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Modeling Spatio-Temporal Divergence in Land Vulnerability to Desertification with Local Regressions

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Abstract: Taken as a classical issue in applied economics, the notion of 'convergence' is based on the concept of path dependence, i.e., from the previous trajectory undertaken by the system during its recent history. Going beyond social science, a 'convergence' perspective has been more recently adopted in environmental studies. Spatial convergence in non-linear processes, such as desertification risk, is a meaningful notion since desertification represents a (possibly unsustainable) development trajectory of socio-ecological systems towards land degradation on a regional or local scale. In this study, we test—in line with the classical convergence approach—long-term equilibrium conditions in the evolution of desertification processes in Italy, a European country with significant socioeconomic and environmental disparities. Assuming a path-dependent development of desertification risk in Italy, we provided a diachronic analysis of the Environmental Sensitive Area Index (ESAI), estimated at a disaggregated spatial resolution at three times (1960s, 1990s, and 2010s) in the recent history of Italy, using a spatially explicit approach based on geographically weighted regressions (GWRs). The results of local regressions show a significant path dependence in the first time interval (1960–1990). A less significant evidence for path-dependence was observed for the second period (1990–2010); in both cases, the models' goodness-of-fit (global adjusted R^2) was satisfactory. A strong polarization along the latitudinal gradient characterized the first observation period: Southern Italian land experienced worse conditions (e.g., climate aridity, urbanization) and the level of land vulnerability in Northern Italy remained quite stable, alimenting the traditional divergence in desertification risk characteristic of the country. The empirical analysis delineated a more complex picture for the second period. Convergence (leading to stability, or even improvement, of desertification risk) in some areas of Southern Italy, and a more evident divergence (leading to worse environmental conditions because of urban sprawl and crop intensification) in some of the land of Northern Italy, were observed, leading to an undesired spatial homogenization toward higher vulnerability levels. Finally, this work suggests the importance of spatially explicit approaches providing relevant information to design more effective policy strategies. In the case of land vulnerability to degradation in Italy, local regression models oriented toward a 'convergence' perspective, may be adopted to uncover the genesis of desertification hotspots at both the regional and local scale.

Keywords: convergence; geographically weighted regression; environmentally sensitive area index; sustainable land management; Mediterranean Europe

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1. Introduction

Derived from the economic literature, 'convergence' has been a paradigmatic notion for decades. Since the 1990s, this concept was more frequently adopted to interpret social and environmental problems, adapting the predictions of economic convergence theory to different, possibly more complex, issues [1–3]. Convergence approaches imply a quantitative analysis of developmental paths characteristic of complex systems evolving toward distinctive growth stages over time and space with intrinsic regulation of the latent system's properties [4–6]. This long-term path depends on the system state at the beginning of the observation period and on the evolution steps at various investigation times. Path dependence from the previous trajectory, during its recent history, is clearly at the base of such a process. Global convergence implies that all the different components of the system evolve synergistically towards a target objective, which is generally a policy objective or a non-regulatory target (i.e., an objective dictated (or mediated) by human preferences instead of political instruments). Local convergence implies a spatially heterogeneous process where only some units tend to converge over time.

The notion of convergence derives from a wide economic literature initially focusing on the long-term evolution of production systems [7–10]. These studies were mainly oriented toward the investigation of national (or supranational) systems where the different units (e.g., regions or individual countries) converge to steady-state equilibrium conditions (e.g., the same long-term growth rate). This assumption implies that the poorest units grow more than the rich ones and, consequently, territorial disparities are reduced [11–13]. Economic divergence instead implies a territorial polarization in rich and poor areas, caused by a differential growth regime separating affluent countries, more equipped with resources and infrastructures, from poor countries, experiencing a structural gap in resources and infrastructures [14,15]. These two alternative conditions can be analyzed in different spatiotemporal domains taking into account the impact of local background contexts.

The 'convergence' issue has become popular in political analysis because it is commonly seen as a target for policy strategies addressing, both directly and indirectly, the reduction of territorial gaps and the promotion of a long-term (and spatially sustainable) economic growth, promoting resilience of local systems [16,17]. At the same time, this concept has been applied in social science when addressing the intrinsic relationship between sociodemographic phenomena and institutional mechanisms having a strict linkage with policy regulation mechanisms, as in the case of identifying a welfare regime in advanced economies [18–20]. Since the early 2000s, the 'convergence' notion has also been applied to environmental processes under intense political regulation, and characterized by structural territorial disparities [21–23].

What has been done so far in the ecological field requires, however, additional research aimed at broadening the analysis to a wider range of environmental processes possibly connected with the sociodemographic context. Enabling refined investigation techniques and methodologies relying on an unprecedented amount of digital data—provided with a more frequent temporal resolution and with a higher spatial detail—is a pre-requisite for such studies [22]. An environmental process that was preliminarily investigated under a convergence framework was land degradation, defined as a 'reduction in the economic value of ecosystem services and goods derived from land as a result of anthropogenic activities or natural biophysical evolution' [23]. Land degradation is a worldwide issue [24–30], which can be assumed to be representative of a long-term development trajectory of a given socio-ecological system characterized by intrinsic impulses towards complexity on either regional or local scales [31–34]. Internal forces shaping long-term evolutionary paths depend on the intrinsic features of local systems, implying human actions aimed at regulating these processes, but also at supplying or using (more or less sustainably) natural resources connected with these phenomena. External drivers have finally influenced land degradation both directly (as in the case of (i) unsustainable urbanization resulting in urban sprawl; (ii) grazing regime determining high soil erosion rates and loss in plant productivity; (iii) extensive land transformations in semi-arid climates causing the expansion of barrens; and (iv) wildfires causing damages to biodiversity) and indirectly (as in the case of climate change), being frequently associated with anthropogenic activities [33–42].

