AHP is a pairwise comparison procedure, commonly applied as a multi-criteria decision--making method (Saaty & Vargas, 2012; Yalcin, 2008) It gives each variable a weight in relation to the rest of the variables. The degree of importance was introduced as a factor divided in 5 categories: much more important (5), little more important (3), equally important (1), little less important ($^1/_3$) and much less important (⅕). From this table we obtained a comparison matrix for each threat, where Z corresponds to the evaluation matrix; Z_{21}, Z_{n1} correspond to each comparison weight for the input variables 1, 2, …, n; and Z_{12}, Z_{1n} to their reciprocals. Main diagonal elements of this matrix (Z_{11}, Z_{22}, …, Z_{33}) correspond to the comparison of each variable with itself; thus, cell values of the main diagonal are always 1 (equally important). The principal eigenvector of this matrix represents the best fit of weights (�) for the variables (Saaty, 1977, 1988), since it delivers unambiguous ranking when the evaluations are consistent (Saaty & Hu, 1998; Saaty, 2003). The consistency of the individual evaluations by the experts is crucial to have meaningful results; we considered a Consistency Ratio (CR) < 0.1 to be a good indicator of consistency (Saaty, 1988). CR becomes increasingly important as the number of variables included in the model grows and is calculated as the ratio between the Consistency Index (CI) and the Random Index (RI) (Saaty, 1977). The Consistency Index is calculated as $CI=(\lambda - n)/(n-1)$; where λ represents the mean value of the product of the consistency vector and the values present in the evaluation matrix; *n* is the number of variables. RI is a fixed value that depends on the number of variables.

The combination of evaluation matrices leads to the obtention of a consensus criterion. Despite the subjectiveness of each individual pairwise evaluation, if the comparisons are consistent with each other, the resulting eigenvector of the matrix is consistent as well, because it represents the best fit of weights for the variables (Saaty, Thomas L. & Hu, 1998; Saaty, Thomas L., 2003). To minimize individual bias, an

Table 2
Variables and subvariables obtained (a complete description of the datasets and their sources is given in Table A1) and the direction of their effect on soil threats is represented by red (increase), blue (decrease), black (neutral) and absence of known effects in white. Information on these effects was compiled from existing literature, see Table 1. DOM: Decline in soil Organic Matter, HYDROG. RISKS: Hydrogeological Risks.

