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Vulnerability to climate change, depopulation and the global food regime: An index-based approach for rural Spain

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ABSTRACT

Rural regions in Europe currently face multiple interacting stressors, including climate change, depopulation, and the deepening of a global a food regime. Research on the overlapping impact of these climate, demographic and socio-economic phenomena on rural livelihoods is mounting, yet efforts to identify larger-scale patterns at country level are still scarce. In this article, we develop a rural vulnerability index that accounts for these dynamics, encompassing 27 variables calculated at municipal and county levels from publicly available data. We apply the index to the case of Spain, one of the largest producers of agricultural commodities and one of the most affected by depopulation and climate change in the European Union. We demonstrate the existence of a vulnerability belt around the country's central plateau, which is notably driven by shifts in climate, the adverse effects of the global food regime, and low adaptive capacity of the municipalities that conform such belt. We also show that most and least vulnerable counties exhibit contrasting spatial distributions at the municipal level, and that overlapping impacts of the three stressors occur mostly in remote rural areas. The research illustrates the importance of integrating depopulation in the study of multi-stressor rural vulnerability and sheds light on the potential and limitations of using a quantitative and spatially explicit indices for the assessment of rural vulnerability in Spain, and potentially other European countries.

1. Introduction

Rural regions cover more than 80 % of the European Union (EU)'s territory and are home to almost 30 % of its population (European Commission, 2021). They are key providers of human food, animal feed and vegetal fibre products, and harbour an important part of human history and cultural heritage (Van Vliet et al., 2015; Kristensen, 2016; European Commission, 2021). However, since the early 1950s, European rural regions have lost approximately 20 million inhabitants, i.e., 9 % of their population, mostly for the benefit of urban regions (Pinilla & Sáez 2021). In the most mountainous and isolated rural areas, outmigration has translated in land abandonment and in the regeneration of local vegetation cover (MacDonald et al., 2000; Stürck et al., 2018; Fayet et al., 2022). In more fertile and less isolated regions, agricultural activities have intensified, and rural property has concentrated in fewer hands, leading to changes in cropping patterns, local livelihoods, and biodiversity (Caraveli, 2000; Bais-Moleman et al., 2019). Compounding these dynamics are climate-induced shifts in rainfall and temperature, soil degradation, the volatility of globalized rural economies, and inadequate infrastructure, all of which increase the environmental and social vulnerability of European rural regions (Lazarte, 2017).

Spain represents a paradigmatic case of overlapping rural vulnerabilities within Europe. Three key stressors stand out for their significant – either direct or indirect- impacts on the wellbeing of Spain's rural: climate change, depopulation, the global food regime (see Section 2.2 for further details). Spain has suffered from droughts more than any

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other European countries over the last two decades (van Daalen et al., 2022), and estimations confirm that the country will continue to experience reductions in average precipitation, increases in average temperatures, and higher frequencies of heatwaves in the coming decades (IPCC 2021). Also, many rural areas in Spain have lost and continue to lose population, driven by decreasing birth rates – the lowest in the EU (Rudakova et al., 2023) -, agricultural mechanization, and the economic and cultural appeal of cities (Pinilla and Sáez, 2017; Mesa, 2019). Depopulation, and specifically outmigration, can also be partly explained by the fact that small-scale and family farmers have been increasingly marginalized from and unable to participate in the global food regime. This regime is broadly understood as a system of food production and consumption dominated by global agrifood transnational corporations, driven by world market prices and short-run profitability, geared towards the cultivation of food for export and vertical value chains, and supported by fossil fuels, large-scale mechanization, agrochemicals and transgenic organisms (McMichael, 2013; Akram-Lodhi, 2018). Spain, particularly its export oriented regions, has become a global player in the global food regime (González de Molina et al., 2019, Guzmán et al., 2022); however, they have also become increasingly vulnerable to global price volatility and protectionist shifts, such as those recently led by the United States (Delle Femine, 2025).

Ad-hoc accounts of these overlapping threats to the viability and sustainability of rural livelihoods exist in growing numbers in Spain and other countries. However, efforts to identify larger-scale patterns that inform comparative case study work and more effective rural development policy remain scarce. This is particularly the case when integrating the study of population with other global threats like climate change or economic globalization.

Given all the above, this study addresses the following questions: ¿To which extent vulnerability to depopulation intersects with vulnerability to climate change and the global food regime in Spain's rural areas? Which patterns emerge from those intersections? Which lessons can be drawn from the study of intersecting vulnerabilities in Spain?.

To answer our research questions we develop a spatially informative Socio-Environmental Rural Vulnerability Index for Spain (hereafter referred as SERVI), grounded on integrated approaches to multi-stressor vulnerability (Füssel, 2007; IPCC, 2007). The index is composed of three main analytical categories: the level of exposure and sensitivity of a given system to an experienced stressor (e.g., a rural household's exposure and sensitivity to declining rainfall patterns), and its capacity to adapt (e.g., a rural household's ability to respond, or even take advantage of such reducing rainfall). As we illustrate, the index allows the identification of several patterns, including most notably the localization of a "vulnerability belt" of high-vulnerability municipalities, as well as distinctive spatial patterns across higher and lower vulnerability municipalities and types of rural areas. Scholarly, the study contributes to integrating the effects of depopulation in the study of vulnerability to multiple threats. To our knowledge, the index is the first attempt to incorporate depopulation as one of multiple stressors driving rural vulnerability and probably the first index of this kind developed for a European country. Policy wise, the index provides evidence supporting integrative rural development policies that maximize synergies and minimize trade-offs of dealing with multiple threats simultaneously.

What follows provides a brief overview of the literature on vulnerability indices, background information on Spain's rural areas, and a justification of the three stressors highlighted above. We then outline the analytical framework and methods used to calculate the SERVI, before presenting and discussing the main findings. The article concludes with policy implications resulting from this research.

2. Measuring socio-environmental rural vulnerability and the case of Spain

2.1. Vulnerability indices

Vulnerability has been understood as "*the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt*" (Adger, 2006, p.1). Research in this field has mainly explored how individuals, households, and communities are stressed by ecological, socio-economic, and political changes, and how any resulting impacts are modulated by endogenous factors, such as demographic characteristics, or resource availability (Lazarte, 2017). Inspired by disasters research, human geography, human ecology, and various other academic traditions, the vulnerability concept has evolved and become multifaceted (Adger, 2006, Hinkel, 2011). Early contributions helped to shed light on its social dimensions, showing how the susceptibility of groups to harm is also the product of social and spatial inequalities (Cutter et al., 2012). Socio-ecological systems research connected vulnerability to the systemic analysis of changes and shocks in interactive social and ecological sub-systems (Gallopín, 2006). Notable contributions also came from disasters research, with scholars devoted to investigating the conditions that modulate the impact of disasters on specific social groups, looking at socioeconomic and demographic factors (Flanagan et al., 2011; Fatemi et al., 2017).

Vulnerability assessments have also evolved over the past three decades: the initial observation of vulnerability to single stressors has been progressively replaced by a growing interest in the overlap and interactions between multiple stressors (Räsänen et al., 2016; Drakes and Tate, 2022). Much of this research has been qualitative and case study based (Kim et al., 2017), with larger-scale quantitative assessments consisting mostly of indices concerned with single vulnerability stressors, climate change in particular (Nguyen et al., 2016). Within the latter scholarship, vulnerability indices have flourished in the past 20 years, offering frameworks that enable operationalizing vulnerability research in a variety of contexts (e.g., Hahn et al., 2009; Balica et al., 2012; Shah et al., 2013; Nguyen et al., 2017; Hadipour et al., 2020).

Vulnerability indices offer a concise representation of complex realities (Vincent, 2004; Tate, 2012; Angeon and Bates, 2015), enabling comparisons across regions through spatial visualizations and facilitating the assessment of changes over time (O'Brien et al., 2004; Holand et al., 2011; Armaş, Gavriş.,2013). While it is undeniable that indices simplify complex dynamic processes in social-ecological systems by representing them through measurable static variables, they present great potential as a tool to support rural policy design and implementation (Shah et al., 2013; He et al., 2021).