The intrinsic complexity of developmental paths in local systems affected by land degradation reflects non-linear trajectories of growth in advanced economies (as already demonstrated in [43]) and, therefore, needs monitoring procedures at finer spatiotemporal resolutions aimed at evaluating the driving forces that guide this path [44]. In other words, understanding the trajectories of such systems implies the opportunity to design multi-scalar policies that may contain the negative effects of those forces triggering (or exacerbating) land degradation. At the same time, these policies may more effectively contribute to regulating the impact of human activities, as in the case of the adoption of specific agri-environmental measures to contrast degradation in eroded vineyards and critical areas [45,46]. Other examples of such policies include soil conservation measures slowing down land abandonment, such as building/consolidation of terraced slopes able to contain some processes (runoff, erosion, landslides) in fragile Mediterranean catchments [47,48]. These policies can also mitigate the effect of exogenous shocks, such as climate change, and maintain a resilience potential to preserve the pristine stock of resources [49,50]. In this context, it is reasonable to assume a development process that is, at least partially, dependent on the previous path. An intrinsically complex, path-dependent process is strictly linked to the previous development state while being subjected to external forces moving the system away from the initial conditions. Testing against spatial imbalances, the present study verifies a long-term equilibrium in the evolution of land degradation processes in Italy, a European country with intense socioeconomic divides [51,52].

Generally speaking, the issue of land degradation has now become very topical throughout Europe, because the Old Continent has experienced rising levels of land degradation, and 13 European Union (EU) Member States have declared themselves as affected parties under the United Nations Convention to Combat Desertification (UNCCD). At both the European and global level, as reported in the latest institutional reports (e.g., European Environment Agency, Intergovernmental Panel On Climate Change, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, see [53–55]), land is drastically degrading. A significant expansion of degraded areas aligns Italy with global and European trends: now, over a third of the national territory should be considered partially or completely degraded [56]. To document convergence (or divergence) processes in the evolution of desertification risk, we tested a path-dependent development of land degradation analyzing spatiotemporal variations in a composite index, the ESAI (Environmental Sensitive Area Index [57,58]), at a relatively detailed geographical resolution at three time points (1960s, 1990s, and 2010s) corresponding to different stages of the socioeconomic development path in Italy.

The adopted model follows a classic convergence scheme testing path dependence between the early 1960s and the early 1990s, and between the early 1990s and the early 2010s. Salvati et al. [59] have previously explained the importance of these two periods in the history of Italy as representative of socioeconomic, demographic, and territorial dynamics common to other Mediterranean countries. The first time interval (1960–1990) was characterized by a development path not associated with specific policies mitigating desertification impacts and, because of this context, the period can be labeled as 'pre-codified desertification'. Only in the mid-1990s, with the establishment of the United Nations Convention to Combat Desertification (UNCCD) and the corresponding National Committees, specific policies have been promoted to face the desertification risk in Italy, as well as in the other Mediterranean countries of the UNCCD Annex IV. Notably, the Italian Committee to Combat Drought and Desertification (CNLSD) has been fully active since 1999 and promoted actions at the national level with the National

Action Plan (NAP), which introduced guiding principles for designing policy strategies at the regional scale, e.g., through the Regional Action Plans (RAPs). These were spatial planning tools that each regional administration should have developed on the basis of the specific degradation processes and in line with NAP guidelines. Local action plans, aimed at containing desertification risk and maintaining an appropriate stock of natural resources, were occasionally proposed. This implies that a comprehensive analysis of territorial dynamics over the second observation period allows for the estimation of the initial impact of the national strategy for land degradation mitigation in Italy [60].

Based on these premises, we run—for the first time, to our knowledge—a quantitative analysis of convergence processes in the evolution of the desertification risk over time based on a pixel-based, local regression, controlling for the modifiable area unit problem (MAUP)—characteristic in the use of administrative units. Taken as a function of (supposedly) different evolutionary paths, we run a regression analysis between the stock of land resources (i.e., reflecting the level of vulnerability) at two consecutive times (t = 0 and t = 1), as derived from spatially explicit ESAI values and change over two time spans (1960–1990 and 1990–2010). We assume that the level of land degradation vulnerability converges over space with reduced territorial gaps, determining a less asymmetric distribution of the ESAI over time. Formal or informal actions (i.e., spontaneous or regulatory) may regulate this path. By contrast, we expect divergence when the existing gaps widen and, consequently, the variations over time exacerbate these spatial divides. Divergence, in turn, creates spatial polarizations with the consequent formation (or consolidation) of land degradation hotspots, i.e., serious conditions of land vulnerability, which may evolve towards desertification.

2. Materials and Methods

2.1. Study Area

Italy is a Northern Mediterranean country extending more than 300,000 km^2 and is composed of balanced, mainly steep topography mixing lowlands (23%), uplands (42%), and mountains (35%). Climate regimes in Italy were highly dependent on topography, latitude, and distance from the sea coasts, ranging from Alpine to semi-arid [61,62]. The distribution of natural resources and human activities across the study area reflects the historical interplay between biophysical factors and anthropogenic pressures, revealing economic and sociopolitical disparities (such as the land accessibility favored by different transport infrastructure, income levels, etc.). The country's geography is delineated considering three macro-regions (North, Centre, and South), displaying important differences, as far as population density, urban form, availability of natural resources, topographic features, and economic well-being, are concerned (Figure 1). Northern Italy has an economic profile similar to the most developed European areas, while Southern Italy is still considered a region with a developmental deficit [63]. Central Italy is positioned in-between these regions and alternates between areas with thriving activities and economically disadvantaged zones (basically, rural and mountain areas). These pronounced differences generate a diverse range of ecosystems responses to natural and anthropogenic disturbance, sometimes exacerbated by the effects of climate change (e.g., irregular precipitation regimes, heatwaves, late frost events, and flooding [64–66]). Thanks to such factors, Italy is particularly suitable for testing the impact of these geographical gradients in the spatial distribution of vulnerable areas to land degradation [67–69].