Variables	Subvariables	DOM	EROSION	COMPACTION	CONTAMINATION	DESERTIFICATION	SALINIZATION	SEALING	HYDROG. RISKS
Soil properties	**Soil Organic Carbon** (t/ha)	blue	blue	blue	red	blue	blue	blue	blue
	Soil pH (in H_2O)	blue	white	white	blue	blue	blue	white	blue
	Soil Texture: Sum of average of Clay (%) and Silt (%)	blue	blue	red	white	blue	red	red	blue
Vegetation	**Forest change:** Diff. forest land use (%)	blue	blue	blue	blue	blue	blue	blue	blue
	Forest: Forest land use (%)	blue	blue	blue	blue	blue	blue	blue	blue
	NDVI (index value)	blue	blue	blue	blue	blue	blue	blue	blue
Fire	**Fire risk**: 5 categorical classes of fire risk	red	red	red	red	red	red	red	red
Agriculture	**Agriculture change**: Diff. agricultural land use (%)	red	red	red	red	red	red	blue	red
	Agriculture: Agriculture land use (%)	red	red	red	red	red	red	blue	red
Land management	**Irrigated areas** (%)	red	red	red	red	blue	red	blue	red
	Agroforestry machinery: machines (N)	red	red	red	red	white	red	red	red
	Manure: Agricultural land use with manure application (%)	blue	blue	white	red	blue	red	white	red
	Slurry: Agricultural land use with slurry application (%)	blue	white	white	red	blue	red	white	red
Grazing	**Animals per farming holding** (N)	red	red	red	red	red	red	blue	red
	Livestock density index: Normal heads per agricultural area (nh/ ha)	red	red	red	red	red	red	blue	red
	Stabled: number of places for cattle livestock (%)	white	blue	blue	red	blue	red	red	white
Industry	**Industry change** : Diff. industrial land use (%)	red	red	red	red	red	red	red	red
	Industry: Industry land use (%)	red	red	red	red	red	red	red	red
Urban	**Road density:** Index based on main roads and streets	red	red	red	red	red	red	red	red
	Urban change: Diff. Urban land use (%)	red	red	red	red	red	red	red	red
	Urban: Urban land use (%)	red	red	red	red	red	red	red	red
Population	**Population density**: N people/km^2	red	red	red	red	red	red	red	red
N deposition	**Nitrogen deposition** (mol/m^2 NO_2)	blue	red	red	red	red	red	red	red
Water	**Potential evapotranspiration** (kg/m)	red	red	white	white	red	red	blue	red
	Precipitation change (kg/ m^2 month) Diff. In monthly precipitation	blue	red	red	blue	blue	blue	white	red
	Soil moisture: Index based on Available Water Content and Soil Surface Moist.	blue	blue	blue	blue	blue	blue	blue	blue
Temperature	**Temperature change**: Diff. monthly mean temperatures (°C)	red	red	red	red	red	red	red	red
Wind	**Wind speed** (m/s)	red	red	black	red	red	red	black	red
Land turnover	**Land use turnover**: Index of land use change	red	red	red	red	red	red	red	red
Contaminants	**Herbicides**: Diff. organic and total agriculture area (ha)	red	red	red	red	red	red	red	red
	Heavy metals: Index with Cu (mg/kg) and Hg (μg/kg)	red	red	red	red	red	red	red	red
	Waste efficiency: Municipal waste for reuse and recycling (%)	blue	blue	blue	blue	blue	blue	blue	blue

average matrix of pairwise evaluations was calculated for each soil threat. Weight factors were then extracted from this matrix, so that each soil threat has a corresponding weight vector (�), standardized weight vector (S�) and a degree of consistency measured with CR.

2.3. Mapping soil threat vulnerability

Individual subvariables were standardized (i.e. centered and scaled with a 0 to 1 range) in all cases, then a balanced proportion of these subvariables was achieved with their average for composed variables (Table 2). Final variables were brought to a grid based in the Portuguese administrative subdivision of *Freguesia* (civil parish; NUTS V) with the Spatial Analyst extension of ArcGis (ArcGis Desktop 10.7.1; *Zonal Statistics as Table*). This methodology achieves a unified result, taking into account the relative importance of each variable on the soil threat. Variables were tested for multicollinearity using Variance Inflation Factor (VIF) with the R package usdm (Naimi, 2015). We combined the final list of variables by raising each one by the power of its standardized weight vector (S�) (Guerra et al., 2013), so for each soil threat:

$$f\ (\text{Soil threat vulnerability}) = \mathbf{a}_{V1}{}^{S�V1} + \mathbf{b}_{V2}{}^{S�V2} + \mathbf{c}_{V3}{}^{S�V3} + (\ldots) + \mathbf{o}_{V15}{}^{S�V15}*$$

*V1 to V15: variables, **a** to **o:** values per parish, S�: standardized weight vector. Following Guerra et al., 2013.

To further investigate possible relationships between edaphoclimatic and anthropogenic drivers throughout soil threats, Pearson correlation analyses of the drivers were done for the north, center and south of Portugal, with the R package Hmisc (Harrell Jr & Harrell Jr, 2019) (Fig. A1). This three-way division of the country is related to the administrative areas proposed by the European Union Statistical Regions NUTS II (European Commission, Statistical Office of the European Union, 2022), here the south region comprises Area Metropolitana de Lisboa, Alentejo and Algarve NUTS II regions.