In general, climate change vulnerability indices combine indicators related to both temperature and precipitation variability, and have explored very distinct geographical contexts, including the Indian Himalayas (Gupta et al., 2020), mountain villages in Vietnam (Nguyen and Leisz, 2021), and European cities (Tapia et al., 2017), among others. However, climate change is only one among a variety of stressors that drive rural vulnerability (O'Brien et al., 2004). O'Brien and Leichenko (2000) and O'Brien et al. (2004) innovatively analysed vulnerability to climate change and market-based price fluctuations in India and found that the combination of these two stressors exacerbated rural vulnerability, creating a new set of "double losers" and "double winners" among Indian rural households. Since these two seminal works were published, a growing body of scholarship has shown how multiple stressors interact and affect socio-environmental vulnerability (see e.g., Nyantakyi-Frimpong and Bezner-Kerr, 2015; Lele et al., 2018; Freduah et al., 2019), and how indices that capture vulnerability to multiple threats can support the design of more integrative rural development policy programs (He et al., 2021).

Also, indices must be carefully designed to fit local contexts and stressors, as well as the socio-economic, institutional, and cultural factors that determine vulnerability (e.g., Flanagan et al., 2011; Kuhlicke et al., 2011). For example, the Livelihood Vulnerability Index - LVI-IPCC (Hahn et al., 2009) was originally designed to assess rural vulnerability to climate change in Mozambique, where other compounding threats such as malaria influence the sustainability of rural livelihoods. This index has been adapted and applied in other African and South-East Asian countries, including India, Bangladesh, Ghana, China, Nepal, and Ethiopia, both at local and regional scales (Kumari et al., 2023). Similarly, the Composite Livelihood Vulnerability Index - CLVI (Nguyen and Leisz, 2021) was applied to ethnic minority groups in Vietnam and includes variables that are not entirely meaningful in other contexts.

2.2. Three inter-connected stressors: climate change, depopulation and the global food regime

Climate change, depopulation, and the global food regime are transforming rural regions in Spain, as well as in many other EU countries, by affecting farms' generational renewal and land-use patterns, and by compromising the viability and sustainability of farm-based livelihoods. They share the characteristic of being both endogenous and exogenous stressors. For example, shifts in rainfall and temperature may justify the intensification of agriculture, which in turn can contribute to higher greenhouse gas emissions as well as land abandonment and depopulation (Quintas-Soriano et al., 2023). Population losses are driven by the economic and cultural appeal of cities, but also by reduced hope about the future of rural livelihoods in contexts of rural depopulation and the family farm crisis (Pinilla & Sáez 2017); and the increasing dominance of the global food regime is both a cause and a consequence of the weakened agency of family farming (Etxezarreta et al., 2015).

Although other stressors—such as soil erosion and biodiversity loss—could have been incorporated into the development of the proposed index, we selected depopulation, the global food regime, and climate change due to their central role in existing analyses of rural trends and challenges in Spain (Borras-Pentinat and Villavicencio-Calzadilla, 2023; Collantes and Pinilla, 2019; Rolo and Moreno, 2019). These stressors had been included in Spain's Recovery, Transformation, and Resilience Plan, which identifies climate change, territorial inequality, population aging, and the urban–rural divide as key current and future national challenges (Gobierno de España. Plan de Recuperación, 2021). We also chose the stressors based on our own research, which shows that Spanish farmers frequently cite climatic, demographic, and market-related issues as major sources of both productive and well-being distress (Villamayor-Tomasás, 2018; Albizua et al., 2019; Facchini et al., 2023). Lastly, our findings resonate with broader studies predicting that rural impoverishment in Spain will likely intensify under climate change scenarios (Vargas-Amelin and Pindado, 2014). As noted by Quiroga and Suárez (2016), climate change-induced droughts—particularly in southern and interior regions—have exacerbated income inequality, disproportionately affecting lower-income farmers and placing rainfed agricultural areas, such as those reliant on olive and grape production, at heightened risk.

Indeed, Spain's climate is changing. Since 2010, the country has experienced an increase in the number of warmer years, with 11 of the past 13 years recording an average annual temperature above that of the previous 30-year average (AEMET. Agencia Estatal de Meteorología., 2023). These warmer temperature anomalies have been accompanied by a lengthening of the summer season, an increase in the number of heat waves, a slight decrease in average rainfall, and a trend towards earlier spring rains and reduced summer rains (Vicente-Serrano et al., 2017; AEMET. Agencia Estatal de Meteorología.,2023). Projections indicate that climatic trends will intensify in the coming decades, with significant impacts on rural livelihoods, including reduced water availability, lower crop yields, increased soil degradation and desertification, and greater health risks from extreme events like heatwaves (MITECO, 2020). These climatic impacts and risks will particularly affect the 7.6 million people living in Spain's rural areas, 16 % of the country's total population in 2020 (MAPA, 2021).

Rural areas occupy around 72.5 % of the national territory (~367 thousand km^2) and encompass 6714 municipalities. Primary sector activities represent only 9 % of the gross value added of rural areas and employ approximately 25 % of the rural active population (BOE, 2010). Yet, such activities are essential for the maintenance of key provisioning and cultural ecosystem services (Spanish National Ecosystem Assessment, 2014). Since the second half of the twenty century, however, Spain's rural population has decreased in absolute numbers (from 13,3 million in 1950–9,4 million in 2001) and in relative numbers (from 49 % in 1950–24 % by the early 2000s) (MPTAP, 2019; Pinilla and Sáez 2021). Such depopulation trend is driven by high emigration rates, increasing predominance of male individuals, ageing, negative natural population growth, lack of employment opportunities, the cultural and social appeal of not-so-distant cities, and limited social infrastructure and services (Pinilla & Sáez 2021; Gil-Alonso et al., 2023). While some suggest that depopulation has had positive environmental effects, such as the increase in forest cover (Melendez-Pastor et al., 2014), others highlight that it contributes to the loss of traditional ecological knowledge, practices, and technologies, thus reducing rural peoples' adaptive capacity (Quintas-Soriano et al., 2016; MITECO, 2020).

Depopulation, and the resulting labour scarcity, have also contributed to the reconfiguration of rural livelihoods, both in type and number. Where feasible, small-scale, diverse rural landscapes are becoming mechanized and properties are being concentrated in fewer hands. This shift has accompanied and facilitated Spain's growing integration into the global food regime. Spain is the fourth-largest net exporter of raw and processed agricultural and fishery products in the European Union, after the Netherlands, Germany, and France (MAPA, 2023). The number of export-focused agribusinesses in the country has increased by 14.5 %, and the gross exported value by 89.3 % since 2013 (MAPA, 2023). Spain is currently the fourth-largest producer of pig meat globally, with the pig industry accounting for 14 % of the country's industrial GDP (MAPA, 2023). Despite these benefits, the global food regime has also created its own vulnerabilities. The increase in food production and exports nationally and globally has come at the expense of higher greenhouse gas emissions, biodiversity loss, and soil and water pollution (Springmann et al., 2018), as well as the simplification of human diets (Willett et al., 2019). In Spain, export-oriented territories have become particularly sensitive to the volatility of global market prices and economic downturns (Moral-Pajares et al., 2024), decreased market power of farmers (Herranz De Rafael and Fernández-Prados, 2018), or protectionist cycles like the one recently led by the United States (Gutiérrez Chacón & Machuca 2021; Pons, 2025). Additionally, the global food regime has meant the opening of the Spanish market to foreign products and the potential displacement of local production by those products. Spain is the fifth-largest importer of agricultural products in the European Union (MAPA, 2023).

2.3. Developing the SERVI

As hinted above, different indices have studied vulnerability in different ways (Hinkel, 2011). In this study we adopt Adger's (2006) approach, also used in the IPCC (2007) and several subsequent studies (Polsky et al., 2007, Nguyen et al., 2017, Albizua et al., 2019, Yoo et al., 2011). According to this approach the vulnerability of a given system (e.g., a household, a municipality, or a broader rural region) is a function of three components: exposure, sensitivity, and adaptive capacity (Fig. 1). Exposure is the degree to which a system experiences a given stressor, disturbance, shock, or hazard that is exogenous to such a system. As noted earlier, defining whether climate change, globalization and depopulation are exogenous or endogenous is not straightforward, thus we consider them both exogenous and endogenous. Sensitivity, in turn, refers to the degree to which the system can be adversely affected by the