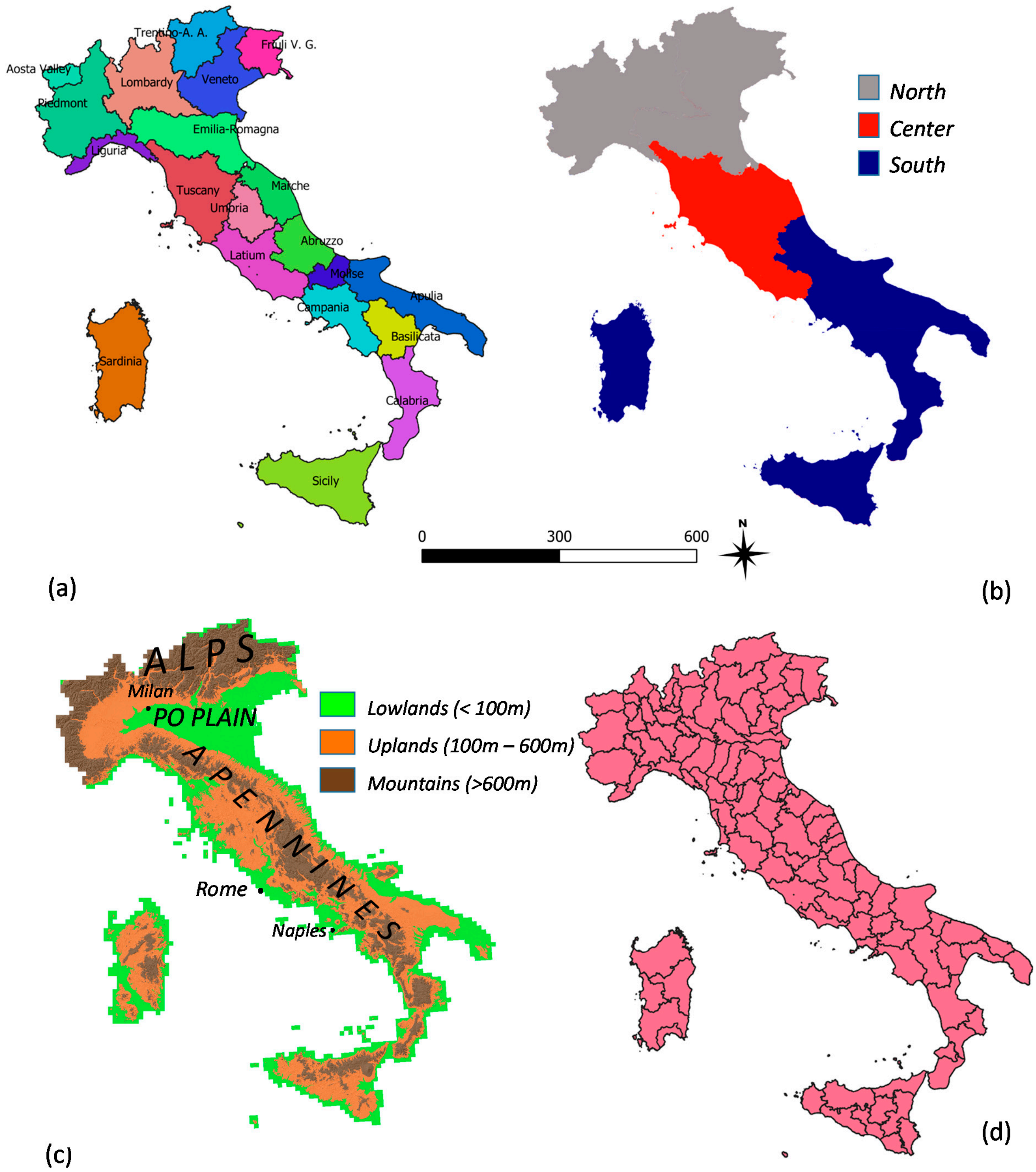

Figure 1. Partitions of the study area into (**a**) 20 regions corresponding to NUTS-2 (European nomenclature of territorial units for official statistics); (**b**) latitudinal belts; (**c**) elevation classes; (**d**) 107 provinces corresponding to NUTS-3 level in Italy.

2.2. ESA Approach

In this work, we adopted one of the most used methodologies in the field of desertification/land degradation: the ESA (Environmentally Sensitive Area) approach. It was developed within the MEDALUS (Mediterranean Desertification And Land Use) project [70] to evaluate the level of vulnerability to land degradation of the study area by means of a simple indicator-based scheme assessing four components: climate, soil, vegetation, and land management. Standard indices concerning each component were commonly used alone or in combination; in fact, they can be integrated or removed depending on data availability and specific environmental and socioeconomic contexts [71]. They contribute to the computation of the respective quality index: Climate Quality Index (CQI), Soil Quality Index (SQI), Vegetation Quality Index (VQI) and Land Management Quality Index (MQI), as the geometric mean of the different scores associated to each input variable. To combine them straightforwardly, each quality indicator was classified in a range from 1 (low vulnerability to land degradation) to 2 (high vulnerability to land degradation), assigning equal weights to each layer. The model, accurately validated through extensive field measurements (e.g., [72]), has been successfully applied to case studies in other European and non-European countries [73–77]. The present study evaluated land degradation vulnerability in Italy in a time interval of 50 years (1960–2010) and, more precisely, at three time points (1960, 1990, and 2010, see Figure 2), the only dates currently available to exploit the full model at a national scale with the whole range of requested input variables [78]. Further details on the specific databases used to compute the quality indices were provided in what follows.