2.4. Clustering analyses

The information of the spatial distribution of soil threat vulnerability in Portugal was analyzed with a hierarchic clustering methodology based on Ward's (Ward, 1963) clustering criterion with *hclust* function of the R package stats (R Core Team, 2022) to ascertain whether there is a spatial clustering of Portuguese soils based on their potential vulnerability to soil threats. The degree of clustering was obtained with the agglomerative coefficient from cluster package (Maechler et al., 2022) and 30 indices were compared to determine the optimum number of clusters with nbclust package (Charrad et al., 2014). We performed random forest, a tree-based machine learning algorithm, to assess the major drivers of these clusters with randomForest package (Liaw & Wiener, 2002) and 1000 trees. Then, partial dependence plots were constructed with the top 2 variables of each model with pdp package (Greenwell, 2017) to better interpret the results of our models. All R

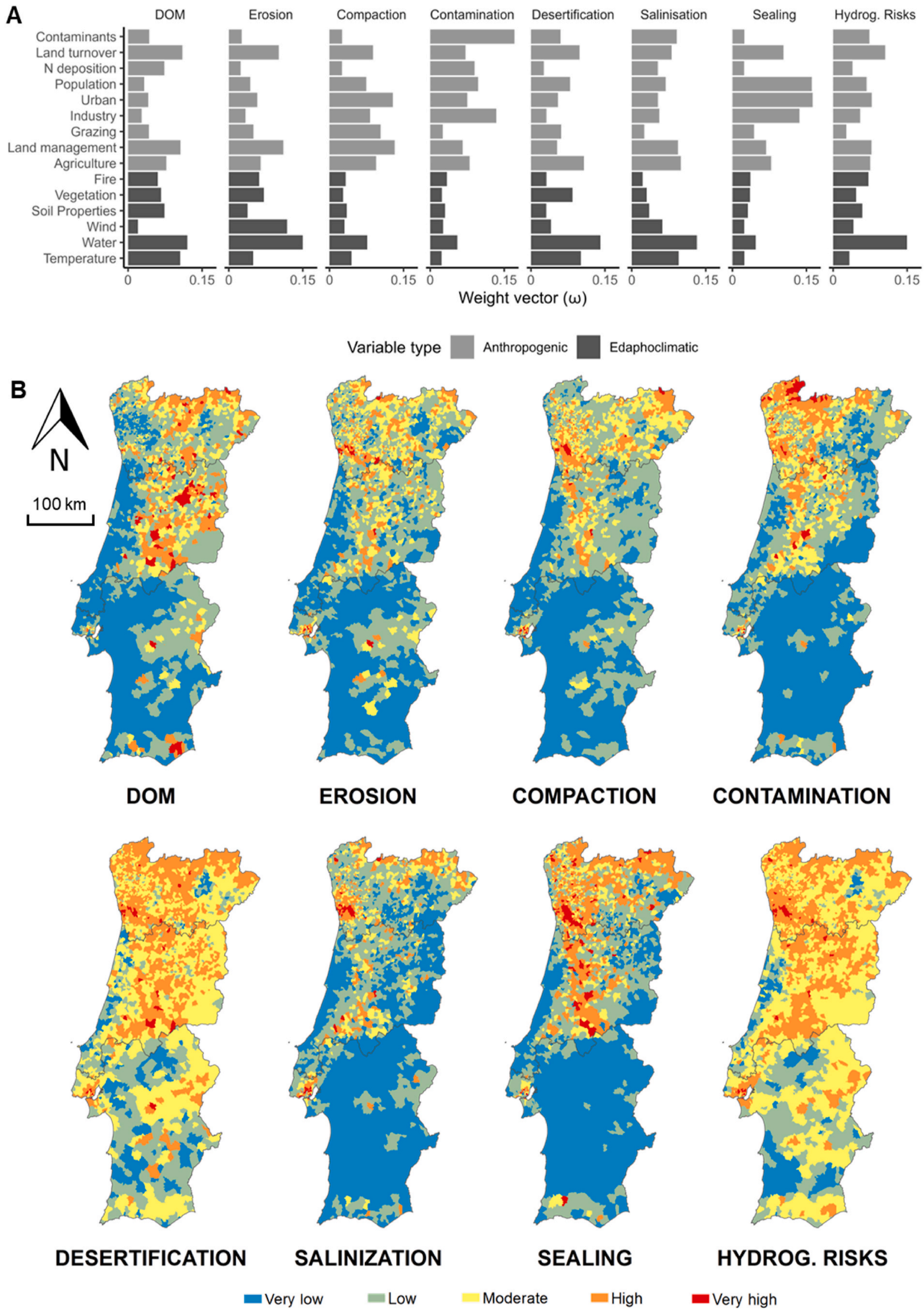

Fig. 1. Variable scoring resulted in weight vectors (�) for each variable per soil threat (A); Maps of vulnerability to soil threats on Portuguese civil parishes (B). DOM: Decline in soil Organic Matter, HYDROG RISKS: Hydrogeological Risks. Grey borders refer to northern, center and southern regions of Portugal.

analyses were done in version 4.2.1 (R Core Team, 2022).

3. Results

3.1. Drivers of soil degradation