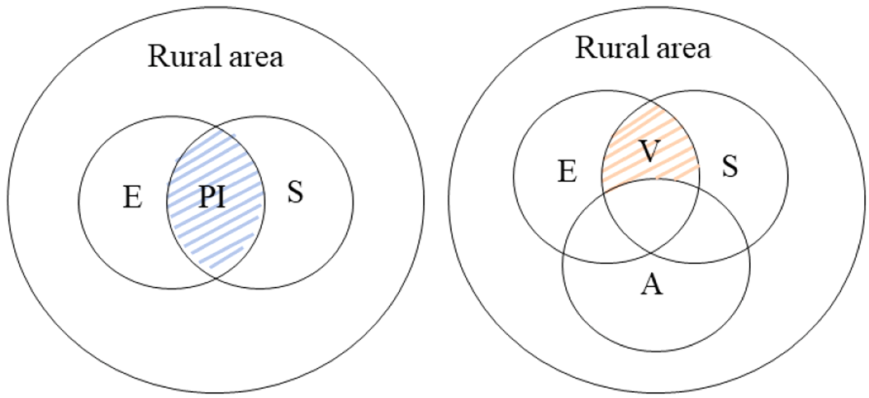

Fig. 1. Relationships among vulnerability components. Note: The areas in the Venn diagrams represent the degree of Exposure (E), Sensitivity (S) and Adaptive Capacity (A) of a territory to a stressor. Potential impact (PI) emerges from the intersection of exposure (E) and sensitivity (S). Territories that are highly exposed and sensitive to a stressor, face a high potential impact of that stressor. Vulnerability emerges after subtracting adaptive capacity to potential impact. The higher the adaptive capacity the more it offsets the potential impact of a stressor in a territory. Source: adapted from Nguyen et al. (2017).

stressor(s), and it is typically influenced by the natural, physical, or socio-economic characteristics of the system. Exposure and sensitivity in combination determine the potential impact of the system's stressor, disturbance, shock, or hazard (Nguyen et al., 2017). Lastly, adaptive capacity refers to the resources the system has or lacks to adjust to the stressor, take advantage of opportunities, or cope with the consequences. The level of adaptive capacity of a system is thus a function of human, natural, physical, and financial resources (Eakin and Luers, 2006), as well as the presence or absence of individual and collective agency to deploy those assets within particular social, institutional, and cultural contexts (Brown and Westaway, 2011).

Integrating these components, consider a scenario wherein a rural area experiences droughts, as depicted in Fig. 1. The level of exposure (E) of the rural area to droughts would be contingent upon factors such as geographical coverage, frequency, length, or intensity of the drought events. The level of sensitivity (S) would be, in turn, influenced by the reliance of its economy and/or livelihoods on water-dependent activities like rainfed agriculture. The rural area would exhibit a high level of adaptive capacity (A) if it had the means to develop responses that could reduce future levels of exposure and sensitivity to drought. The latter may involve actions such as planting drought-tolerant crops or diversifying livelihood activities. The resulting potential impact (PI) characterizes an area facing both high exposure and sensitivity to droughts. Consequently, an area that is solely exposed or sensitive alone may experience minimal impact from the stressor (Fritzsche et al., 2017; Nguyen et al., 2017). Therefore, a vulnerable area (V) to droughts is one that can be potentially impacted and shows adaptive capacity deficits, i.e. a lack of necessary resources and ability to effectively adapt and cope with the effects of droughts.

To develop the *SERVI*, we considered the potential levels of exposure, sensitivity, and adaptive capacity of rural livelihoods to climate change, depopulation, and the global food regime (Fig. 2). We selected the variables of the index based on a literature review, interviews and an expert survey (see Supplementary Material 1). The literature review (see Supplementary Material 2) included articles that referred to all or any of the three components of vulnerability in the context of climate change, globalization or depopulation worldwide. The list of variables was then refined and complemented through semi-structured interviews with 12 experts in rural development in Spain, selected via snowballing sampling. The survey included 49 variables that had resulted from the

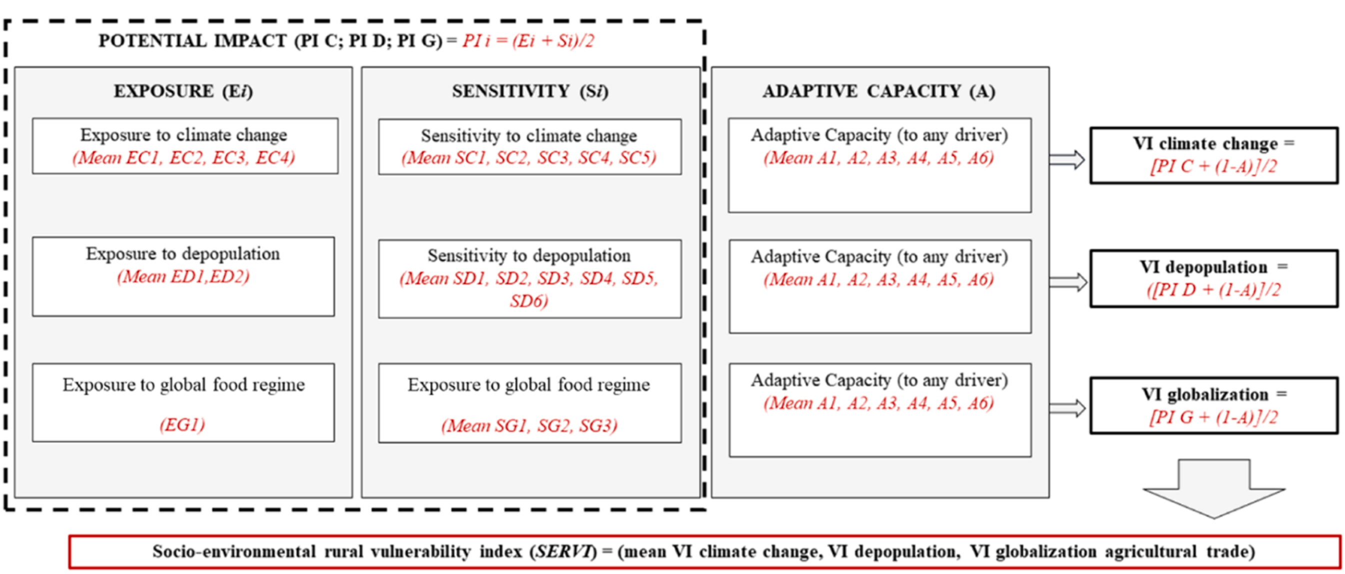

Fig. 2. Socio-environmental rural vulnerability index (SERVI) and its constituted components. Detailed list of variables for each component is provided in Table 1. Note: The index builds on the premise that exposure, sensitivity and adaptive capacity interact, with the former two aggravating vulnerability and the latter ameliorating it. Alternatively, the index does not presuppose specific interactions between vulnerability scores to the different stressors, which are averaged to compute the overall SERVI.

previous two steps (see Supplementary Material 3). The expert sample included 113 local agents of the European LEADER rural development program (45 % response rate); and 60 Spanish researchers (67 % response rate) from universities and research centres selected based on their expertise in each of the studied stressors. The survey resulted in a final selection of 27 variables (Table 1 and Supplementary Material 4).

To calculate the index we first calculated vulnerability sub-indices (VI) for each stressor (Fig. 2). Exposure and sensitivity scores were first averaged to calculate potential impact scores for each stressor. The resulting scores were then averaged with "adaptive capacity deficit" scores (1-Adaptive capacity scores). The same adaptive capacity deficit scores were used to calculate all vulnerability sub-indices. Data was obtained from a variety of public sources and rescaled (see Supplementary Material 4 for details). The sub-indices were then averaged to calculate the overall index (SERVI) for the ensemble of the three stressors. All indices were calculated at the municipal level and then averaged across municipalities to obtain county-level scores (see Supplementary Material 1).

3. Results

3.1. Socio-environmental rural vulnerability in Spain

The value of the SERVI for Spanish rural municipalities is on average 0.42, with a standard deviation (SD) of 0.10 (Table 2). This number does not mean much by itself as the index is unitless; however, it can be used as reference to assess the score of individual municipalities and/or compare with the average potential impact and adaptive capacity deficit, and the vulnerability sub-indices. At large, adaptive capacity deficit weights considerably more in the computation of vulnerability (average score of 0.57) than potential impact (scores of 0.18–0.33). The potential impact of the global food regime stands out for its comparatively lower average score (0.18) and therefore lower contribution to vulnerability than the potential impact of the rest of the stressors (see Section 3.2.3 for further details). Despite this, the vulnerability sub-indices are relatively similar with each other (ranging from 0.38 to 0.45), due to the homogenizing effect of adaptive capacity deficits (the three sub-indices share the same adaptive capacity scores) (Table 2).

