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RESEARCH

Toward spatially polarized human pressure? A dynamic factor analysis of ecological stability and the role of territorial gradients in Czech Republic

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Abstract In light of global change, research on ecosystem dynamics and the related environmental policies are increasingly required to face with the inherent polarization in areas with low and high human pressure. Differential levels of human pressure are hypothesized to reflect development paths toward ecological stability of local systems vis à vis socioeconomic resilience. To delineate the latent nexus between socioeconomic development paths and ecological stability of local systems, we proposed a multidimensional, diachronic analysis of 28 indicators of territorial disparities, and ecological stability in 206 homogeneous administrative units of Czech Republic over almost 30 years (1990–2018). Mixing time-invariant factors with time-varying socio-environmental attributes, a dynamic factor analysis investigated the latent relationship between ecosystem functions, environmental pressures, and the background socioeconomic characteristics of the selected spatial units. We identified four geographical gradients in Czech Republic (namely elevation, economic agglomeration, demographic structure, and soil imperviousness) at the base of territorial divides associated with the increased polarization in areas

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with low and high human pressure. The role of urbanization, agriculture, and loss of natural habitats reflective of rising human pressure was illustrated along the selected gradients. Finally, policy implications of the (changing) geography of ecological disturbances and local development paths in Czech Republic were briefly discussed.

Keywords Regional disparities · Geographical gradient · Indicators · Multiway factor analysis · Central Europe

Introduction

World ecosystems have experienced increased human pressures in recent times, leading to significant changes in their structure, relationships and functions (Cinner & Barnes, 2019). All together, these factors made the negative impact of global change on ecological stability even more unpredictable and hard to assess quantitatively (Baho et al., 2017). A declining capacity to cope with environmental change may lead to widespread erosion of ecological stability and undesirable regime shifts in social and economic equilibriums at both local and regional scales (Hughes et al., 2013). With this perspective in mind, ecological stability has been defined as the ability to maintain environmental functions despite disturbances (Turner et al., 1993). Ecosystem resilience, the most discussed component of ecological stability (Carr, 2019), was in turn defined as the capacity of a system to absorb and respond to a given disturbance (Holling, 1973), while maintaining its essential structure and functions (Folke et al., 2002). Resilience is frequently considered a measure identifying key ecological issues (Walker et al., 2009) and drivers of change in socioeconomic systems (Resilience Alliance, 2010).

Different mechanisms play a role in ecological stability (Oliver et al., 2015), operating at multiple territorial and landscape levels in complex (adaptive) cycles that respond to external changes and influence each other (Falk et al., 2019). Holling (2001) defined this hierarchy of adaptive cycles as "panarchy." The (intrinsically multidisciplinary) nature of territorial complexity makes the operational definition of ecological stability hard to set up (Capdevila et al., 2020), and some scholars even find it unquantifiable (Quinlan et al., 2016). At the landscape level, Bitterman and Bennett (2016) assumed ecological stability as dependent on (i) the state of system components, (ii) the complex interactions among components, as well as (iii) timing, location, and magnitude of disturbance. Based on this assumption, an integral assessment of ecological stability should include a multidimensional measurement of both (natural and human-driven) disturbances and conditions for system's stability, considering the intrinsic relationship with the background territorial and socioeconomic context (Egli et al., 2019).

In a given landscape, preconditions of ecological stability are features (or relationships) with a positive influence on ecological stability (Cumming, 2011; Carpenter et al. 2001; Nickayin et al. 2022). This implies consideration of both internal components (consisting of individual habitat features, their arrangement, boundaries, or spatial change) and external components (e.g. relationships, connectivity, dispersal of organisms, or spatial feedbacks). Biodiversity is one of the most frequently mentioned properties in connection with resilience and ecological stability influencing it positively at genetic, species, and landscape levels (Angeler & Allen, 2016; Brenkert & Malone, 2005; Folke, 2006; Mori et al., 2013). Landscape structure and configuration in turn promotes the maintenance and exchange of genetic information (Kéfi et al., 2007). The theory of "species legacy" predicts how species that survive disturbance can create ecological memory (Nyström & Folke, 2001) and, in appropriate arrangements (e.g., specific patterns and system connectivity), recolonize disturbed ecosystems and support their recovery (Jõgiste et al., 2017; Lavorel, 1999; McDonnell & Pickett, 1990). The ratio of natural to non-natural habitats has often used to approximate ecological stability at the landscape level (Hodgson et al., 2011). Landscape metrics evaluate shape and spatial arrangement of patches in a landscape that influence diversity, fragmentation, and structural connectivity (Lipský et al., 2011), thus playing a role in ecosystem dynamics and landscape stability (Lavorel et al., 2015). The statistical distribution of distances between patches is another indicator of biotic integrity related to habitat connectivity (Rüdisser et al., 2012). To assess resilience, McGarigal et al. (2018) used habitat connectivity together with hydrological connectivity and similarity. Empirical investigations of functional connectivity based on graph theory intensified more recently (e.g., Pascual-Hortal & Saura, 2006).

Disturbance regimes—especially in systems with a relatively low ecological stability—determine changes in species distribution and falling species abundance (Turner et al., 1993), and reduce the potential of stabilizing ecosystem mechanisms (Windsor et al., 2023). Such processes definitely lead to a deeper loss of ecological stability, narrowing the "resilience basin" (Scheffer et al., 2015), and making ecosystems even more vulnerable (Jackson et al., 2001). There are many types of disturbance regimes (e.g., van Nes & Scheffer, 2007), and their characteristics include duration, spatial extent, intensity, frequency, and type (Turner, 2010). Next to natural disturbances, ecosystems are also subject to human disturbances negatively impacting biodiversity and ecological integrity (McGarigal et al., 2018). Such disturbances are frequently recognized as important factors causing a (more or less) rapid decline in ecological stability (Sala et al., 2000). Representative disturbance factors in ecological science include climate change, land-use transformations, nitrogen deposition, atmospheric CO_2 and biotic exchange (Thuiller, 2007). Climate and land-use changes are expected to be particularly influential in temperate regions in the near future (Boulangeat et al., 2014).

As the result of urbanization, agricultural intensification and rural abandonment, land cover/land-use changes, a particularly impactful cause of ecological stability decline (e.g. Kairis et al., 2015), are associated with other negative aspects, such as the progressive reduction of natural and semi-natural habitats (Ceccarelli et al., 2014; Frondoni et al., 2011; Plieninger, 2012), fragmentation and loss of connectivity (Jongman, 2002; Van Eetvelde & Antrop, 2009; Wang et al., 2013), reduced water retention capacity and altered water regimes (Kedziora, 2010; Rockström et al., 1999; Skaloš et al., 2014), nitrogen pollution (Koerner et al., 2016; Payne et al., 2017; Tilman et al., 2001), and land degradation at large (Erdogan et al., 2011; Kosmas et al., 2016; Salvati et al., 2008).