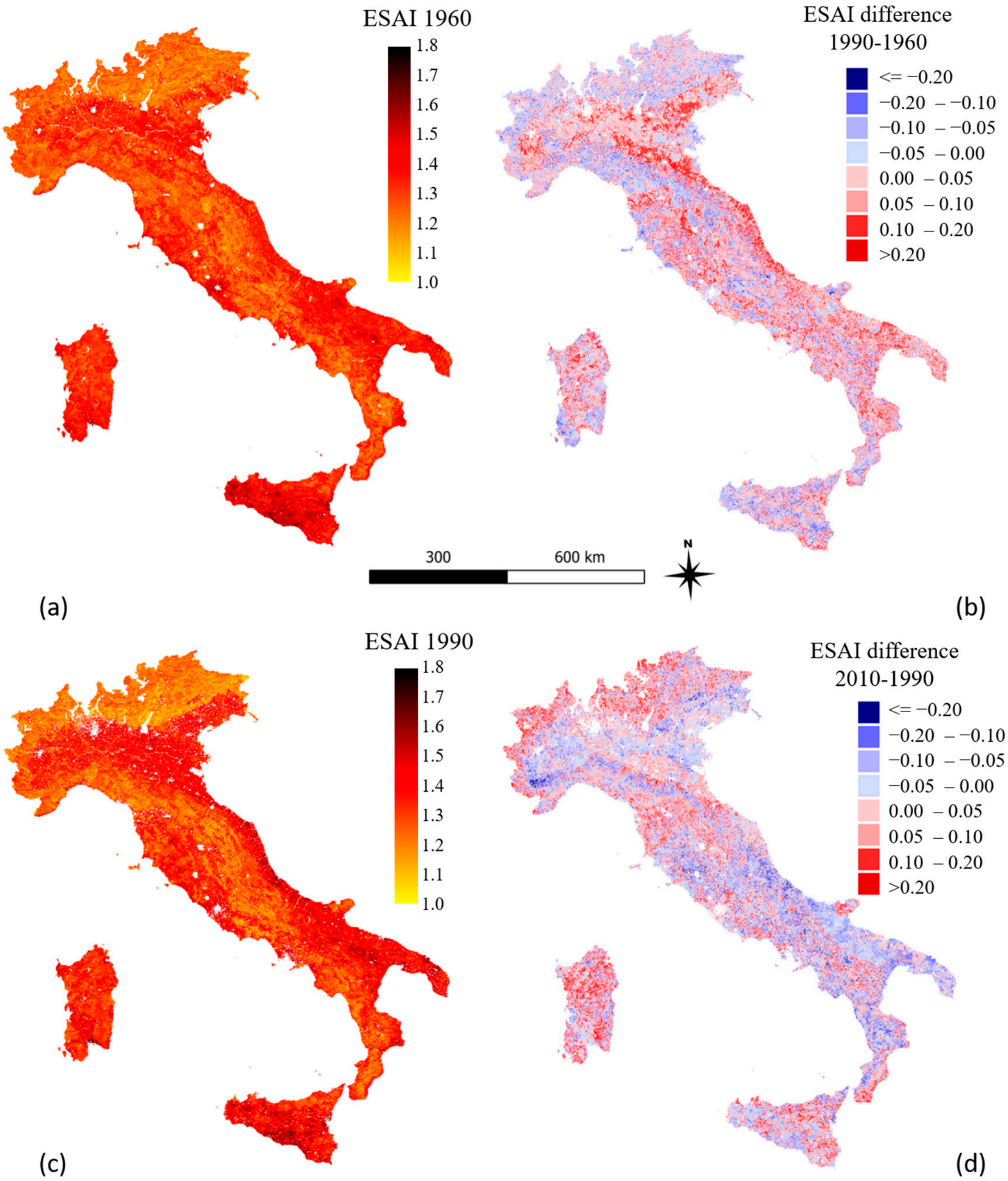

Figure 2. (**a**) ESAI, 1960; (**b**) ESAI change over time, 1960–1990; (**c**) ESAI, 1990; (**d**) ESAI change over time, 1990–2010.

Climate quality was estimated taking into account three variables: the average annual rainfall rate, the aridity index, and the slope aspect; all calculated from the Agrometeorological Database of the Italian Ministry of Agriculture, which has available about 3000 weather stations with daily records since 1951 [79]. The soil layer was regarded as a quite static variable since changes are negligible over 50 years because of the dominance of pedogenesis factors, usually very slow over time. We used a set of standard ESA layers (soil depth, texture, slope, and parent material) from the European Soil Database (Joint Research Centre, JRC) provided at 1 km^2 spatial resolution and from ancillary sources: (a) the Italian 'Map of the water capacity in agricultural soils' (provided by the Italian Ministry of Agriculture); (b) the Eco-pedological and Geological maps of Italy (realized by JRC and the Italian Geological Service); and (c) a map of Italian land systems realized by the National Centre of Soil Cartography (Florence). The vegetation layer considered four input variables: plant cover, fire risk, erosion protection, and drought resistance. These variables were estimated from reclassification of land cover maps realized on behalf of the CORINE initiative (CLC, see e.g., [80]) for the years 1990 and 2012 and a CORINE-like 'Topographic and Land Cover Map of Italy' made available by the National Research Council (CNR) of Italy and the Italian Touring Club (TCI) in 1960 with a hierarchical land system compatible with those of the CORINE Land Cover maps [81]. The land management layer encompasses various indicators considering population dynamics (density and annual growth rate of resident population by the Italian National Institute of Statistics) and agricultural intensification [82], derived from an indicator of land-use intensity based on the sequence of the abovementioned maps [79].

2.3. Local Regressions

To predict spatial variability in the level of land vulnerability to degradation across Italy in light of the 'convergence' notion, the empirical results of descriptive statistics and maps were refined with a spatially explicit strategy based on local econometric models, namely geographically weighted regressions (GWRs) run on the percent annual rate of change over time in the level of land vulnerability along the time interval t + 1/t as dependent variable, and the stock variable (level of land vulnerability at time t) as predictor. The implicit spatial structure of both the dependent variable and the lagged variable was considered using a W weighting matrix that computed the linear distance between elementary spatial units. Regressions were estimated separately for each study period (1960–1990 and 1990–2010). A model's goodness-of-fit was assessed using global R^2 coefficients and local slope and intercept coefficients.