The distribution of vulnerability is not homogeneous across Spain's rural areas. The most vulnerable counties are found in the regions of *Castilla y León* (here, 77 % of the counties have a vulnerability ranging from 0.46 to 0.56), *Navarra* (43 % of the counties), and *Castilla la Mancha* (34 % of the counties) (Fig. 3, panel A). High vulnerability values owe to high potential impact (exposure and/or sensitivity) scores and/or low adaptive capacity scores (see results of the vulnerability indices for each stressor in forthcoming sub-sections, i.e., Fig. 4). Also, there is large heterogeneity at the municipal level, particularly in the highest vulnerability counties (Fig. 3, panel B1).

The Spanish counties with the lowest SERVI values are mostly found in central and southern Spain, specifically in the autonomous communities of *Las Islas Canarias*, *Murcia*, *Islas Baleares* (100 % of the counties have a relatively low vulnerability score ranging from 0.20 to 0.35), *País Vasco* (55 % of the counties), *Comunidad Valenciana* (54 % of the counties), *Madrid* (50 % of the counties), and *Andalucía* (47 % of the counties) (Fig. 3, panels A1-A2). At the municipality level, there is significantly less heterogeneity as compared to the most vulnerable counties (*F Test* =1.307; p-value=0.000; see also Fig. 3, panels B1 and B2).

The scores of potential impact distributions for depopulation and global food regime across counties are right-skewed (see Supplementary Material 6). This suggests that the potential impact of such stressors in a county is explained by a comparatively smaller group of municipalities than it is for climate change. In contrast, adaptive capacity deficit scores are left-skewed, suggesting that an important proportion of Spain's rural counties has relatively low adaptive capacity. Overall, the values of the SERVI across rural Spanish counties illustrate a clear vulnerability belt

Table 1
Selected variables and indicators for climate change, depopulation, and the globalization of agricultural trade; and for each vulnerability component, i.e., exposure, sensitivity, and adaptive capacity (the full description of data sources and calculation can be found in Supplementary Material 2).

Vulnerability component	Variable (Name – Acronym)	Indicator
Climate change / Exposure	Increase in mean temperature – EC1	Annual change of mean temperature in °C for the period 1950 – 2010
	Decrease in mean rainfall – EC2	Annual change of mean precipitation in mm for the period 1950 – 2010
	Variability in mean temperature – EC3	Annual change of intra-annual coefficient of variation for the period 1950 – 2010
	Variability in mean rainfall – EC4	Annual change of intra-annual coefficient of variation for the period 1950 – 2010
Climate change / Sensitivity	Dependence on rainfed agriculture – SC1	Percentage of rainfed agriculture in the total utilised agricultural area for the year 2010
	Aged population (65-year-old and above) – SC2	Percentage of the population aged 65-year-old and above in the year 2020
	Wildfires risk – SC3	Number of wildfires per year per 100 ha for the period 2001 – 2014
	Soil erosion – SC4	Average soil loss in tons per hectare per year for the period 2002–2012
	Availability of water resources (quantity and quality) – SC5	Quantity and quality of groundwater and surface water for the period 2015–2021
Depopulation - Exposure	Ageing rate change – ED1	Percentage of annual growth of the aging population for the period 2011–2020
	Natural population growth rate change – ED2	Annual change of the natural population growth for the period 2016–2018
Depopulation - Sensitivity	Economic diversification – SD1	Shannon Economic Diversity index for the year 2019–2020
	Road connectivity (road density) – SD2	Density of roads in km/km^2 in the year 2020
	Concentration of social infrastructures – SD3	Concentration of social infrastructures at the county level for the year 2019–2021
	Proportion of small population centres – SD4	Percentage of municipalities in the county with a population of 500 inhabitants or less in the year 2020
	Availability of labour for women and youth – SD5	Percentage of women and youth unemployed per 100 economically active inhabitants in the 2019 and 2020
	Aged population – SD6	Number of people aged 65-year-old and above per 100 inhabitants under 15-year-old in 2020
Global food regime - Exposure	Economic losses – EG1	Economic losses driven by changes in crop prices received by producers over the period 2015 – 2021
Global food regime - Sensitivity	Dependence on agricultural exports – SG1	Agricultural export trade index for the year 2010
	Competition from imported food products – SG2	Agricultural import trade index for the year 2010.
	Dependence on small-scale rainfed agriculture – SG3	Percentage of small-scale rainfed traditional cereals in the year 2010
Adaptive Capacity	Education level – A1	Contribution to education of the province (educated

(*continued on next page*)

Table 1 (*continued*)

Vulnerability component	Variable (Name – Acronym)	Indicator
		inhabitants between 25 and 29-year-old in 2020)
	Women and young living in the territory – A2	Percentage of women and young people in the year 2020
	Professionalization of economic sectors – A3	Average number of companies in the period 2012–2020
	Development of social infrastructures – A4	Percentage of social infrastructures in the year 2019–2020
	Internet coverage – A5	Percentage of the population with internet coverage in the year 2019
	Well-conserved natural resources – A6	Percentage of the Natura 2000 network in the year 2020

Table 2
Values of the vulnerability index at the municipality level: the higher (lower) the value, the higher (lower) the vulnerability.

Index	Mean	Min	Max	SD
Socio-environmental vulnerability index	0.42	0.14	0.69	0.10
Climate change vulnerability index	0.43	0.15	0.69	0.08
Climate change potential impact	0.30	0.08	0.65	0.07
Depopulation vulnerability index	0.45	0.15	0.83	0.12
Depopulation potential impact	0.33	0.08	0.87	0.12
Global food regime index	0.38	0.08	0.83	0.12
Global food regime potential impact	0.18	0.00	0.90	0.18
Adaptive Capacity deficits	0.57	0.13	0.94	0.15

around the country's central plateau, and the existence of important heterogeneities within it, at the municipal level.

3.2. Single stressor vulnerabilities

3.2.1. Climate change

The vulnerability to climate change of Spanish counties is on average 0.43 (SD = 0.08). The highest level of climate change vulnerability is found in central and northern Spain (Fig. 4, panel A). The highest scores of vulnerability to climate change (scores ranging from 0.47 to 0.57, corresponding to the top quartile of the country-wide distribution) concentrate in *Cantabria* (83 % of the counties in that Autonomous Community), *Castilla y León* (61 % of the counties), *Galicia* and *Asturias* (40 % of the counties), *Extremadura* (36 % of the counties), and *Castilla la Mancha* (34 % of the counties). Low levels of vulnerability to climate change (scores ranging from 0.20 to 0.39, corresponding to the bottom quartile of the country-wide distribution) are observed in counties of *Las Islas Canarias* (100 % of the counties)*, Murcia* (83 % of the counties)*, Madrid* (67 % of the counties), *Comunidad Valenciana* (69 % of the counties)*,* and *Andalucía* (62 % of the counties). Climate change vulnerability seems to be driven more by exposure and sensitivity (potential impact) than by adaptive capacity deficits. This is particularly so in counties of *Cantabria*, *Galicia*, and *Extremadura* (Fig. 4, panel A and D).

As shown in Fig. 5, panel A, the average vulnerability to climate change of the most vulnerable municipalities to climate change (top quartile) is notably higher (25 % higher; score of 0.53) than average vulnerability of the rest of the municipalities (score of 0.40). *Increase in mean temperature* (EC1) and *decrease in mean rainfall* (EC2) are the exposure variables that contribute the most to climate change vulnerability. EC2 seems also to contribute the most to the distinctiveness of the most vulnerable municipalities (top quartile). Among sensitivity variables, *dependence on rainfed agriculture* (SC1) and *availability of water*