Pairwise comparison matrices obtained from the variable scoring by soil threat were consistent in the estimations. The variable comparisons provided by each expert had internal coherence (Consistency Ratio<0.1; Table A2). And when combined, the average matrix for each soil threat (Table A2), had also low Consistency Ratios of the mean comparisons (from 0.02 to 0.03) (Fig. 1).

AHP analyses provide a weighted importance of each variable per soil threat in decimals that add up to 1. This way, higher decimals equals a higher influence of a variable on a soil threat. Water was considered the most important variable throughout all soil threats, with an average contribution of 0.11 (Standard Deviation (SD) = 0.04; mean contribution across all variables = 0.06, SD = 0.01). It was followed by land turnover and land management, with 0.09 (SD = 0.01 and 0.03 respectively) averaged weighted importance on soil threats. Variables were classified as anthropogenic and edaphoclimatic according to their main origin, and these two classes of variables have particularly contrasting degrees of contribution to certain soil threats. Thus, erosion is mainly affected by edaphoclimatic variables (averaged 0.08 degree of importance, SD = 0.04), while contamination, compaction and soil sealing are mostly affected by anthropogenic variables (average 0.08–0.09 degree of importance, SD = 0.03–0.05). Variables were tested for multicollinearity using VIF (Table A.5) and all were below the