The model specification assumes a part of variance not explained by the lagged predictor. The convergence hypothesis is thus tested according with the level of the global R^2 and local slopes. High R^2 means an indirect verification of the appropriateness of a convergence model for desertification risk in Italy. GWR was adopted in this study with the aim at identifying local-scale variability in desertification risk, using a bi-square nearest neighbor kernel function [83] to calculate weights for the estimation of local models [84]. The methodological framework underlying GWR is similar to that of local regression models; contrary to a spatially implicit ordinary least squares regression (with location invariant regression coefficients), a GWR runs an econometric specification for each location s = 1, . . . , n, as follows:

$$Y(s) = X(s)B(s) + e(s) \tag{1}$$

where, Y(s) is the dependent variable at location s, X(s) includes the predictors (in our case the ESAI), B(s) includes the regression coefficients, and e(s) is the random error, all at location s. As a result, GWR gave rise to a distribution of local estimated parameters [84].

2.4. Software

GWR elaborations and spatial analysis providing simple statistics were carried out in the free, open-source environments of QGIS 3.16.11 and GRASS GIS 7.8.5 (see http://qgis.osgeo.org and https://grass.osgeo.org/, last access on 25 June 2022). In particular, r.gwr-the specific GRASS add-on (https://grass.osgeo.org/grass78/manuals/addons/r.gwr.html (accessed on 25 June 2022)) was adopted to run GWRs on the empirical data available in this work.

3. Results

The empirical results have witnessed a significance dependence structure of the increase (or decrease) in the level of desertification risk with time (see Table 1. As a matter of fact, the outcomes of local regressions (specifically, the global adjusted R^2) show a very high path dependence in the first period (1960–1990) and a moderate sign of path dependence in the second period (1990–2010). Regression models show a strong heterogeneity in the local coefficients for both the endogenous processes of land vulnerability represented by the estimated value of the regression intercept and the specific temporal dynamics of convergence (or divergence) expressed through slope coefficients (Figures 3 and 4).

Slope coefficients took on very different values in Italy, highlighting different convergence dynamics in the two periods. The first period was characterized, as already highlighted in other works adopting alternative methodologies [66], by a strong polarization along the latitudinal gradient. In other words, Southern regions worsened and Northern regions remained mostly stable. On the contrary, the following period (1990–2010) highlighted a more complex and alarming picture: we observed stability or even an improvement of some areas of Southern Italy and a marked worsening of Northern regions considered as unaffected from a regulatory point of view (NAP).

For instance, a pivotal regional action plan in Northern Italy was initially approved by the Emilia-Romagna regional authority (https://ambiente.regione.emilia-romagna.it/it/acque/approfondimenti/documenti/Sintesi_PAL_def.pdf, last access on 10 August 2022) which, since the 1990s, had experienced more intense climate changes, especially in flat and coastal areas [85]. This has resulted in significant environmental damages and income losses, especially for the agricultural sector, representing a significant part of the regional added value. Losses are concentrated in areas devoted to intensive, high-income agriculture with greater consumption of technical inputs (e.g., water, agrochemicals, mechanization). From this point of view, the most recent convergence phenomena actually underlie a process of territorial polarization, loss of the agronomic quality of soils and, in general, of the ecological quality of landscapes.

Table 1. Descriptive statistics of regression models (local slope and intercept coefficients) with the ESAI level at time *t* as dependent variable in Italy by time interval (AICc = Akaike information criterion; BIC = Bayesian information criterion).

	1960–1990	1990–2010
No. pixels	276,335	274,467
Adjusted-R^2	0.650	0.613
AICc	-1.61×10^6	-1.58×10^6
BIC	-1.61×10^6	-1.58×10^6
Intercept		
Mean	0.714	0.790
St.dev	0.300	0.246
Min	−0.545	−0.256
Max	1.672	1.610
Slope		
Mean	0.481	0.417
St.dev	0.211	0.180
Min	−0.192	−0.152
Max	1.396	1.150