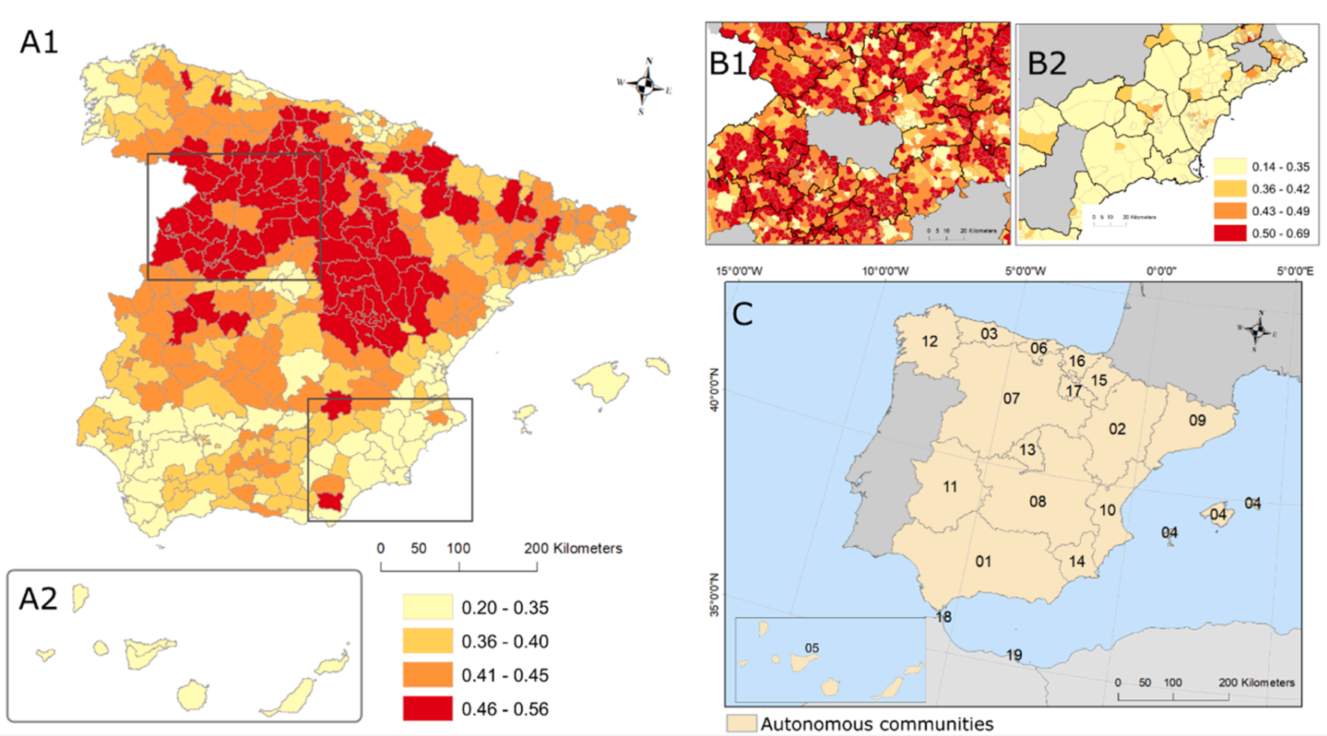

Fig. 3. SERVI values distribution across Spanish autonomous communities, counties and municipalities. Note: Panel A. Range of socio-environmental rural vulnerability at the county level. Panel B. Levels of vulnerability at the municipal level in a selection of the most (panel B1) and least (panel B2) vulnerable counties. In both panels, the higher (lower) the value, the higher (lower) the socio-environmental vulnerability score at the municipality level. Panel C. Spanish Autonomous Communities: *Andalucia* (1), *Aragón* (2), *Asturias* (3), *Islas Baleares* (4), *Las Islas Canarias* (5), *Cantabria* (6), *Castilla y León* (7), *Castilla la Mancha* (8), *Catalunya* (9), *Comunidad Valenciana* (10), *Extremadura* (11), *Galicia* (12), *Madrid* (13), *Murcia* (14), *Navarra* (15), *Pais Vasco* (16), La *Rioja* (17), *Ceuta* (18) and *Melilla* (19).

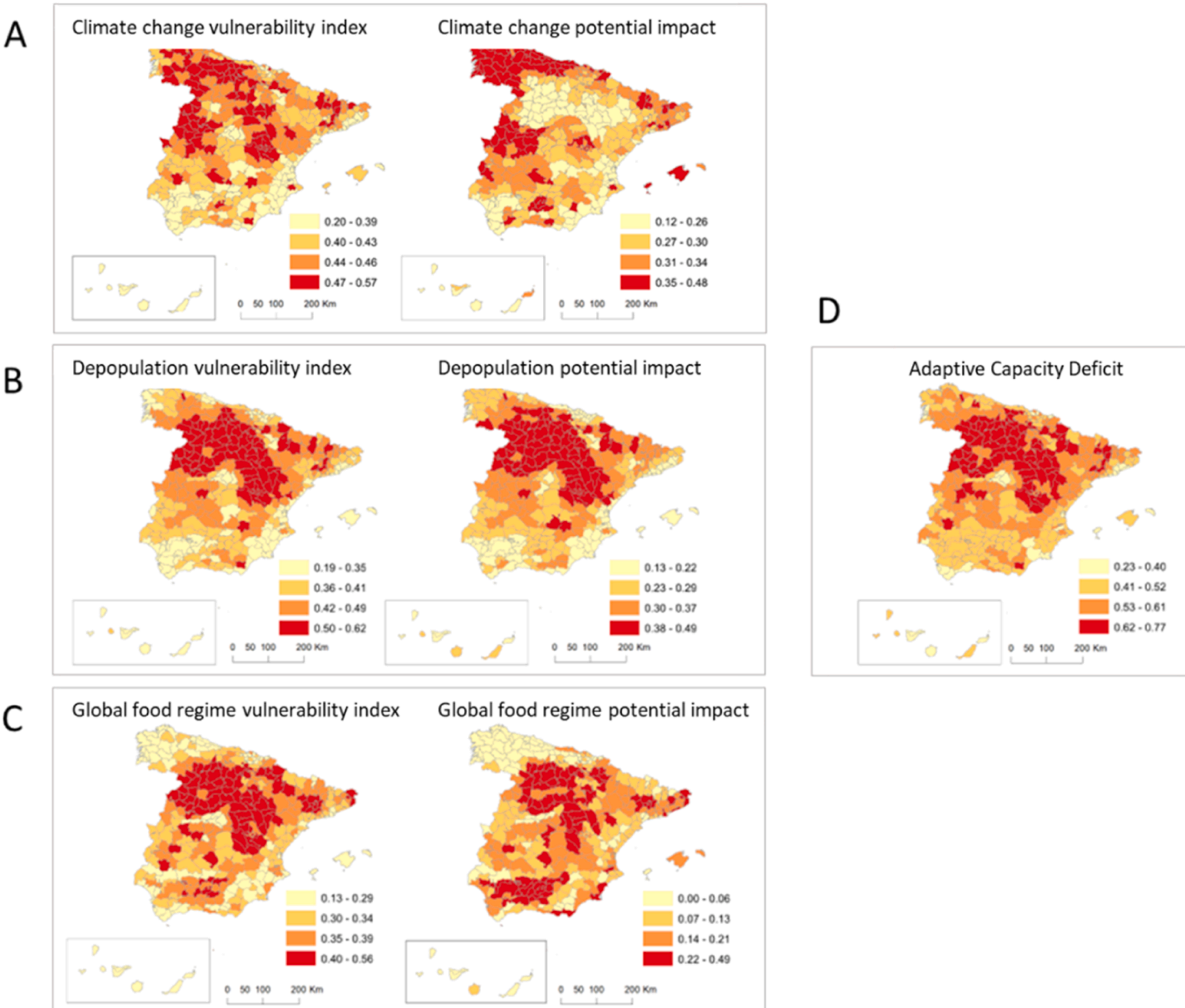

Fig. 4. Spatial distribution at county level of Vulnerability and Potential Impact of climate change (A), depopulation (B) global food regime (C), and of adaptive capacity (D). Note: Adaptive capacity deficit is common to the three vulnerability sub-indices. The higher the value for potential impact, and the higher the adaptive capacity deficits, the higher the vulnerability to the stressor. The colours represent quartiles.