Being quantified as the ability to maintain core functionalities when exposed to disturbance (Bitterman & Bennett, 2016), ecological stability was more recently associated with the resilience of comprehensive socio-ecological systems including (and being representative of) the landscape matrix at a given location together with the local communities interacting with it (Zavaleta & Chapin, 2010). With this perspective in mind, the decline of ecological stability of a given landscape was intrinsically associated with the continuous evolution of the socioeconomic background (Serra et al., 2014). Attempts to quantify ecological stability starting from this notion include rapid assessment approaches (Nemec et al., 2014), discontinuity approaches (Nash et al., 2014), and thresholds for persistence of multiple functions (Standish et al., 2014). By generalizing this concept, measures of ecological stability were based on dynamic equilibriums of local community structures (e.g., socioeconomic/territorial attributes) and landscape patterns that emerge under a particular combination of abiotic conditions such as topography, soils, and climate (Cushman & McGarigal, 2019), assuming such pattern-process dynamics as occurring primarily at the landscape scale (Turner, 1989).

In this context, the relationship between different structural patterns and functions can be more effectively investigated using the gradient approach (Allen et al., 2019). The "gradient" paradigm can be summarized with the assumption that graduated spatial environmental patterns determine the corresponding structure and function of ecological systems—whether populations, communities, or ecosystems (McDonnell & Pickett, 1990). The gradient approach allows for differentiation of stability conditions and succession rates and can help address modern concerns about the socioeconomic consequences of disturbance and the sustainability of ecosystem services (Walker, 2011). Ecologists, geographers, and environmental scientists have extensively studied natural gradients (e.g., soil moisture, air temperature, elevation, distance from the sea or inland water bodies) to elucidate the relationship between environmental change and ecosystem structure/functions (e.g., Austin, 1985; Becker et al., 2007; Keddy, 1989). Ecological gradients tend to be complex and relate to many environmental factors, creating multidimensional patterns of change that require specific measurement techniques and analytical strategies (Bajocco et al., 2012; Falk et al., 2019; Kéfi et al., 2019). For instance, climate-related factors such as precipitation and humidity, temperature and wind speed, as well as soil properties, change simultaneously with increasing elevation (Carr, 2019). Earlier studies have documented how these gradients have a given impact on forest, grassland, and other ecological systems (Liu et al., 2019;

Lu et al., 2014; Zhang et al., 2019). More specifically, soil and habitat quality seem to increase with elevation (Yu et al., 2021).

Natural gradients, however, are also relevant to social development because they create a contrasting environment that promotes the expansion of settlements and economic activities at specific locations along the relevant gradient (Galeotti, 2007). For instance, climate regimes, soil quality, and vegetation cover may influence the spatial distribution of urban, agricultural and industrial settlements (Antrop, 2005). Especially in regions with a millenary settlement history (Bajocco et al., 2016; Egli et al., 2019; Ferrara et al., 2020), land resources and climate have likely been key drivers of socioeconomic disparities (Corbelle-Rico et al., 2012), being the base of any polarization in land-use along both urban–rural and elevation gradients (Carr, 2019; Serra et al., 2014; van Meerbeek et al., 2021). Such territorial disparities, especially rural poverty and increased pressure on fragile areas, have been identified as a potential driver of land degradation (Iosifides & Politidis, 2005; Karamesouti et al., 2015; Smiraglia et al., 2016), recognized as one of the most powerful factors of landscape instability (Bajocco et al., 2012; Kosmas et al., 2016; Salvati et al., 2017). In economically dynamic regions, land-use change results in fragmented rural landscapes that rapidly lose their pristine attributes because of the decline of crop-natural mosaics (Cimini et al., 2013; Feranec et al., 2010; Geri et al., 2010; Pelorosso et al., 2009). By quantifying changes in ecosystem structures as a function of specific gradients (Yang et al., 2019), ecological studies may achieve a better understanding of the nature of exogenous impacts (e.g., clarifying the role of natural and human disturbance regimes) on forest, agricultural and urban ecosystems (McDonnell & Pickett, 1990). This will contribute answering pivotal research questions and developing innovative land management strategies (Gladstone-Gallagher et al., 2019).

With this perspective in mind, our study identified natural and human drivers that affect ecological stability at the spatial level of (local) territorial systems that integrate enough wide (and homogeneous) landscape scenes and a coherent socioeconomic community (Carr, 2019), by focusing on the combination of drivers that have caused the greatest decline in the same dimension of change (Falk et al., 2019). We adopted a multivariate exploratory statistical analysis of a number of indicators reflective of territorial change to disentangle the complexity of relationships between and within the various dimensions of ecological stability and territorial gradients (e.g. Capdevila et al., 2020) reflective of different socioeconomic conditions and, hence, human pressure, in Czech Republic (Central-Eastern Europe). In any exploratory study, the selection of relevant indicators is a basically subjective matter. In our case, a graphical illustration of the logical framework (Supplementary Materials Fig. 1) coupled with a comprehensive description of the adopted statistical rationale adopted contributes to delineate the novel contribution of our approach to ecological science vis à vis socioeconomic studies. In this perspective, exploratory statistical techniques provide an appropriate, flexible and multidimensional exploration of the latent gradients at the base of ecological stability (or instability) conditions and the related socioeconomic contexts in a local perspective (Salvati & Serra, 2016). In other words, exploratory multivariate statistics were assumed as a way of delineating the intimate, complex nexus between ecological dynamics and the background territorial and socioeconomic context in homogeneous local districts. For such reasons, despite the rigorous application of quantitative methodologies (Ferrara et al., 2012), the selection of indicators should maintain a margin of flexibility depending on the specific characteristics of the study area (e.g., Ferrara et al., 2016).

Taken as representative of highly urbanized regions with a longstanding (urban, agricultural, industrial) settlement tradition, a diachronic analysis of a vast set of relevant indicators of ecological stability characteristic of Czech landscapes identifies important dimensions at the base of environmental conditions and, indirectly, ecosystem functions along multiple geographical gradients (Cinner & Barnes, 2019). We thought the proposed approach (namely theory, indicators, and statistical techniques) as flexible as possible in order to be applied in broader contexts of both advanced economies and emerging countries (e.g., Ferrara et al., 2012). A summary presentation of the logical framework was provided in a graphical format (Supplementary Materials Fig. 1). Such approach and the related knowledge may represent an informative base contributing to spatial planning and environmental conservation policies in

Central-Eastern Europe and, with some generalizations, to the European continent at large.