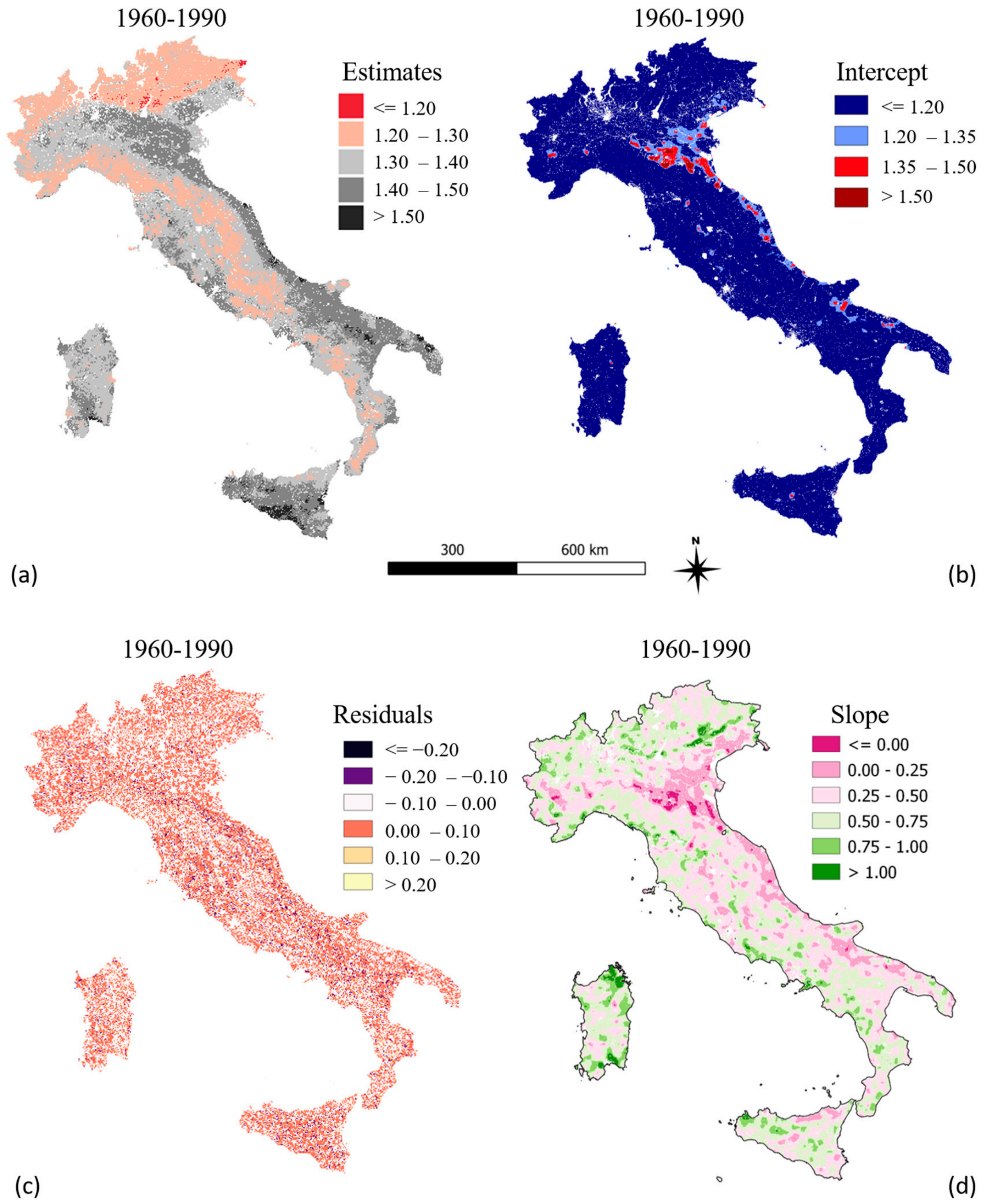

Figure 3. Regression coefficients and residuals of a GWR model estimating the local variation of land vulnerability to desertification at time t and the same index at time t − 1 for the time intervals 1960–1990: (**a**) Estimates, (**b**) Intercept, (**c**) Residuals, (**d**) Slope.

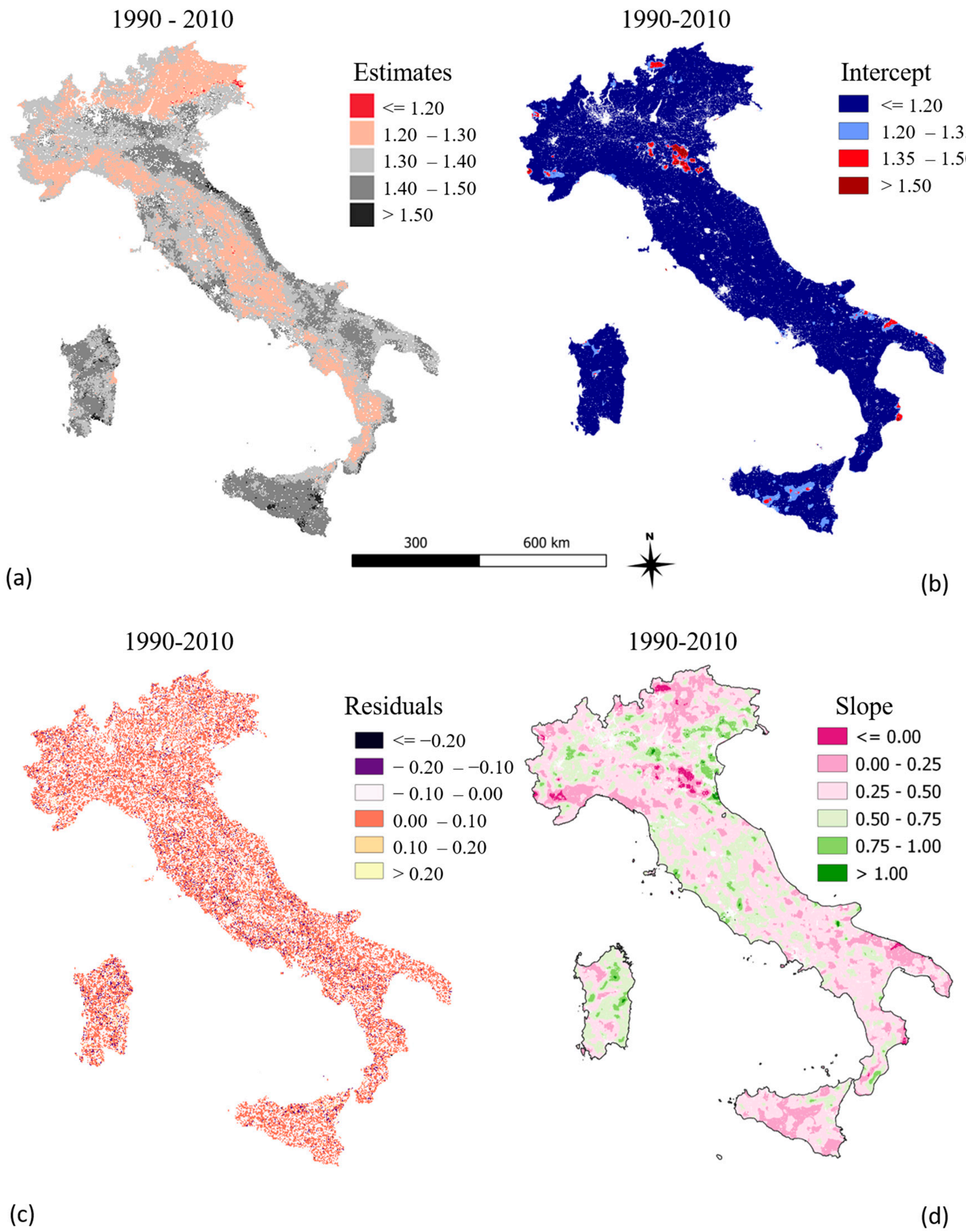

Figure 4. Regression coefficients and residuals of a GWR model estimating the local variation of land vulnerability to desertification at time t and the same index at time t − 1 for the time intervals 1990–2010: (**a**) Estimates, (**b**) Intercept, (**c**) Residuals, (**d**) Slope.