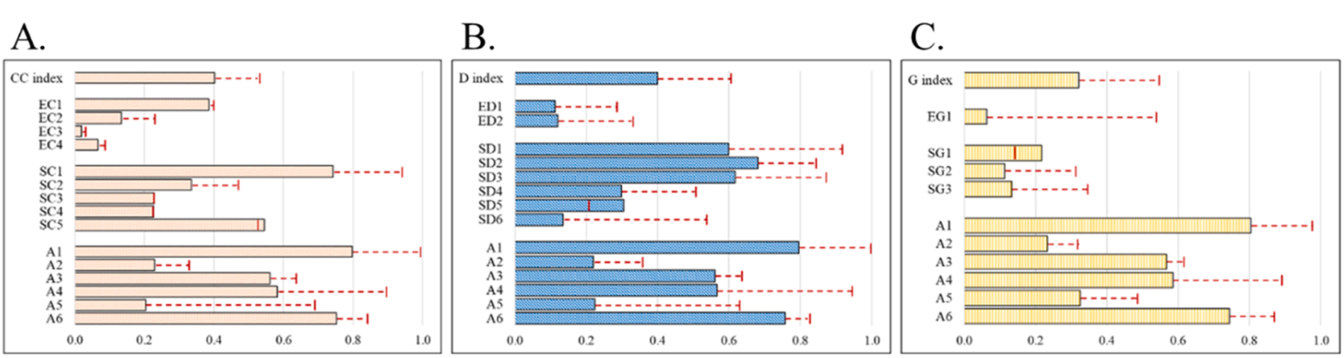

Fig. 5. Contribution of exposure, sensitivity, and adaptive capacity (i.e., adaptive capacity deficit) variables to Spanish municipalities' vulnerability to climate change (panel A), depopulation (panel B) and globalization of agricultural trade (panel C). Note: The dotted line indicates the mean value for highly vulnerable municipalities (above the 75 % climate (CC) /depopulation (D) /global food regime (G) vulnerability percentile in panels a/b/c, respectively). The bars indicate the mean value for all the remaining municipalities. Variable acronyms are included in Table 1. The larger the bar, the stronger the influence of that variable on the vulnerability score. The larger the dotted line the more is the variable contributing to the vulnerability of the top vulnerable municipalities. T-test scores (not displayed) indicated that mean values between the most vulnerable municipalities (top 25 %) and all the rest are different, except for EC1, EC3, SC3, SC4, and SC5. AS shown by variables SC5 and SG1, it is possible that the average score of the top vulnerable municipalities is lower than that of the remaining municipalities.

resources with a good quantity and quality status (SC5) are the most contributing variables to climate change vulnerability. SC1 and *aged population* (SC2) contribute proportionally more to the most vulnerable municipalities. Adaptive capacity deficits in *education level* (A1), in *well-conserved of natural resources* (A6), and in *social infrastructures* (A4) contribute the most to climate change vulnerability. A1 and A4, along with deficits in *internet coverage* (A5), contribute proportionally more to the most vulnerable municipalities. Maps with the results for each of the exposure, sensitivity and adaptive capacity variables for climate change and the other two stressors are presented in Supplementary Material 7.

3.2.2. Depopulation

The vulnerability to depopulation of Spanish counties is on average 0.45 (SD = 0.12) (Fig. 4, panel B). The territories within the top vulnerability quartile (0.50–0.62) are found in C*astilla y León* (83 % of the counties)*, Cantabria* (50 % of the counties)*, Aragón* and *La Rioja* (43 % of the counties), and in *Castilla la Mancha* (34 % of the counties). The lowest values are found in counties of *Murcia*, *Islas Baleares Las Islas Canarias*. Around 95 % of the counties in these Autonomous Communities fall in the lowest vulnerability quartile (0.19–0.35). Rural counties around the metropolitan areas of *Barcelona*, *Madrid,* and *Valencia* also stand out for their relatively low vulnerability scores. The contributions of potential impact and adaptive capacity deficit to vulnerability are less distinguishable than in the case of climate change vulnerability.

Average depopulation vulnerability scores of the most vulnerable municipalities (top quartile) are 34 % higher (score of 0.61) than of the rest of municipalities (score of 0.39) (Fig. 5). This difference is larger than the observed for climate change vulnerability. The two exposure variables, *ageing rate change* (ED1) and *natural population growth rate change* (ED2) contribute similarly to overall vulnerability and to the most vulnerable municipalities. The most influential sensitivity variables include *road connectivity of municipalities* (SD2), *concentration of social infrastructures* (SD3), and *economic diversification* (SD1). *Aged population* (SD6) stands out for contributing the most to the highly vulnerable municipalities, while *labour availability for women and youth* (SD5) stands out for weighting notably less in those same municipalities. Just like in the case of climate change, deficits in *level of education* (A1), *well-conserved natural resources* (A6), and *social infrastructures* (A4), contribute the most to depopulation vulnerability. A4 and *internet coverage* (A5) makes the difference for the most vulnerable municipalities.

3.2.3. The global food regime

The vulnerability of Spain's counties to their farmers' participation in the global food regime (reflected in uneven terms of trade, their focus on export, irrigation-oriented crops, or competition from imports, and an increased exposure to crop price volatility), is on average 0.38 (SD = 0.12) (Fig. 4, panel C). The highest levels of vulnerability are found in counties of *Castilla y León,* where 66 % of them have a vulnerability score ranging from 0.40 to 0.56 (top quartile)*, Navarra* (67 % of the counties), *Castilla la Mancha* (38 % of the counties)*,* and *Aragón* (33 % of the counties). The lowest vulnerability scores are observed in counties of *Las Islas Canarias and Islas Baleares*, where 100 % of them fall in the lowest vulnerability quartile (0.13–0.29)*; Galicia* (87 % of the counties); and *Asturias* (80 % of the counties).

Contrary to climate change, vulnerability to the global food regime is mostly driven by deficits in adaptive capacity and less so by potential impact (Fig. 5). This is visually evident in some counties of *Castilla y León* and *Extremadura* (low levels of exposure and/or sensitivity but strong adaptive capacity deficits and therefore high vulnerability); and a fair number of counties of *Andalucía* and *Murcia* (where low adaptive capacity deficits offset the high levels of exposure and/or sensitivity).

Also, the average vulnerability in the most vulnerable municipalities (top quartile) is 41 % higher (score of 0.55) than in the rest of municipalities (score of 0.32). This difference is larger than that observed for vulnerability to climate change and depopulation (Fig. 5). As shown in Supplementary Material 7, this is mostly driven by the distribution of potential impact, which is highly right skewed. Thus, although the average potential impact is relatively low (0.18), there are several municipalities exhibiting high potential impact levels. The exposure variable that contributes the most to potential impact (and vulnerability) is *economic losses* (EG1). No sensitivity variables stand out for their distinctive contribution to vulnerability; however, some of the sensitivity variables show some spatial patterns. As shown in Supplementary Material 7, *Dependence on agricultural export activities* (SG1) concentrates in the Mediterranean coast and South of Spain, while *Competition from imported food products* (SG2) and *Dependence on small-scale rainfed agriculture* (SG3) concentrate in the inner-country territories. Results regarding adaptive capacity deficits mirror those found for climate change and depopulation.

In summary, the vulnerability values obtained for each individual stressor show that the potential impacts of climate change are relatively widespread compared to the impacts of depopulation, which tend to be concentrated around the vulnerability belt of the country's central plateau. The potential impacts of the global food regime would be both concentrated in the vulnerability belt and in other territories. Additionally, although adaptive capacity deficit scores are relatively high across most municipalities, the greatest deficits are also found in the counties within the vulnerability belt.

3.3. The potential impact of multiple stressors across rural areas

We now turn to analyse the complex nature of vulnerability, looking at how municipalities are simultaneously affected by either one, two, or three of the studied stressors and how such impact gets distributed across different types of rurality (based on Reig Martínez et al., 2016). For this purpose, we focused on *potential impact* instead of SERVI scores. This is because adaptive capacity, which applies equally regardless of the stressor at hand, tends to homogenize results across stressors (see Figs. 4 and 5). Rural remote areas are defined as those with fewer than 150 inhabitants per squared kilometre and located more than 45mts. from the nearest urban centre, while rural accessible areas also have less than 150 inhabitants per squared kilometre but are situated within 45 mts. of an urban centre. Intermediate and urban areas are defined as those with more than 150 inhabitants per squared kilometre (Reig Martinez et al., 2016). With the aim of maximizing contrast, we focused on the municipalities that fell within the top quartile of potential impact (Figs. 6 and 7).

As shown in Figs. 6 and 7, climate change exhibits the most substantial potential impact on rural areas (56.5 % of the most potentially impacted rural areas), followed by depopulation (43.4 %) and the global food regimes (22.9 %). When considering the interaction of multiple stressors, we observe larger tracts of the territory affected by two of the stressors than by three of them. The combination of climate change and depopulation emerges as the most prevalent overlap (12.3 %), followed by the combined impact of depopulation and global food regime (8.4 %). The combination of all stressors affects only 0.9 % of the rural areas. The south of *Galicia*, north of *Extremadura* and some areas of the central Pyrenees (*Aragón*) and of northern *Castilla La Mancha* stand out for the high potential impact of both climate change and depopulation. The entire region of *Castilla y León* and the north of *Castilla La Mancha* include most of the municipalities impacted simultaneously by depopulation and the global food regime while the latter and climate change simultaneously impact most of the municipalities in *País Vasco* and *Navarra*, *Islas Baleares* and southern *Andalucia*.