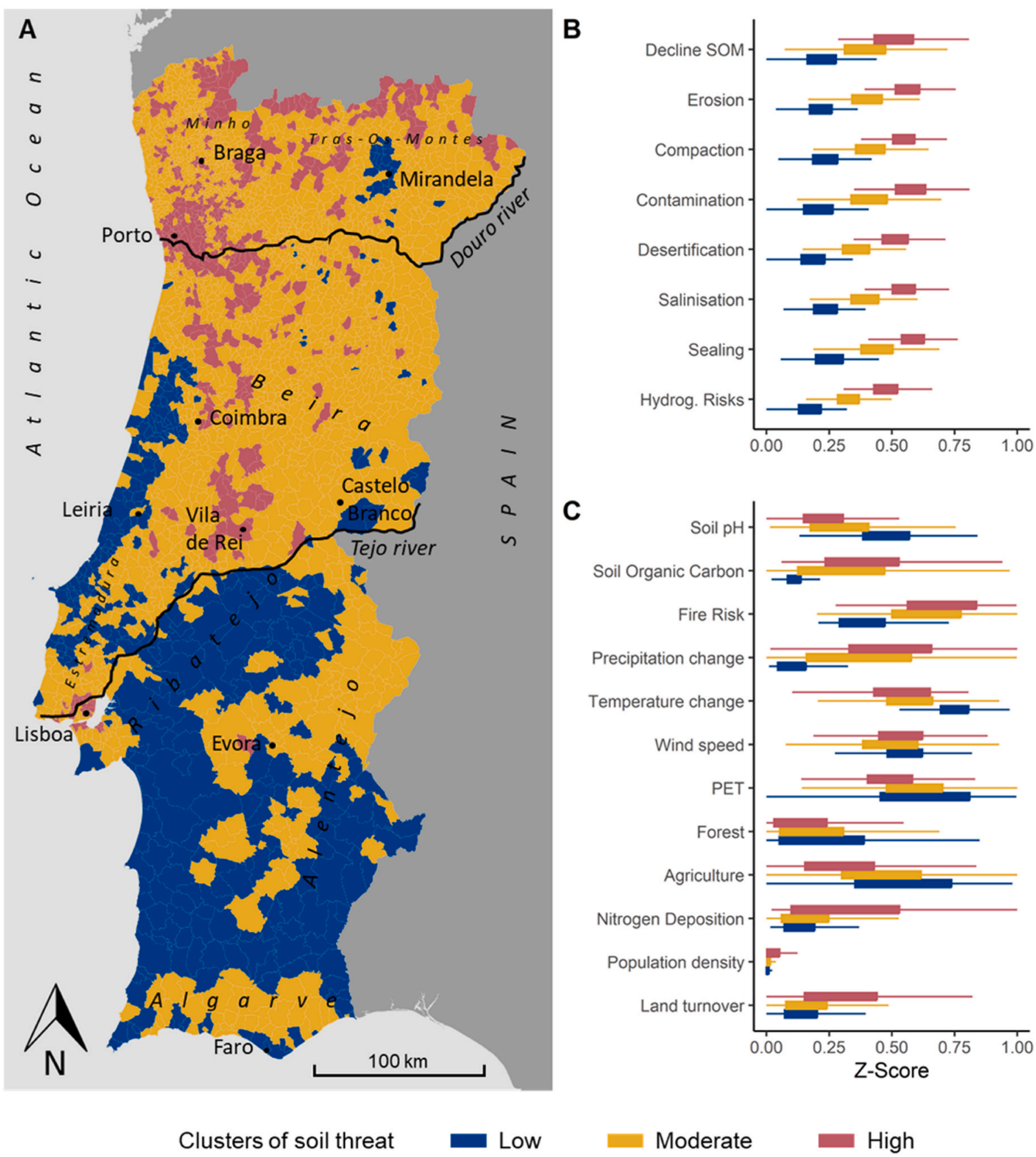

Fig. 2. Soil vulnerability map, a spatial representation of the clusters in which soil threats can be summarized at the parish level (A). Boxplots compare the standardized values (Z-Score) of soil threats (B) and key socio environmental variables (C) on Portuguese civil parishes by their cluster membership (colors). Z-Score values represent the importance of threats and variables within clusters. SOM: Soil Organic Matter; Hidrog: Hydrogeological; PET: Potential Evapotranspiration.

conservative threshold of 5 (Gareth et al., 2013; Vittinghoff et al., 2006).

3.2. Distribution of soil threats

Each map of vulnerability to soil threats was divided into five classes using a geometrical classification method: very low, low, moderate, high, and very high threat probability. Areas with intermediate threat values correspond to areas in the center of the distribution; thus we consider them to have a moderate vulnerability to soil threats. Although each map has its unique features and spatial representation of the soil threats, most of the concerning areas are distributed in the north and center of the country (Fig. 1B). In the comparison of the impacts between anthropogenic and edaphoclimatic drivers of soil degradation we found a systematic decline throughout the country (north, center and south) for all soil threats, except for the decline in organic matter (DOM) in central Portugal (Fig. A1). Negative correlations between anthropogenic and edaphoclimatic drivers are especially strong in the north of Portugal (r values from −0.5 to −0.7 in compaction, desertification, erosion, hydrogeological risks, salinization and soil sealing threats; Fig. A1).