This is because, as evidenced with the empirical results of this study, Northern Italy tends towards a counterintuitive polarization, not reflecting the typical north-south gradient, but, on the contrary, developing according to other meso-geographical gradients responding to land-use, population density, or industrial specialization [86]. The results of this work also indicate socioeconomic disparities as having a strong impact on environmental dynamics. The recent evolution, which is strongly linked to the past development path, highlights the intrinsic features of complex local systems, as well as system properties that should be considered when interpreting (and possibly predicting) land degradation dynamics for a refined formulation of multi-scalar policies (Figure 5).

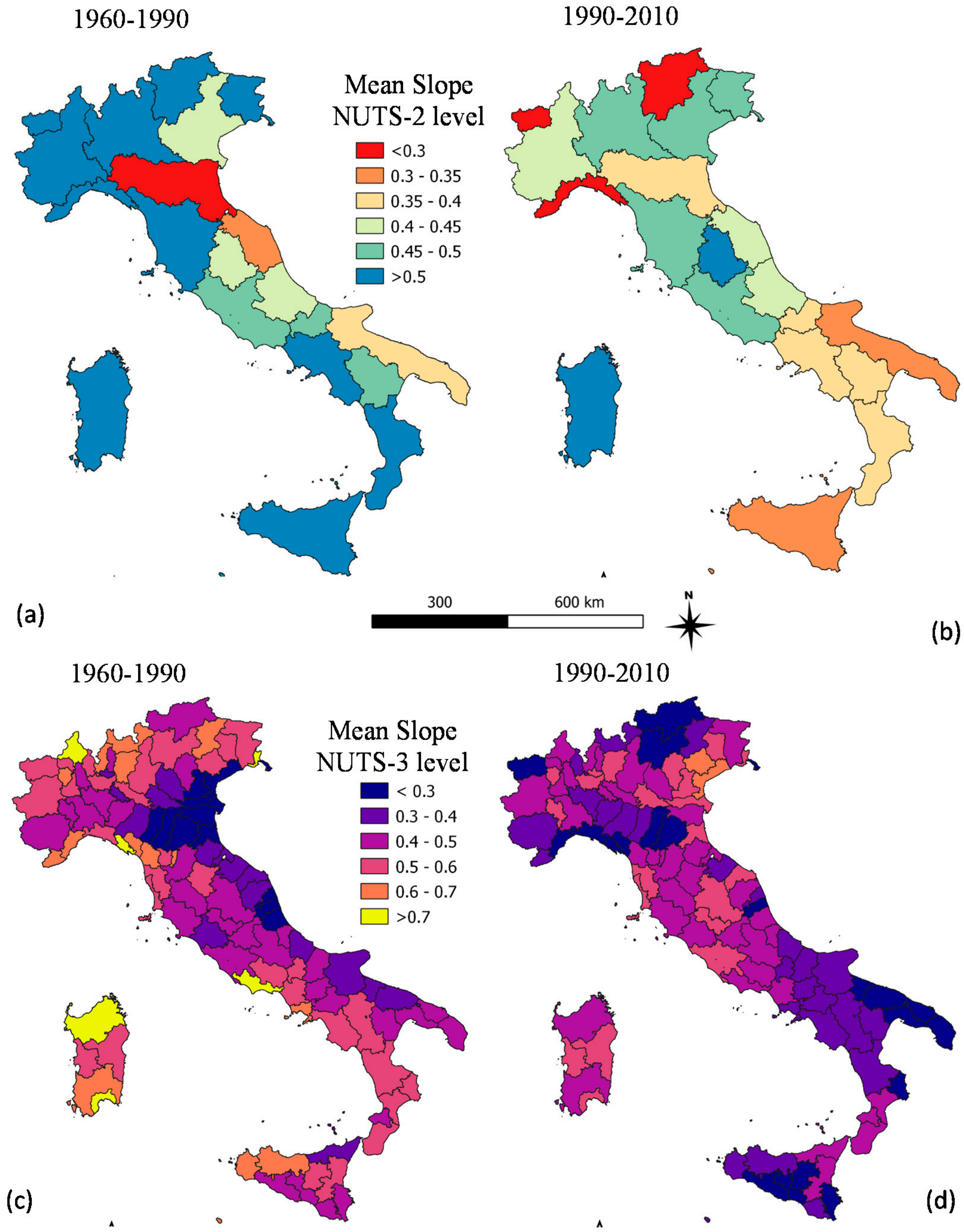

Figure 5. Results of the regression results (coefficient estimate) comparing NUTS-2 (administrative region) and NUTS-3 (province) scales for the time intervals 1960–1990 (**a**,**c**) and 1990–2010 (**b**,**d**); NUTS-2 and NUTS-3 are representative of two spatial levels of policy, reflecting the impact of Regional Action Plans (RAPs) and Local Action Plans (LAPs) against desertification in Italy.

A final approach was proposed illustrating a map of the intercept-to-slope ratio derived from the regression results (Figure 6). Higher values of this ratio (deriving from a considerably high value of the intercept and a significantly low value of slope coefficient) indicate a substantial stability of desertification risk, in turn, delineating districts with urgent (and structural) interventions to contain present (and, possible, future) degradation processes. Notably, the most vulnerable areas (ratio > 10) concentrated in the Eastern side of the Po plain (Emilia-Romagna), along the Adriatic Sea coast (Marche and Abruzzo region), Apulia, and Central Sicily. These areas expanded in the second time interval (1990–2010). In other words, the intercept-to-slope ratio may provide visual evidence of the formation (or consolidation) of desertification hotspots in Italy, as associated with high values of the ratio.