Climate change shows a similar level of potential impact on both remote and accessible rural areas (58.4 % vs. 54.5 %, respectively). However, depopulation impacts rural remote areas to a greater extent than rural accessible areas (52.8 % vs. 33.6 %, respectively), while the impact of the global food regime is lower in rural remote areas (15.5 % vs 30.5 %, respectively). In terms of overlapping vulnerabilities, remote rural areas stand out due to the simultaneous impact of climate change

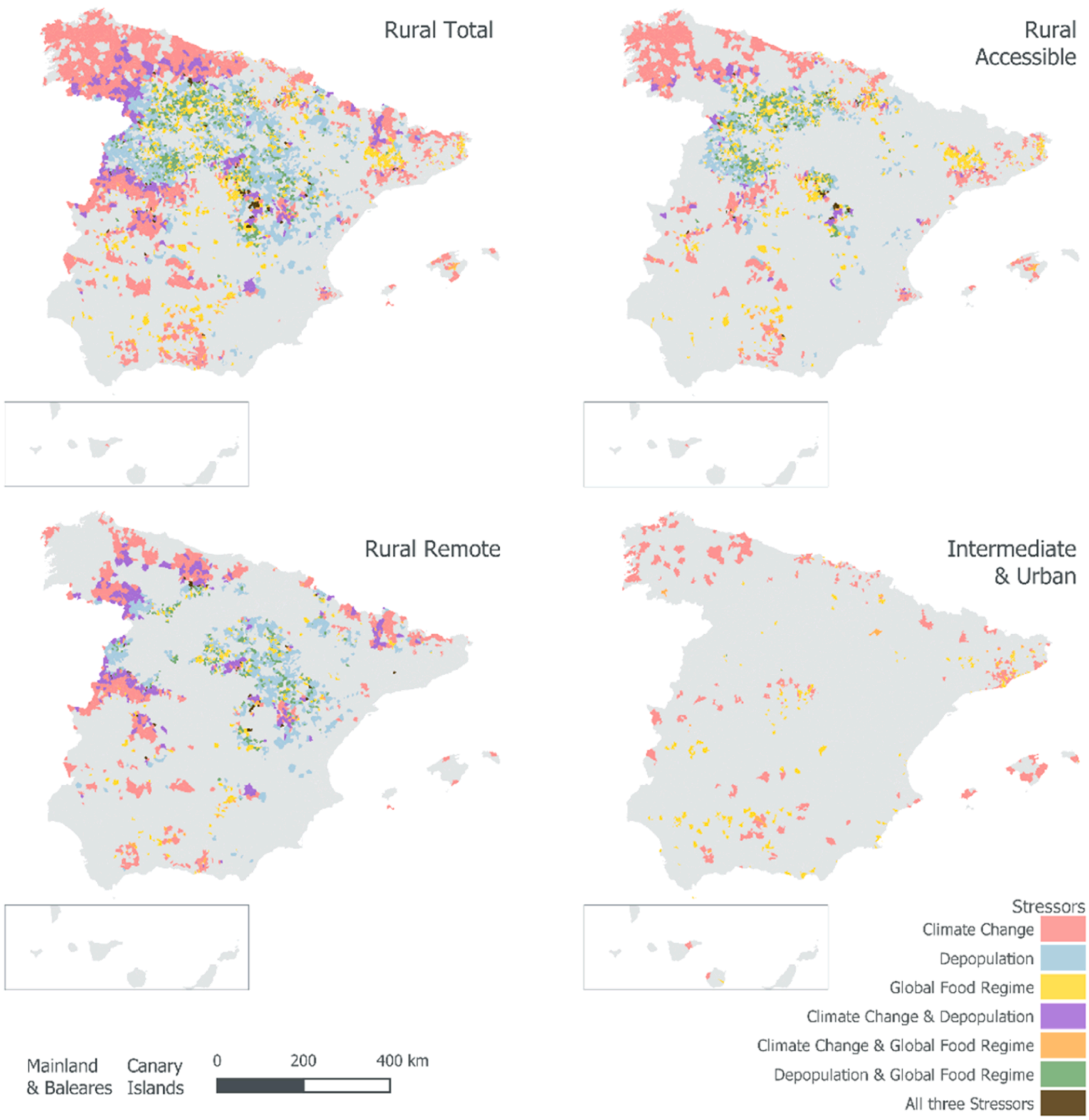

Fig. 6. Distribution of potential impact of different stressors and their combinations for the most vulnerable municipalities (top quartile) across different types of rural territories.

and depopulation (18 % of the area). Conversely, accessible rural areas are predominantly affected by the combined impact of depopulation and the global food regime (9.6 %).

4. Discussion

4.1. Intersecting vulnerabilities: drivers and consequences

The analysis of vulnerability at the municipal level reveals that most rural municipalities are affected by two, rather than three of the studied stressors. Climate change is the most widespread source of vulnerability, but it is depopulation that overlaps most frequently with the other two stressors. Double or triple-exposure effects tend to occur more frequently in remote rural areas. This is evident in municipalities of *Galicia*, *Extremadura* and the central *Pyrenees* which concentrate most of the municipalities impacted by both climate change and depopulation. Many of these municipalities are found in loosely connected, elevated, forested/pasture areas (e.g., *Dehesa* of Extremadura, prairies and *pazos* in Galicia, and various National Parks in the Pyrenees). These are historically sparsely populated areas that were nevertheless affected by a slow process of migration and population aging (Collantes and Pinilla, 2004, Ruiz-Labrador et al., 2023), with many villages simply now "disappearing". Most people have left (or passed away) and traditional agriculture and livestock breeding is being replaced by ecotourism activities and/or leading to land abandonment and forest regeneration (Bruno et al., 2021, Ruiz-Labrador et al., 2023, Sineiro-García et al., 2014). Some areas have also become climatic refuges for tourists, but this may change in the future given climate change projections. These are all relatively humid areas and climate change is particularly noticeable in the form of decreasing rainfall or snowfall. The concentration of forest regeneration in river catchments in some of these areas (e.g., Pyrenees) has also contributed to water scarcity in lower lands (López-Moreno et al., 2014).

Intersecting vulnerabilities are also evident in remote areas of *Castilla y León* and *Castilla La Mancha*, which concentrate most of the municipalities affected by depopulation and the global food regime. These areas fall in the popularly known region of "the empty Spain", which has indeed suffered from severe depopulation since the 1950s

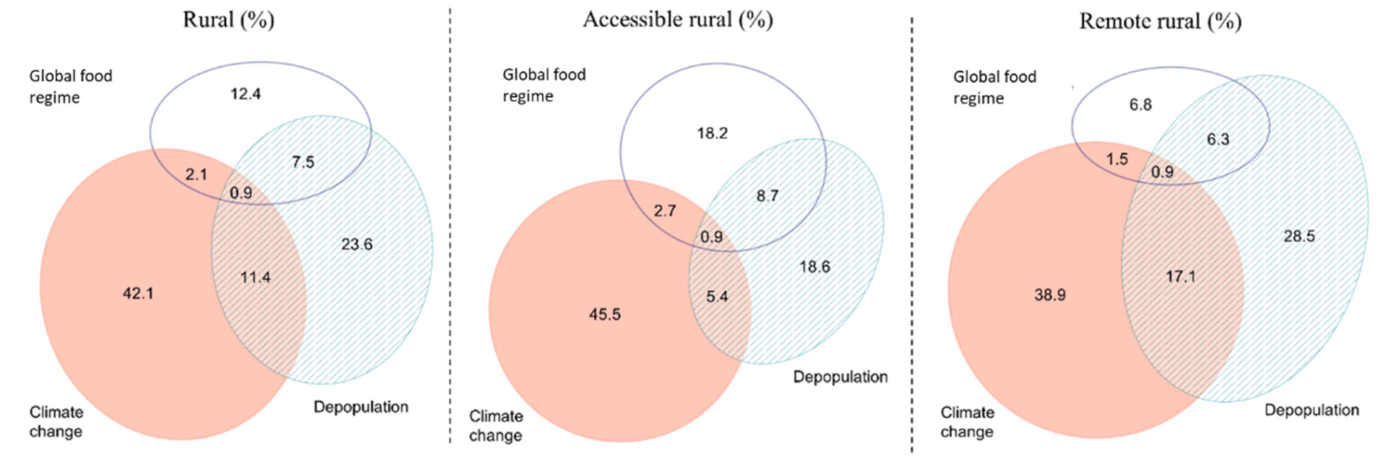

Fig. 7. Share (%) of the rural, rural remote and rural accessible rural areas most impacted (top quartile – representing 25 % of municipalities with the highest scores for potential impact) by single stressors and their combinations. Note: The Venn diagrams, generated using eulerAPE (Micallef and Rodgers, 2014), visually depict both individual and overlapping impacts on rural areas.