Methodology

Study area

Territorial and socioeconomic contexts associated with ecological stability along specific geographical gradients were investigated over the entire territory of the Czech Republic, a Central European country extending 78,866 km^2 (Cudlín et al., 2020) and with an undulated topography (20% lowlands, 39% uplands at 300–600 m above the sea level, 30% highlands at 600–900 m above the sea level and, finally, 11% mountains at more than 900 m above the sea level). The climate regime of Czech Republic is predominantly temperate, with oceanic and continental influences that cause intense precipitation variability with recurrent droughts mainly affecting lowlands—where temperatures are generally higher and rainfall lower (Trnka et al., 2016). The study area is also diversified as far as soil and vegetation conditions. The specific location on the border of two mountain systems (Hercynian and Carpathian Mountains) accounts for a heterogeneous geology and a high diversity of natural/semi-natural habitat types (Cudlín et al., 2021). Lowlands with the highest productivity potential are intensively used as arable land or converted into urban and peri-urban settlements close to large cities and are therefore exposed to high human pressure (Pechanec et al., 2021). Conversely, population density is low in mountainous districts leading to extensive land management (Skaloš et al., 2011). In the last two decades, the main landscape changes included arable land abandonment and/or conversion to grassland; a more intense use of grassland and urbanisation of tourism-specialized districts were observed more frequently in recent years (Skaloš et al., 2014).

Indicators

Because ecological stability depends on the state of landscape components (ecosystems) and their interaction, and the degree of disturbance (e.g., Bitterman & Bennett, 2016), we attempt to assess each of these dimensions in a separate set of predictors. Thus, when we have considered ecological stability drivers, we included not only indicators of disturbance (or pressure), but also indicators relating to landscape features that are important for ecological stability (referred to as “stability preconditions”). Therefore, we classified the adopted indicators into distinctive groups as follows: (i) descriptive variables distinguishing between different landscape types and states, (ii) anthropogenic pressures, (iii) ecological stability preconditions, and (iv) manifestation of ecological stability, which we defined as the ability of the landscape to perform ecosystem functions in a stable manner over time. The list of selected indicators and the datasets used for their elaboration was presented in Table 1.

First, we used descriptive variables (i) to distinguish different conditions that may be important in identifying the relationship between various drivers. For this purpose, we used the classification of Landscape Types (LT) according to Löw (2005), specific territorial conditions as the total proportion of land belonging to LFAs, and population structure by age (index of elderly people, AGE). We also added subsidies for environmental improvements as an indicator evaluating the impact of financial support invested into the care for landscape (SUBS1) and into the care for landscape together with urban green spaces (SUBS2). To quantify the impact of landscape conservation on selected drivers and their relationship, an (expertly assessed) level of landscape protection (PLA) was used as additional variable.

Disturbance factors affecting ecosystems are both natural and anthropogenic; we have focused on anthropogenic disturbances to explain the effects of human pressures on ecosystems. Our goal was to consider a broad range of anthropogenic pressures affecting landscape stability. The factors selected to fall into the category of “anthropogenic pressures” include indicators related to climate change, land use change, and pollution; these three groups have been shown to have major impacts on ecological stability, leading to both reductions in ecological stability preconditions and ecosystem disturbances. The negative effects of land-use change (especially its intensification) on naturalness or biodiversity and thus, on ecological stability, were described by Jongman (2002), Frondoni et al. (2011), Plieninger (2012), and Ceccarelli et al. (2014); the negative effects of anthropogenic pollution (especially nitrogen) on biodiversity and thus, on ecological stability, were described by Borer

Table 1 List of indicators used in the present study to assess ecological stability and to derive relevant geographical gradient and the related territorial conditions associated with ecological stability in the Czech Republic. The specific method used for their quantification was delineated in the Supplementary Materials

	Description of indicators	Short name in tables	Time series (number of layers)	Scale	Years	Baseline dataset
Additional parameters	Elevation	ELEV	1	10m/px	2018	DMR5G © Czech Office for Surveying, Mapping and Cadastre
	Elevation range	ELRANG	1	10m/px	2018	DMR5G © Czech Office for Surveying, Mapping and Cadastre
	Total percentage area belonging to LFA	LFA	1	1: 10 000	2015	Own source
	Expertly assessed levels of landscape protection	PLA	1	1: 10 000	2020	Boundaries of protected areas © Nature Conservation Agency of the Czech Republic
	Belonging to the landscape type	LT	1	1: 50 000	2010	Own source
	Subsidies for environmental improvement applied in landscape	SUBS1	1	MEP	2007-2013	Data from the State Environmental Fund of the Czech Republic
	Subsidies for environmental improvement applied in landscape and urban greenery	SUBS2	1	MEP	2007-2013	Data from the State Environmental Fund of the Czech Republic
	Population age structure	AGE	4	MEP	2001, 2006, 2012, 2018	ArcCR © ARCDATA PRAHA, ZÚ, CSO
Anthropogenic pressure	Population density	POP	4	MEP	1991, 2001, 2011, 2018	ArcCR © ARCDATA PRAHA, ZÚ, CSO
	Distance to nearest urban area	DisU	5	1: 100 000	1990, 2000, 2006, 2012, 2018	Corine Land Cover © Copernicus
	Distance to nearest transport infrastructure	DisT	5	1: 100 000	1990, 2000, 2006, 2012, 2018	Corine Land Cover © Copernicus
	Air pollution: Five-year average concentrations of NO_2	NO_2	5	500m/px	2007-2011, 2010-2014, 2014-2018	CLIDATA © Czech Hydrometeorological Institute
	Air pollution: Five-year average concentrations of PM10	PM10	5	500m/px	2007-2011, 2010-2014, 2014-2018	CLIDATA © Czech Hydrometeorological Institute
	Air pollution: Five-year average concentrations of PM2.5	PM2.5	5	500m/px	2007-2011, 2010-2014, 2014-2018	CLIDATA © Czech Hydrometeorological Institute
	Air pollution: Five-year average concentrations of BaP	BaP	5	500m/px	2007-2011, 2010-2014, 2014-2018	CLIDATA © Czech Hydrometeorological Institute
	Water pollution and degradation: ecological status/potential of surface water bodies	WP	1	1: 50 000	2015	HEIS © T.G.Masaryk Water Research Institute
	Exceedance of N-critical load	NCL	1	1: 10 000	2010	Detail combined layer of habitat (DCL), own source
	Degree of soil sealing	SSEA	3	20m/px	2006, 2012, 2018	Sentinel-2 © ESA
	Climate aridity index: Minar moisture index	ARI	1	500m/px	1990-2010	Climate data © Global Change Research Institute CAS & Czech Hydrometeorological Institute
Preconditions of ecological stability	Index of the ecological stability	CES	1	1: 10 000	2018	Detail combined layer of habitats (DCL), own source
	Naturalness of habitats according to HVM method	NAT	5	1: 100 000	1990, 2000, 2006, 2012, 2018	Corine Land Cover © Copernicus
	Landscape metrics: Edge Density	ED	1	1: 10 000	2018	Detail combined layer of habitats (DCL), own source
	Landscape metrics: Median Patch Size	MedPS	1	1: 10 000	2018	Detail combined layer of habitats (DCL), own source
Manifestation of ecological stability	Rate of anthropogenic degradation according to Habitat mapping	DEG	1	1: 10 000	2019/2004	Biotope Natura2000 mapping layer by © Nature Conservation Agency of the Czech Republic
	Ecosystem functions performance: Evapotranspiration	EVA	5	1: 100 000	1990, 2000, 2006, 2012, 2018	Corine Land Cover © Copernicus
	Ecosystem functions performance: Regulation of short water cycle	SWC	5	1: 100 000	1990, 2000, 2006, 2012, 2018	Corine Land Cover © Copernicus
	Ecosystem functions performance: Production function	PRO	5	1: 100 000	1990, 2000, 2006, 2012, 2018	Corine Land Cover © Copernicus
	Ecosystem functions performance: Carbon stock	CS	5	1: 100 000	1990, 2000, 2006, 2012, 2018	Corine Land Cover © Copernicus

et al. (2014), Koerner et al. (2016), and Hautier et al. (2009). These scholars have used a range of indicators, including land-use change, N-eutrophication, climate warming, and drought. The impact of climate change on ecological stability has also been discussed extensively, particularly in the context of drought and temperature rise impacts (Walker et al., 1999) or pathogen and invasive species impacts (Chapin III et al., 2000; Duffy, 2002; Trumbore et al., 2015).