3.3. Mapping soil vulnerability

The analysis of the combined effects of soil threats, resulted in an optimum classification of Portuguese civil parishes into three clusters of soil vulnerability degree (12 of 22 indices proposed 3 clusters). A vast majority of the territory (58% of area, 2026 civil parishes) is under moderate levels of threat; in these areas, soils have high values of potential soil threats (Figs. 1B and 2B). Potential evapotranspiration (PET) is the top predictor of this cluster according to the random forest model (33.13% IncMSE) and it occurs around values in the middle of the distribution of PET (Fig. 2C; Fig A.3). But multiple variables (e.g. nitrogen deposition, organic carbon, agriculture land use and wind speed) have high predictive power in modeling the cluster (Fig. 2C, Table A.3). Areas with low threat levels have low levels of fire risk (Fig. 2C), and it represents the top random forest variable with 42.54% IncMSE (Fig A3). Climate variables, such as temperature and precipitation also have a high degree of importance in this cluster (Fig. 2C, Table A3). This cluster is mainly distributed in the south of the country (almost occupying 60% of the southern region) and encompasses 32% of the country's area (389 civil parishes) (Fig. 2C, Table A3). The least abundant cluster is the one with the highest level of soil threat (10% of the country area); the most important predictor of this cluster is land use change, it occurs in areas with high land turnover (land turnover; 61.03% IncMSE). Nitrogen deposition, population density, fire risk and PET are also important variables for the distribution of the high threat cluster. Strongly vulnerable areas are composed of small and dispersed patches, and are mainly distributed in the north and center of Portugal in 467 civil parishes (Fig. 2C, Table A3).

Portugal has 22.6% of its terrestrial surface subjected to some kind of environmental protection with nationally (*Rede Nacional de Áreas Protegidas*, RNAP) and internationally (Natura 2000 *Zonas de Protecção Especial* ZPE, *Sítios de Importância Comunitária* SIC and Ramsar) protected parks and reserves (Rodrigues et al., 2021). These protected areas (PA) are mainly located in areas of moderate (56.45% of PA) and low vulnerability (32.55% of PA) followed by areas subjected to high soil threat (10.95% of PA) (Table A.4).

4. Discussion

4.1. General overview

The spatial distribution of threats obtained in this research (Fig. 1B) aligns with previous knowledge on the environmental and socioeconomic characteristics of the area (Carvalho Ribeiro & Lovett, 2009; Molina et al., 1991; Ramos et al., 2017); however, it should be noted that these maps show vulnerability of these areas to soil degradation and not the current distribution of threats. Also, the spatial resolution of our analyses, civil parish, provides outcomes that are useful and meaningful for future policy and management implications but are not designed with an ecological perspective. We found anthropogenic characteristics as key drivers of soil degradation: regions located around highly populated areas are subjected to multiple pressures and we included land use changes in our analyses as indicators of future trends which is key to assess soil vulnerability. In fact, not only land-use changes, but in particular, changes in land management can trigger soil degradation, even when agri-environmental measures are applied, for instance a forest area increases the risk of forest fires and soil loss (Jones et al., 2011). Yet, threat distribution relates to both human and natural pressures in a country with very wide environmental gradients as the latitudinal variations in temperature and precipitation and the elevation differences, which together distinguish north and center from the south of the country. As with anthropogenic drivers, these environmental conditions are also subjected to variation, namely because of climate change, which was considered taking into account differences in precipitation and temperature over the last twenty years. Key soil drivers are determined by the interaction of multiple pressures; for example, mapping of soil organic matter (SOM), a predictor of soil health (Arias et al., 2005), is subjected to the high variability of soil characteristics across the country. Higher values of SOM are found in the north-west and center of the country because of geographical and climatic conditions, while lower values are found in the south, which experiences higher temperatures and lower precipitation (Ramos et al., 2017). As a result, the potential losses from SOM decline were higher in the north and center, except for a group of southern Alentejo and Algarve parishes where their high soil vulnerability is also mediated by human pressures.