(Llorent-Bedmar et al., 2021). Pushed by decreased profitability in a context of global competition, many of these municipalities have specialized in large scale, mechanized cereal production after a progressive professionalization that has also involved land concentration. This process, however, has not protected these areas from increased competition from imported cereals (Gutiérrez-Moya et al., 2021) or a historical trend of livestock industrialization and concentration of market power in the hands of large livestock farms and feed mills and other corporate intermediaries (Navarro, 1997; Moliner, 2008). Also, this process has coevolved with generational renewal deficits in the agricultural sector, the rural exodus of the youth to urban areas since the 1960s, and distinct waves of foreign immigration (Collantes et al., 2014).

Our analysis also permits to visualize other vulnerable rural "Spains" (e.g., a "globalized" Spain and "warmed" rural Spain) as per their exposure and sensitivity (potential impact) to (of) the global food regime and climate change, respectively. The valley of the river Guadalquivir in southwestern Spain and some enclaves in the Mediterranean coast and north of Spain stand out for the potential impact of the global food regime, since agricultural production has geared completely towards export-based crops and is thus subject to price fluctuations and shifts in the terms of trade. The current protectionist shift led by the United States is expected to have a limited overall impact on the Spanish economy, as only 5 % of Spain's exports are destined for the U.S. However, the effects will vary by sector, with agricultural products—especially olives and wine—being disproportionately affected. (Delle Femine, 2025). The Spanish northwest—including parts of Galicia and Asturias—is particularly affected by climate change. Although these regions still experience relatively low temperatures and high rainfall compared to much of Spain, it is essential to interpret these trends within their local context. Notable progress has been made in mitigating drought impacts in Galicia; however, persistent structural challenges—such as inadequate infrastructure, poor maintenance, and deficiencies in water supply systems—continue to hinder resilience (Seguido, 2019).

4.2. Beyond "one size fits all" policy solutions

Our findings are important for the present and future of European rural development policy and related private investments and activities. First, we have made evident that high vulnerability counties are significantly and spatially more heterogeneous than low vulnerability ones. The former can include very vulnerable municipalities as well as relatively low-vulnerable municipalities. This suggests that there is not a unique experience of territorial vulnerability, not even at small administrative governance scales, which points to the need of taking scale seriously in socio-environmental assessments (Wilbanks and Kates, 1999) and avoiding fallacious conclusions about rural vulnerability when generalizing patterns from higher to lower scales (Meadowcroft, 2002).

Second, the influence of adaptive capacity deficits on vulnerability regardless of the stressor at hand suggests that a straightforward strategy for reducing rural vulnerability in Spain would be to invest in adaptive capacity, instead than in reducing sensitivity. For example, attempts to increase the education and professional skills of rural populations or to develop more, evenly spread, infrastructure and social services (all these measured here as adaptive capacity indicators) can contribute to diversify rural local economies, and reduce the sensitivity to depopulation while increasing the adaptive capacity to other stressors (Llorent-Bedmar et al., 2021). Our analysis shows, however, that not every investment in adaptive capacity may be worth it. As we found, some exposure, sensitivity and adaptive capacity variables carry greater weight than others in determining rural vulnerability and this varies also with the level of vulnerability of municipalities. In the case of adaptive capacity variables, *education level* and *well-conserved natural resources* contribute to reduce the vulnerability across the board of municipalities, but they are comparatively less influential than the *development of social infrastructures* and *internet coverage* in the case of high-vulnerable municipalities.

Finally, the patterns of intersecting vulnerabilities suggest that attempts to adapt to some stressors should consider effects on the exposure or sensitivity to other stressors. For example, as shown elsewhere, modernization and specialization of agriculture can contribute to maintaining jobs and halting depopulation in Spain and other European countries (Silvestre and Clar, 2010, Giannakis and Bruggeman, 2015), but also increase the dependence on and contamination of water resources, contribute to biodiversity loss, and/or deepen local dependence on global export-oriented crops (Emmerson et al., 2016, Albizua et al., 2019, Hostiou et al., 2020, Duarte et al., 2021). Rural development policies and projects are inevitably complex and should at least consider (and at best tackle) multiple environmental and social stressors at once. Single stressor and issue-focused initiatives are likely to fail or enhance single or multi-stressor vulnerability or maladaptation in the long term (Barnett and O'neill, 2010).

4.3. Usability and limitations

We believe that the vulnerability index and the spatial approach proposed in this article could serve as a reference for the development of a Europe-wide decision-support mechanism that includes a database with municipal-level public data and observes vulnerability to different threats over time. Climate change, depopulation, and the sustainability of family farms in the context of the global food regime are pressing issues across many if not all European rural regions (European Commission, 2021, 2022). Similarly, our analytical approach could be also adapted and improved for the study of rural vulnerability beyond the European context. It could also be used subject to many adjustments, for example, to understand the connections between urbanization, rural-urban migration, the feminization of agriculture, and shifts in land ownership, agricultural practices and food security levels in the global South (Leder, 2022; Langill et al., 2023; Doss et al., 2022); or to assess climate change impacts in countries with vast territories and diverse development levels.

Like similar spatial composite indices (Adger, 2006), the SERVI has limitations. The selection of variables inevitably involved a degree of arbitrariness. Although it was informed by a literature review and expert survey, the final index excluded some seemingly intuitive variables, such as agricultural income. Also, the validation process was conducted only at the national level, which likely led to the omission of variables that may be highly relevant in specific regional contexts. Moreover, our index suffers from typical limitations of spatial composite indexes, including: (1) its static nature – it is built based on data representing a point in time, although it can updated; (2) its spatial accuracy – it relies on representative numbers for administrative regions, such as counties or municipalities, not allowing expression of other geographies; (3) it includes a diversity of data types and timeframes, which range from climatic raw data over more than 50 years to static pre-processed data on water quantity and quality; and (4) it prioritizes transparency over precision by aggregating data through unweighted averages acknowledging that alternative technical approaches to index construction may affect the results (Fekete, 2012; Tate, 2012).

Taking into consideration these limitations, the application of our index should be complemented by situated and locally grounded qualitative research that explores the subjective experience of vulnerability and emerging responses (Adger, 2006; O'Brien and Wolf, 2010; Kuhlicke et al., 2011; Grothmann and Patt, 2005). Ultimately, individuals assess stressful situations based on their perceived likelihood of being affected and their capacity to take preventive or mitigating actions in specific contexts. (Cote and Nightingale, 2012; Manuel-Navarrete, 2015).

5. Conclusion

In this article we have developed the first comprehensive index to examine how climate change, depopulation and the global food regime influence rural vulnerability in Spain. The index, grounded on expert-selected variables, measures exposure and sensitivity to each of these three stressors, and integrates such analysis with an overarching assessment of adaptive capacity, at municipal and county levels. This approach permits to assess the relative importance of each of the three stressors and each of the components within, as well as their overlapping distributions across the territory.

We have revealed the existence of a vulnerability belt around Spain's central plateau, and demonstrated that, generally speaking, depopulation has a stronger weight on rural vulnerability than the other two stressors. We have also shown that high vulnerability counties are more heterogeneous at the municipal level than low vulnerability counties, which hints at the importance of scale in measuring vulnerability and designing or implementing policies for sustainable rural development. In this regard, we have argued that future climate change adaptation and agricultural development policies will be misguided if they do not account for the challenges that depopulation brings to Spain's rural areas, and if they are not attentive to trade-offs across vulnerability components, and across stressors. Future spatial analyses of vulnerability should be complemented with ethnographic and modelling research to better understand dynamics of multiple-exposure and to suggest pathways for vulnerability reduction and more resilient and sustainable rural areas.

CRediT authorship contribution statement

Gaitán Cremaschi Daniel: Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Sergio Villamayor-Tomas:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Conceptualization. **Esteve Corbera:** Writing – review & editing, Supervision, Project administration, Investigation, Conceptualization. **Pierri Daunt Beatriz:** Formal analysis, Investigation, Software, Visualization, Writing – review & editing. **Santos de Lima Leticia:** Formal analysis, Investigation, Software, Visualization, Writing – review & editing.

Declaration of Competing Interest

the authors declare no conflict of interests.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2025.104254.

Data availability

Data will be made available on request.

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