Indicators of air pollution (NO2, PM10, PM2.5, and BaP) that increase environmental toxicity, which is expected to negatively affect the health and reproduction of organisms and the stability of ecosystems, were used as factors influencing anthropogenic pollution. Human pressures on watercourses and water bodies were expressed by the Water Pollution and Degradation (WP) indicator, which assesses human alteration and the chemical status of water bodies. The Critical Nitrogen Load (NCL) exceedance indicator focuses on areas where nitrogen loading exceeds the ecosystem's ability to tolerate it and is most likely to result in ecosystem alteration. The climate change indicator we chose focuses on drought, which is a major climate change issue in the Czech Republic (Trnka et al., 2015). We quantified it diachronically using a standard Climate aridity index (ARI) derived from mean annual air temperature and total precipitation. Land-use change was represented by increases in human pressure, expressed as per cent change in population density (POP) over four time periods since 1991. Two other indicators were used as proxies for increasing urbanization, being determined as the distance from the nearest urban area (DisU) and the distance from the nearest transportation infrastructure (DisT), separately for five time periods beginning in 1990. Land degradation was also included, using a proxy, namely the percentage of soil sealed area (SSEA), which was assessed based on satellite data at three observation times; the issue of land degradation was already addressed in a previous study analysing land degradation risk in the same municipal units (Pechanec et al., 2021).

Another group of indicators focuses on the preconditions of ecological stability and assesses features of habitats and landscapes that have been shown to influence ecological stability. The most commonly discussed landscape characteristics that promote resilience or ecological stability include biodiversity (Folke, 2006; Lavorel, 1999; Mori et al., 2013), landscape structure (Nyström & Folke, 2001; Angeler & Allen, 2016; Jõgiste et al., 2017), and connectivity (Lavorel et al., 2015; Mitchell et al., 2013; Pascual-Hortal & Saura, 2006). The ratio of natural to non-natural habitats has often been used to approximate ecological stability at the landscape scale (Hodgson et al., 2011), using a gross indicator, namely the abundance of natural vegetation patches, such as O'Neill et al. (1997), who also adopted fragmentation and connectivity to describe landscape resilience and integrity, combining them with indicators of ecological pressure (land-use, water pollution, erosion risk). With this perspective in mind, we used (i) the degree of naturalness of habitats according to the Habitat valuation method (HVM), assessed in five time periods to evaluate changes since 1990 (Cudlín et al., 2020), and (ii) the ratio between natural and unnatural habitats expressed in the Czech ecological literature as the Index of ecological stability (CES, Reháčková & Pauditšová, 2007). Landscape metrics (Edge Density, ED) and Median Patch size (MedPS) were used to evaluate the shape and spatial arrangement of patches in a landscape influencing landscape heterogeneity and habitat fragmentation.

Variables that express manifestation of landscape-level stability or instability and relate to changes in landscape and ecosystem structures and functions were finally considered in this study. These included the rate of human degradation according to habitat mapping (DEG), which indicates the proportion of natural and semi-natural habitats that have remained unchanged between two habitat mappings in 2004 and 2019; this indicator expressed the stability of habitats and their structures. The stability of ecosystem functions was expressed as the performance of ecosystem functions in five time periods since 1990, including values for carbon production (PRO), climate regulation expressed by evapotranspiration (EVA), short water cycle regulation (SWC), and carbon stock (CS). All these variables were made available at 206 (homogeneous) administrative units, namely the municipalities with extended jurisdiction (MEP), covering the whole territory of the Czech Republic.

Statistical analysis

Assuming individual districts (hereafter Municipalities of Extended Power, or MEPs) as the reference spatial unit of this study (Demšar et al., 2013), a spatially explicit, dynamic factor analysis was run on a data matrix constituted of 28 indicators (see above) made available for each MEP (Pechanec et al., 2021). Allowing a summary overview of the structural (ecological and socioeconomic) characteristics and background (territorial) conditions of each individual district (e.g., Serra et al., 2014), the broad approach of dynamic factor analysis include a family of (two-way and multi-way) exploratory multidimensional techniques that can be run on a wide set of input variables at multiple locations and times (Salvati & Serra, 2016). This approach is particularly suitable to summarize first-order and higher-orders complex, multivariate relationships among input variables in a redundant data matrix (Ciommi et al, 2018), outlining few relevant dimensions that can be fully characterized by inspecting the pair-wise correlation coefficients (i.e., loadings) with each input variable, i.e., the 28 background indicators in our case (Rontos et al., 2019). The number of significant components was chosen according to the scree-plot criterion fixing the minimum eigenvalue threshold to 1 (Ciommi et al., 2019).

Results were analysed considering both loadings (the ‘indicator’ side) and scores (the “municipality” side) over time (Rontos et al., 2016). Loadings were specifically extracted and analysed with the aim at identifying the multivariate relationship among indicators (Kelly et al., 2015). The spatial distribution of scores was illustrated through maps (Recanatesi et al., 2016). Based on (tabular and graphical) inspection of loadings and scores projected on the same axes’ system (i.e., the extracted factors corresponding with the most relevant dimensions characteristic of the elementary analysis’ units), exploratory factor analysis allows a comprehensive investigation of both time-invariant descriptors and indicators varying (more or less rapidly) over time (Ciommi et al., 2019), even when they are available under a different number of temporal observations (e.g., years). Moreover, this technique provides a complete analysis of the distribution of each spatial unit (i.e., MEP), along the identified dimensions (Di Feliciantonio et al., 2018), giving a fundamental contribution to delineate geographical gradients at the base of territorial conditions assuring ecological stability (or instability) of any local system (Colantoni et al., 2015). Spatial coherence, namely close locations, of two (or more) reference units (namely, similar scores) over the same dimension indicate comparable conditions of ecological stability (or instability). A study of the temporal coherency of (or break-points in) input variables was also intrinsically reflected in the structure of loadings over time, for all time-varying indicators (Ferrara et al., 2016).