4.2. Spatial considerations

Soil threats share multiple drivers and interact with each other, usually by increasing their impact with detrimental effects for soil health (EU Soil Observatory, 2023; Stolte et al., 2016), and this contributes to their similarities in spatial distribution. Socio environmental pressures also have some degree of spatial concentration or clustering, and thus, the interaction between these similarities and the socio environmental conditions contributes and enhances the concentration of vulnerability in certain areas. Most threats have a similar spatial distribution with a higher proportion of vulnerable areas in the north and center and lower vulnerability in the southern part of the country. However, a distinct distribution is shown in desertification and hydrogeological risks with the expansion of their vulnerability to moderate and high values in the south. Despite these general spatial trends, each soil threat has its own particular distribution depending on the combination and degree of importance of drivers involved (Fig. 1A). In the case of the threat posed by soil erosion, its distribution is highly determined by a combination of Portuguese topography with high values around mountains and high rainfall, but also human land use impacts, such as the intensification of agriculture. Soil compaction is directly related to the use of heavy machinery; thus, it is mainly determined by human drivers, such as the proportion of urban and industry land use and agriculture, and especially where agricultural practices are more intensive. Soil contamination directly depends on the number of pollutants in the area; thus, we find concerning values in the northwestern part of the territory, with an almost continuous patch of moderate to high vulnerability resulting from industrial activity, population density and highly contaminant practices, such as slurry deposition.

The south of the country is the Portuguese region where most desertification occurs today due to aridity levels (ratio of total annual precipitation to potential evapotranspiration ranges from 0.05 to 0.65) and environmental conditions (Pace et al., 2011; Ramos et al., 2017). Despite this, our mapping of desertification showed central and northern Portugal comprised the majority of highly vulnerable areas, whereas the

South has moderate to low threat levels. This is explained by the high degree of losses in precipitation and a consistent increase of temperatures in the north (Costa et al., 2012). In addition, these areas experienced profound land use changes that potentially promote desertification (Caetano & Marcelino, 2017; Freire & Caetano, 2005). At the same time, while the south of Portugal has systematically suffered from desertification in the past decades, the north of Portugal is now showing sever indications of high vulnerability to drought and other desertification factors, which is evidenced by our results. Salinization is distributed mainly in northern Portugal, areas with high levels of rainfall, and the center because of the agricultural impact of intensive irrigation. Soil sealing is mainly determined by socio environmental pressures related to the construction of infrastructures (roads, industry) or building; thus, it is concerning in highly populated areas (northwest) and civil parishes that are subjected to high land use change (northeast and center). Flooding and landslides (Hydrogeological risks threat) are mainly related to the amount of precipitation as triggering factor, but a combination of high anthropogenic factors, such as population and urbanization in areas of high susceptibility or land turnover, also increase the soil vulnerability to this threat dramatically becoming a widely distributed threat throughout the country.

4.3. Regional combinations of anthropogenic and environmental factors

Interestingly, we found mostly negative correlations between anthropogenic and environmental variables across soil threats (Fig. A1). This was especially evident for the north of Portugal, and also occurs when socioeconomic development is compared with other environmental indicators, such as forest landscape metrics (Carvalho Ribeiro & Lovett, 2009). These results indicate the strong influence that human practices have on this territory, and that potential changes towards better management decisions could result in a regional amelioration of soil health. In areas with less potential vulnerability, that is mostly in the south of the country, we found pressures in soils are more related to edaphoclimatic conditions, such as harsh temperatures and drought. This indicates a lesser capacity of improvement of soil health based on management practices, and provides a recommendation for policies focused on the adaptation to these harsh climatic conditions, which are likely to become even harsher over the years (Costa et al., 2012; Rodrigues et al., 2021).

The combination of soil threats into one map of soil vulnerability shows that potentially vulnerable soils can appear in both highly populated areas, where soils are probably already degraded, and in rural areas. The latter can be found close to the northern border with Spain, in protected sites such as the Peneda Gerês National Park or the surroundings of Serra da Estrela Natural Park. This appearance can be related to two very different conditions in these civil parishes: highly populated areas with strong human pressures including contamination or soil sealing through the high level of urbanization; and rural areas that have no demographic stress but a high rate of land use change, which presents one of the most important drivers of soil degradation. Our maps also show areas of intermediate threat levels that could serve as good indicators of places where guided management may have a positive effect on soil health.