Results

Descriptive statistics were elaborated for each input variable and survey year and tabulated accordingly (Supplementary Materials Table 2). Correlation matrices using pair-wise (parametric and non-parametric) coefficients were reported as Supplementary Materials Table 3 (Pearson coefficient) and Supplementary Materials Table 4 (Spearman coefficient). The intrinsic redundancy in the data matrix was subsequently treated using multidimensional statistical analysis with the aim at decomposing the dimensions of ecological stability/instability under specific territorial contexts and, thus, identifying the most relevant geographical gradients linking ecological conditions with socioeconomic dynamics, removing in turn the multi-collinearity typical of real datasets formed by multi-domain indicators. Consequently, the empirical results of the multivariate analysis of ecological and socioeconomic indicators (as illustrated in Table 2) were based on the spectral decomposition of the latent dimensions of territorial complexity in Czech Republic. More specifically, we extracted the main factorial axes describing the latent dimensions of territorial complexity on the basis of the scree-plot, and we studied the related loading structure (namely, the intensity of correlation with each latent dimension) for each indicator.

Four dimensions that reflect the territorial complexity of 206 administrative units (MEPs) in Czech Republic were extracted and analyzed, explaining 79% of the overall variability of the data matrix. Taken together, these dimensions summarized the correlation and redundancy structure of 28 ecological and socioeconomic indicators. Dimensions 1 and 2 explained respectively 51.5% and 18.2% of total variance, and delineated the most relevant geographical gradients and the related aspects of ecological stability and the associated socioeconomic conditions in Czech Republic. Conversely, Dimensions 3 and 4 accounted for 5.7% and 4.6% of the overall variance, respectively, and delineated less important territorial gradients. All together, the selected dimensions reflect the structure of key geographical gradients associated with distinctive socio-ecological functions (Fig. 1). Indicators’ loadings were used to describe the latent association between socio-ecological functions and territorial gradients. Temporal dynamics of ecological functions along the selected gradients were

Table 2 Loadings of ecological and socioeconomic indicators delineating territorial complexity in the individual administrative units (Municipalities with Extended Power, MEPs) of Czech Republic* by extracted dimension

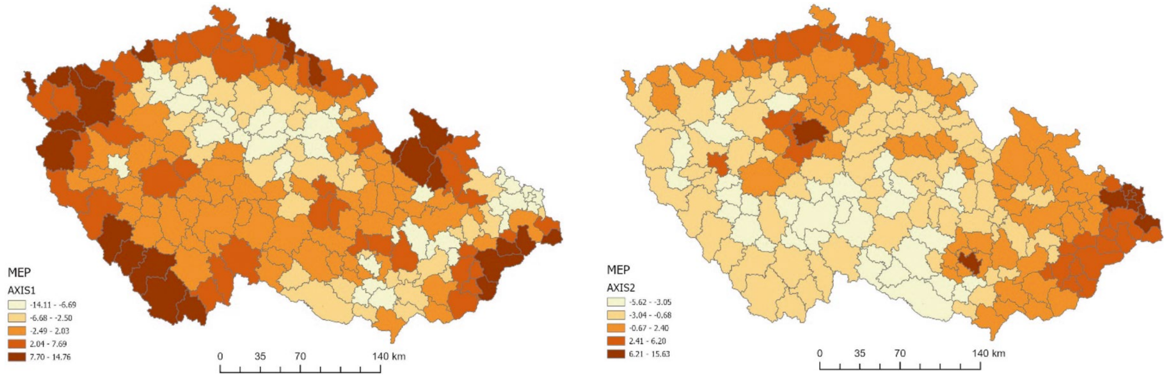
Descriptor	Component 1	Component 2	Component 3	Component 4
Elevation (ELEV)	**0.84**	-0.18	0.10	0.00
Elevation range (ELRANG)	0.34	0.13	-0.14	0.07
Total percentage area belonging to LFA (LFA)	**0.78**	-0.11	0.22	-0.15
Expertly assessed levels of landscape protection (PLA)	**0.66**	0.21	-0.06	0.08
Naturalness of habitats (1990–2018) (NAT)	**0.94**	0.30	0.05	-0.02
Belonging to the landscape type (LT)	**0.91**	0.36	0.09	0.01
Population density (1990–2018) (POP)	-0.45	**0.79**	0.16	0.25
Distance to nearest urban area (1990–2018) (DisU)	**0.78**	-0.27	-0.27	0.20
Distance to nearest transport infrastructure (1990–2018) (DisT)	**0.59**	0.17	-0.34	0.15
Five-year average concentrations NO2 (2007–2015) (NO2)	**-0.69**	**0.58**	-0.03	0.20
Five-year average concentrations of PM10 (2007–2015) (PM10)	**-0.64**	**0.66**	-0.23	-0.26
Five-year average concentrations of PM2.5 (2007–2015) (PM2.5)	**-0.62**	**0.65**	-0.23	-0.33
Five-year average concentrations of BaP (2007–2015) (BaP)	**-0.44**	**0.73**	-0.25	-0.31
Water pollution and degradation (WP)	**-0.60**	0.01	-0.12	-0.01
Exceedance of N-critical load (NCL)	**-0.59**	-0.28	0.29	0.02
Degree of soil sealing (2006–2018) (SSEA)	**-0.50**	**0.49**	0.24	**0.62**
Edge density (ED)	-0.21	**0.76**	0.34	-0.01
Median patch size (MedPS)	-0.22	**-0.60**	**-0.43**	0.05
Subsidies for environ. improvement (landscape) (SUBS1)	-0.20	-0.11	-0.10	0.17
Subsidies for environ. improvement (landscape and urban greenery) (SUBS2)	-0.29	0.35	0.12	0.04
Population age structure (2001–2018) (AGE)	-0.05	-0.20	**0.62**	-0.23
Rate of anthropogenic degradation (DEG)	-0.09	-0.06	-0.03	-0.12
Ecosystem functions performance: Evapotranspiration (1990–2018) (EVA)	**0.91**	0.38	0.04	-0.04
Ecosystem functions performance: Regulation of short water cycle (1990–2018) (SWC)	**0.90**	0.40	0.07	0.01
Ecosystem functions performance: Production function (1990–2018) (PRO)	**0.96**	0.19	0.07	-0.10
Ecosystem functions performance: Carbon stock (1990–2018) (CS)	**0.95**	0.22	0.11	0.01
Climate aridity index: Minar´s moisture index (ARI)	**-0.45**	-0.11	-0.13	*0.42*
Explained variance (%)	***51.5***	*18.2*	*5.7*	*4.6*

[*] Dimensions 1 to 4 are representative of (i) the elevation gradient, (ii) the urban–rural gradient, (iii) a demographic gradient based on population age structure, and (iv) a land imperviousness gradient based on the increasing rate of sealed soils; bold indicates significant coefficients over the selected dimensions

studied using indicators' scores over the selected dimensions (Table 3).

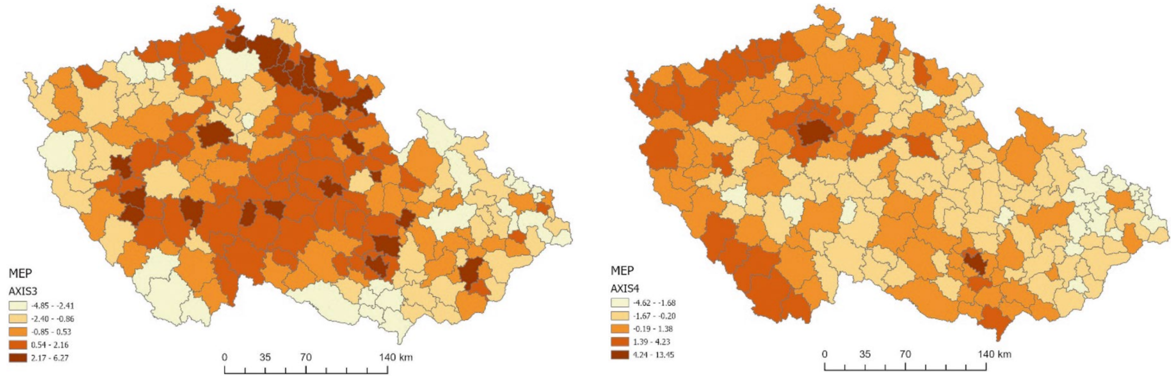
The spatial structure of territorial gradients

Dimension 1 represents the elevation gradient in Czech Republic (lowlands and mountainous locations respectively associated with negative and positive indicators' loadings) and the related ecological functions. On average, indicators of landscape quality (LFA, PLA, NAT, CES) and ecosystem functioning in a broad sense (EVA, SWC, PRO, CS) were positively associated with this gradient, suggesting how the level of ecological stability preconditions and ecosystem functions increased with the reduction of human pressures – assumed to be less intense in uplands and mountainous districts than in lowlands. At the same time, all the indicators of environmental pressure (e.g., air and water pollution) were negatively correlated with Dimension 1. Population density, the



Dimension 1 (elevation gradient)

Dimension 2 (urban-rural gradient)



Dimension 3 (population age structure)

Dimension 4 (soil sealing gradient)

Fig. 1 The spatial distribution of factor scores for each Municipality of Extended Power (MEP) in Czech Republic by extracted dimension and the related geographical gradient

level of land imperviousness (namely the per cent rate of sealed soil), and a climate index reflective of the structural aridity level, were more weakly (and negatively) correlated with Dimension 1.

Dimension 2 identified the urban–rural gradient in Czech Republic. Irrespective of the elevation gradient outlined above, this dimension associated high-density urban areas with positive axis' values. Environmental pressure indicators related to air pollution and, in part, land imperviousness, as well as selected metrics (such as ED) reflecting landscape fragmentation, resulted to be associated positively with this axis. Dimension 3 outlined a specific territorial dimension (i.e., demography) independent of elevation and urban–rural gradients, and mostly associated with population structure by age; the elderly index was the variable showing the most intense correlation with this dimension, which was in turn correlated negatively with landscape integrity (MedPS). Such a loadings' structure suggests the existence of an indirect relationship between demography (e.g., the older population seems to be concentrated in accessible, 'intermediate-density' suburban areas) and land-use (e.g., landscapes in these demographically homogeneous areas seem to be particularly fragmented and diversified, reflecting a high human pressure). Finally, Dimension 4 outlined the spatial polarization of Czech municipalities (MEPs) in different levels of land imperviousness. Being statistically independent from Dimension 2 (reflective of the urban–rural gradient), Dimension 4 did not discriminate between strictly urban and strictly rural locations. It focused instead on the proportion of soil sealing, whose levels can be locally high even in areas with low population density (because of, e.g., industrial areas, commercial districts, intense agricultural models based

Table 3 Temporal structure of indicators' loadings (bold: >|0.6|; italics: |0.4|-|0.5|) by extracted dimension (abbreviations shown in Table 1)

Predictor	Component 1	Component 2	Component 3	Component 4
NAT				
1990	**0.930**	0.306	0.049	-0.021
2000	**0.941**	0.301	0.055	-0.018
2006	**0.939**	0.298	0.038	-0.021
2012	**0.945**	0.292	0.044	-0.029
2018	**0.946**	0.289	0.047	-0.031
POP				
1990	*-0.446*	**0.795**	0.168	0.222
2000	*-0.444*	**0.798**	0.156	0.229
2012	*-0.469*	**0.781**	0.155	0.269
2018	*-0.475*	**0.775**	0.146	0.282
DisU				
1990	**0.783**	-0.270	-0.264	0.197
2000	**0.784**	-0.270	-0.264	0.193
2006	**0.775**	-0.282	-0.285	0.206
2012	**0.778**	-0.280	-0.283	0.202
2018	**0.781**	-0.293	-0.266	0.186
DisT				
1990	**0.701**	0.126	-0.389	0.088
2000	**0.701**	0.126	-0.389	0.088
2006	**0.439**	0.215	-0.273	0.285
2012	**0.651**	0.167	-0.360	0.144
2018	**0.603**	0.128	-0.385	0.102
NO2				
2007	**-0.552**	**0.609**	0.078	0.302
2011	**-0.736**	**0.560**	-0.016	0.175
2015	**-0.751**	**0.579**	-0.091	0.143
PM10				
2007	**-0.617**	**0.682**	-0.248	-0.242
2011	**-0.609**	**0.681**	-0.260	-0.266
2015	**-0.684**	**0.621**	-0.204	-0.278
PM2.5				
2007	**-0.579**	**0.667**	-0.237	-0.342
2011	**-0.583**	**0.661**	-0.255	-0.356
2015	**-0.667**	**0.621**	-0.218	-0.300
BaP				
2007	*-0.400*	**0.719**	-0.202	-0.229
2011	*-0.456*	**0.736**	-0.256	-0.326
2015	*-0.458*	**0.726**	-0.239	-0.380
SSEA				
2006	*-0.490*	*0.491*	0.242	**0.616**
2012	*-0.497*	*0.493*	0.236	**0.611**
2018	*-0.508*	*0.486*	0.249	**0.621**
AGE				
2001	-0.280	-0.283	**0.618**	-0.108
2006	-0.221	-0.186	**0.647**	-0.222
2012	-0.029	-0.141	**0.678**	-0.268

Table 3 (continued)

Predictor	Component 1	Component 2	Component 3	Component 4
2018	0.200	-0.118	**0.549**	-0.347
EVA				
1990	**0.896**	0.410	0.042	-0.032
2000	**0.896**	0.403	0.030	-0.015
2006	**0.907**	0.382	0.044	-0.034
2012	**0.913**	0.363	0.044	-0.048
2018	**0.912**	0.366	0.042	-0.045
SWC				
1990	**0.887**	0.433	0.069	0.009
2000	**0.892**	0.426	0.059	0.021
2006	**0.903**	0.408	0.071	0.007
2012	**0.907**	0.397	0.075	0.001
2018	**0.907**	0.398	0.069	0.000
PRO				
1990	**0.949**	0.191	0.083	-0.102
2000	**0.958**	0.198	0.076	-0.081
2006	**0.963**	0.192	0.075	-0.092
2012	**0.967**	0.172	0.076	-0.096
2018	**0.965**	0.175	0.072	-0.099
CS				
1990	**0.938**	0.230	0.109	0.002
2000	**0.942**	0.224	0.113	0.010
2006	**0.946**	0.214	0.112	0.007
2012	**0.944**	0.216	0.118	0.011
2018	**0.945**	0.216	0.112	0.006

on greenhouse crops or renewable energy plants on the ground). Conditions for climate aridity were finally observed in areas with a high level of soil sealing, possibly underlining the (latent) spatial linkage between dry areas and land-use intensification.