4.4. Why threat mapping: usefulness for conservation and land management

Protected areas are designed with the objective to conserve marine and (aboveground) terrestrial biodiversity; therefore, they typically encompass areas with high abundance and diversity of fauna and flora. Despite the paramount importance of soil health for ecosystem functionality and biodiversity, the design of protected areas is not generally based on the status of the soil (Zeiss et al., 2022). We found protected areas tended to have moderate to low values of soil threats as shown in our soil vulnerability map (Fig. 2, Fig. A2, Table A4). However, 10% of soils from protected areas are subjected to high soil vulnerability. The combination of multiple threats into clusters in our vulnerability map is a practical tool to inform future conservation strategies that needs to take into account future biodiversity changes related to human impacts as climate change. We here propose a set of areas with moderate soil vulnerability that should be considered for future protection status to avoid biodiversity and ecosystem functionality loss.

Threat mapping is a useful tool when done with transparent and reproducible structured decision-making processes (Tulloch et al., 2015). Here, the Analytic Hierarchy Process (AHP) resulted in a robust outcome with highly consistent results. This type of Multi-Criteria analysis, takes into account multiple types of pressures and soil threats at a time thus represents an interesting approach for assessing soil vulnerability (Orgiazzi et al., 2016). Soil maps can be used as a source of information in land management decisions to prioritize the more cost-effective conservation actions or the most efficient threat-mitigating strategies (Tulloch et al., 2015). The differing main vulnerabilities to soil threats according to different Portuguese regions implies that planning and legislation aiming at mitigating their causes need to be addressed at sub-national level. The Regional Coordination and Development Commissions in the country, through their direct involvement in territory management and sustainable development, act at a NUTS II level and are ideally positioned to tackle these challenges. Given the multiple interrelated threats, and their anthropogenic and edaphoclimatic components, these are not straightforward tasks. However, suggestions on appropriate threat management, given the specific territorial vulnerabilities, can be made based on their drivers detailed in Table 1. Agriculture, industrialisation (including exploitative activities) and urbanization are expectedly at the forefront of shaping drivers, and are indeed targeted for sustainability improvement within the EU Green Deal, with the much-needed supporting research and innovation being contemplated in EU Missions. Our results strengthen the necessity to implement monitoring strategies that relate the level of threat of soils to their actual soil health state and keep a track on future changes.

5. Conclusion

From the analysis on the spatial distribution of Portuguese soil vulnerability we conclude (i) that almost a 70% of the territory is under high or moderate levels of threat, therefore there is an urgent need to take action to mitigate the consequences of potential soil health losses; (ii) large patterns of distribution of Portuguese soil vulnerability were found, with a distinction between North-Center and South; (iii) our analyses draw special attention to the vulnerability of soils in the northern and central part of the country, where multiple pressures both related to edaphoclimatic (mainly climate change derived as desertification or erosion) but mostly to anthropogenic (contamination, compaction and sealing) are affecting at the same time and (iv) taking all this into account and with the analyses on the relationships between anthropogenic and edaphoclimatic variables, we recommend policies on the northern region more focused on the management of land in terms of decreasing anthropogenic impacts and in the south to be focused on the adaptation to harsh climatic conditions.

Data and codes availability statement

Raw data related to this manuscript is available in Figshare, 10.6084/m9.figshare.22336795.

Declarations of interest

None.

Author contributions

Concha Cano-Díaz: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing-Original draft. Romy Zeiss: Data curation, Formal analysis, Writing- Review & Editing. Claudia Carvalho-Santos: Formal analysis, Writing- Review & Editing. Rui P. Carvalho: Formal analysis, Writing- Review & Editing. Sofia R. Costa: Formal analysis, Writing- Review & Editing. A. Carolina Duarte: Formal analysis, Writing- Review & Editing. Paulo Fernandes: Formal analysis, Writing- Review & Editing. Carlos Guerra: Conceptualization, Methodology, Writing - Review & Editing, Supervision, Project administration, Funding acquisition.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apgeog.2023.103103.

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