Changes over time in territorial gradients

Based on the selected dimensions, Table 3 reports the temporal structure of indicators' loadings. Increasing or decreasing loadings over time, respectively, indicate a stronger (or weaker) relationship between individual variables and the four gradients identified above. For instance, the increase over time in the loadings of Dimension 1 characteristic of landscape integrity, naturalness of habitats (NAT), and fulfilment of ecosystem functioning (EVA, SWC, PRO, and CS) suggests how these indicators were more strictly associated with the positive side of Component 1 in recent times (2018) than in the past (1990). These findings also suggest how environmental quality increased in districts exposed to low human pressure (such as uplands and mountainous areas) along the elevation gradient. At the same time, the correlation structure between Dimension 1 and the average distance from urban settlements remained substantially unaltered over time, and the coefficient of the distance from transport networks showed a marked decline. These findings may document the expansion of infrastructural networks (basically roads and railways) in both "intermediate" upland locations and more remote districts, possibly causing an intense ecological pressure on pristine landscapes. A similar polarization was observed for pollution sources (air, soil, water) receiving higher (negative) loadings in recent times, and thus documenting the progressive consolidation of environmental disparities in high-quality and low-quality districts along the elevation gradient. In other words, elevation in Czech Republic can be considered one of the best predictors of environmental quality, landscape integrity and, thus, human pressure.

Irrespective of elevation, Dimension 2 was representative of the urban–rural gradient in Czech Republic, with compact settlements and low-density areas receiving positive and negative loadings, respectively. Indicators of population/settlement density (including the land imperviousness rate), however, received less intense loadings on Dimension 2 over time, suggesting how urban sprawl into rural districts was taken place in the most recent years, line with empirical evidence from other studies. A similar trend was observed for air pollution indicators (NO_2, PM10, PM2.5) whose spatial distribution was strongly associated with urban areas, with the only exception of BaP, a pollution source less related with dense socioeconomic contexts. Dimension 3 illustrated a demographic gradient becoming increasingly polarized over time, as clearly indicated in the sudden increase of the elderly index loadings. Finally, a slow consolidation of the imperviousness gradient in Czech Republic was observed along Dimension 4, in line with the moderate increase over time of the land imperviousness loadings.

Discussion

Territorial disparities are often reflected in (more or less intense) socioeconomic and ecological gaps among regions and districts (Allen et al., 2019; Salvati & Zitti, 2009; van Meerbeek et al., 2021). Moreover, the unsustainable management of land generating disparities in environmental quality and ecosystem integrity, is recognized as an accelerating factor of ecological deterioration and should be monitored to mitigate the possible "land degradation syndromes" (sensu Smiraglia et al., 2016) at the base of ecological instability and loss in ecosystem functioning. In this perspective, a rising human pressure has demonstrated to exacerbate the level of environmental quality leading to ecologically fragile environments (Biasi et al., 2015; Falk et al., 2019; Kairis et al., 2015). However, a common research framework for a comprehensive assessment of territorial disparities and the evolving socioeconomic contexts, landscape quality, ecological stability, and environmental integrity, was (and still is) rather partial in Europe (e.g., Ciommi et al., 2018; Fares et al., 2017; Zambon et al., 2018), and field studies covering large areas and informing policy implementation at both regional and country scale seem to be occasional and focused on specific, individual phenomena of environmental degradation (Cinner & Barnes, 2019; Karamesouti et al., 2015; Serra et al., 2014).

Territorial organizations at the base of the intimate linkage between human populations and natural ecosystems have been mainly interpreted through linear thinking and explanations grounded on the analysis of individual variables referred to one (or two) geographical gradient(s), statically analysed or explored over short time horizons (Bajocco et al., 2015; Cecchini et al., 2019; Egli et al., 2019; but see also Kéfi et al., 2007). In this perspective, the intrinsic impact of factors bringing local systems out of ecological stability conditions (sensu Chelleri et al., 2015) was assumed to be spatially 'neutral' (determining equilibrium-disequilibrium conditions in the whole region) or "asymmetric" (determining conditions for equilibrium in some districts and disequilibrium in other areas). The latter scenario produces an amplification of the disparities existing between regions, with important consequences in terms of environmental policies and land management practices at both national and regional scale (Delfanti et al., 2016).

To answer the increasing demand of quantitative assessments of ecological stability, ecosystem services, and resilience under intense territorial disparities rising over time (Carr, 2019), relatively few studies have been devoted to explicitly analyse the spatio-temporal dynamics of environmental and socioeconomic indicators in Czech Republic, a broad areal coverage representative of ecological stability/instability conditions and landscape complexity in a large part of Central-Eastern Europe (Cudlín et al., 2020, 2021). More specifically, we studied the latent association of selected human disturbance factors with ecological stability at the landscape level (Falk et al., 2019) considering a full coverage of administrative units, i.e. Municipalities with Extended Powers (MEP), as the appropriate spatial unit to inform trans-scalar policies of environmental conservation and sustainable planning of urban–rural districts (sensu Pechanec et al., 2021). Moulded by rapid changes in societies and modifications in the economic structures with impact on the spatial organization of entire regions (Capdevila et al., 2020), empirical evidence of this study reject the hypothesis of a uniform development path at the base of ecological stability (or instability) conditions in both time and space (Egli et al., 2019). On the contrary, it was demonstrated how territorial factors assuring ecosystem stability or predisposing local systems to instability evolve at different geographical scales determining hardly predictable conditions and environmental impacts (Bajocco et al., 2015; De Marco et al., 2019; Vogt et al., 2011).

More specifically, the empirical results of the multivariate analysis delineated the spatial gradients and the individual factors (sensu Jackson et al., 2001; Hughes et al., 2013; Nash et al., 2014; Donohue et al., 2016) contributing to environmental quality and territorial stability in Czech Republic. From a static point of view, elevation and urban–rural gradients resulted to be the most relevant gradients in the area, in line with earlier studies (Pechanec et al., 2021). Considering MEP as the analysis' reference unit, demographic structures and a residual dimension of human pressure independent of the rural–urban gradient, provided a refined illustration of additional gradients possibly associated with ecological stability (or instability) in the study area (Cudlín et al., 2021). From a dynamic point of view, results of the analysis outline the increasing polarization in areas with high and low human pressure in recent times (Salvati & Zitti, 2008), in line with the empirical evidence of earlier studies reflective of similar European contexts (e.g., Cudlín et al., 2020; Seifollahi-Aghmiuni et al., 2022; Zambon et al., 2018). In other words, local socio-environmental conditions in Czech Republic have documented to worsen rapidly in the last decades when facing with global changes (Cudlín et al., 2021). Combined with climate aridity and drought (Salvati et al., 2016), extensive land-use transformations in Czech Republic have been demonstrated to be a driver of ecosystem instability (Pechanec et al., 2021).

The (changing) role of territorial gradients supposed to Influence conditions for ecological stability remains an intriguing matter of investigation for policy application (Duvernoy et al., 2018; Perrin et al., 2018; Zambon et al., 2017). For instance, while less endangered areas were found in mountainous districts, most of the actually degraded zones (basically, with high human impact) in the Czech Republic concentrated in flat areas with intensive agriculture (Nowak & Schneider, 2017). A low natural capital (namely, scarce precipitation, poor vegetation quality, and a high proportion of land with low water-holding capacity: Trnka et al., 2016) especially characterized the most economically dynamic (and environmentally instable) districts in the North-Western (Labe lowland) and South-Eastern (South Moravia) quadrants of the country (Skaloš et al., 2014). Geo-political facts were also involved in such a landscape transition (e.g., Chelleri et al., 2015). Similarly to what has been observed in other post-socialist countries, the long-term process of agricultural properties' collectivization led, at least indirectly, to land degradation (Prăvălie et al., 2017; Rubio-Delgado et al., 2019; Šarapatka & Bednář, 2015). This process paralleled the intrinsic decline of natural-crop matrices at the base of high-quality rural landscapes (Lipský et al., 2011), associated with land consolidation (Cudlín et al., 2020), the progressive removal of woody elements (Pechanec et al., 2021), and conversion of meadows into arable land (Skaloš et al., 2017).

In this framework, urbanization was another driver of environmental instability (Seifollahi-Aghmiuni et al., 2022). The formal expiration of Soil Protection Act—active since a long time—has indirectly stimulated settlement sprawl into rural areas (Skaloš et al., 2011), opening natural and agricultural landscapes to vastly different commercial interests and speculations (Cudlín et al., 2021). As major land-use changes are expected in the future as a result of climate change (Cudlín et al., 2020), national and regional policies have to face with environmental degradation spirals through effective (i.e., spatially explicit and temporally coherent) measures managing the intimate factors of ecological instability delineated in our study (Skaloš et al., 2014). Among others, land abandonment and forest degradation in uplands/mountainous districts, agriculture intensification and the consequent pollution in lowlands, as well as urban growth, infrastructural development and landscape fragmentation in accessible (and economically dynamic) districts require an integrated, trans-scalar policy response at both normative (i.e., administrative) and functional (i.e., landscape) intervention level (Egidi et al., 2022; Smiraglia et al., 2016; Zambon et al., 2017).

The intrinsic difficulty of a truly sustainable management of land along defined geographical gradients stems from heterogeneous planning approaches possibly applicable at different operational scales (normative and functions), both relevant units for analysis and interpretation of the complex territorial mechanisms at the base of ecological stability or instability of local systems (Recanatesi et al., 2016). While providing an exemplificative and simplified approach to local complexity in both territorial contexts and environmental conditions at the base of ecological stability (Delfanti et al., 2016), our study delineates an expedite framework to interpret the latent inter-linkage between ecosystem dynamics and socioeconomic evolution in homogeneous local districts (Zambon et al., 2018). This intrinsic (and rapidly evolving) nexus is assumed as a possible target of any spatially explicit policy integrating the three pillars of sustainability (Colantoni et al., 2015) with the aim at preserving ecological stability conditions on the base of a given socioeconomic setting (Tombolini et al., 2016). The geographical gradients delineated in our study, and their latent relationship with both the intrinsic conditions for ecological stability/instability and the background socioeconomic context (Salvati et al., 2012), represent a strategic concept in a sustainable development strategy (Colantoni et al., 2016), suggesting the relevance of integrated (socioeconomic and environmental) policies and spatially explicit measures finely tuned with (and possibly differentiated along) the most relevant gradients.

Conclusions

Moving outside the operational perimeter of biological disciplines, conservation science, and environmental policy, our study provides a simplified framework delineating medium- and long-term socioecological dynamics along relevant geographical gradients taken as the relevant spatial domain of application for any strategy that promotes a sustainable development of local systems under complex evolutionary paths. In light of climate change and more intense, human-driven land-use transformations, a country-scale assessment of conditions for ecological stability vis à vis socioeconomic transitions over time provides an appropriate information base to implement a sustainable land management strategy, considering together environmental protection and local development targets.

Socioeconomic and environmental dynamics frequently determine a sort of “spatial mismatch” between the background (local) context responding to broader-scale stimuli and the traditional (natural) organization of territories shaped by long-term human-nature interactions at both regional and country scale. For instance, the empirical results of our study outline a close, but spatially diversified in both intensity and direction, relationship between climate aridity, land-use intensity, and environmental degradation, discriminating territorial contexts with more or less intense human pressure and a rising land vulnerability potential over time. With this perspective in mind, the notion of “geographical gradients” may resemble the intrinsic environmental and socioeconomic diversity characteristic of broad regions that experienced a millenary human settlement and continuous interaction with the landscape. Since resilience of local systems to external shocks was demonstrated to be spatially variable as well, adopting integrated (ecological and economic) measures of mitigation and adaptation to, e.g., local warming along defined geographical gradients is particularly appropriate under scenarios of global change.

Additional efforts are finally required to integrate ecological research with socioeconomic issues further. First, the empirical findings of this study point out the key role of long time series of territorial indicators and appropriate spatial domains for ecological analysis that could be integrated with consolidated data, approaches, and methodologies derived from social science at large. Second, moving towards cross-regional comparisons with the aim at informing strategies for the thorough conservation of environmental quality, landscape complexity, and ecosystem stability is imperative in light of a spatially balanced development path of local systems. Projections of change based on climatic, demographic or economic scenarios can be particularly useful in this perspective. Third, the spatially varying development path of any local system definitely justifies a multi-scale planning approach specifically designed to cope with the emerging organisational models of socioeconomic systems and the related, “spatially asymmetric” biophysical change.

Author contribution Vilém Pechanec: data collection and analysis;
Marcela Prokopová: data collection and analysis;
Luca Salvati: writing – initial manuscript;
Ondřej Cudlín: writing – revisions;
Renata Včeláková: GIS elaboration, literature review;
Tereza Pohanková: data collection and analysis;
Lenka Štěrbová: data collection and analysis;

Jan Purkyt: writing – revisions;

Radek Plch: writing – revisions;

Kateřina Jačková: project technical supervision, literature review;

Pavel Cudlín: writing – initial manuscript.

All authors contributed equally to the study, from introduction to methodology, from writing to literature review, from mapping to graphical analysis.

Data availability Data were available from the authors upon reasonable request.

Declarations

Ethics approval and consent to participate Nothing to declare. All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

Consent for publication All authors agree on submitting the present version.

Conflict of interest The authors declare no competing interests.

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