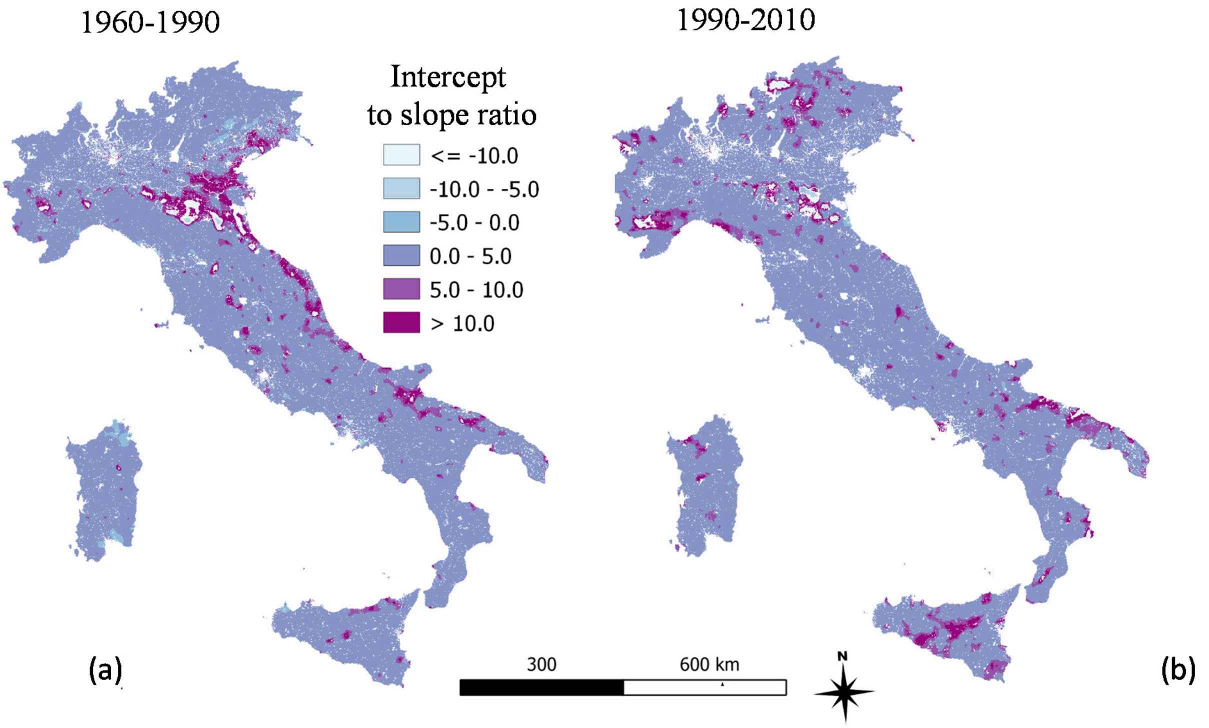

Figure 6. A map of intercept-to-slope ratios derived from local regression results ((**a**): 1960–1990; (**b**): 1990–2010) in Italy.

4. Discussion

The empirical results of our study outline methodological innovation and an original framework that allows discriminating long-term convergence from divergence processes of desertification risk on a local scale, thanks to the spatially explicit analysis of local regression coefficients. In this way, we will be able to capture differentiated socioeconomic dynamics underlying the multiple land degradation processes for Italy. More specifically, local regressions made it possible to outline convergence dynamics in the level of land degradation over time, contributing to the identification of desertification hotspots in a strongly affected country such as Italy. For instance, clusters emerging as priority areas from the intercept-to-slope ratio maps seem to be well-aligned with the dynamics of vegetation productivity and the major sources of information concerning land-use and land-cover changes in Italy. Areas that have the high intercept-to-slope ratio values for the time span 1990–2010 are located prevalently in Apulia, Piedmont, Emilia-Romagna, Sicily, and Liguria. These areas largely correspond to clusters of persistent negative trends in vegetative activity reported by Simoniello et al. [87], i.e., the areas in which the vegetative activity estimated by the satellite time series (NDVI-GIMMS) has shown a tendency to decrease for several consecutive years (1991–2003): see trend and persistence maps provided as Figure S1 in the Supplementary Materials. Moreover, according with field data released by the Italian Institute for Environmental Protection and Research (ISPRA), the Emilia-Romagna and Piedmont regions experienced a sharp urbanization at the expense of agricultural areas between 1990 and 2012, with natural areas remaining stable. Sicily and Liguria showed a decline in natural vegetation because of crop expansion and intensification. Apulia was a peculiar case where sealed areas expanded drastically into rural areas, cropland intensified, and forest areas decreased substantially (see [88] and the report available at https://annuario.isprambiente.it/ada/downreport/html/7037, last accessed on 10 August 2022). Furthermore, as portrayed by the recent literature [89], some Southern Italian regions (namely, Sicily, Sardinia, and Apulia), among the areas most populated by high intercept-to-slope ratio values, are experiencing a considerable temperature increase and precipitation decrease [90–92], impacting the most typical cultivations (i.e., vineyards and olive groves, see [93,94]).

In general, areas identified by this study as needing urgent action, only partially correspond to the geography of vulnerability to degradation, as produced by other independent national elaborations (based also on different methodologies) and by the currently available RAPs. This can be explained by considering that, although based on the ESA methodology, our approach captured only zones characterized by a stability of the desertification risk over time through geographically weighted regressions, whereas most of the mentioned elaborations relied on the mere application of the ESA procedure or made use of remote observations.

In particular, at a national scale, a recent study estimating the mean annual land productivity in the period 2000–2015 seems to match better with the intercept-to-slope ratio map relative to the time frame 1960–1990, with the exception of the major islands ([95]). This last map is in good agreement also with the map of sensitivity to desertification and drought in the Mediterranean basin (Figure S2 in Supplementary Materials, see further details at https://esdac.jrc.ec.europa.eu/public_path/shared_folder/projects/DIS4ME/using_dis4me/dismed.htm, last accessed on 25 August 2022) elaborated in 2003 by the EEA (European Environment Agency) and ENEA (Italian National Agency for new Technologies, Energy and Sustainable Economic Development). Proceeding towards the interregional level (Southern Italy), the paper of Imbrenda et al. [96], based on a modified version of the ESA also including remote sensing data (time series 2000–2010), showed an appreciable degree of similarity in the patterns of land vulnerability for Sicily and Campania with respect to the intercept-to-slope ratio map of the time frame 1990–2010.

Lastly, when considering the regional level at which most studies have focused in recent years, we found different levels of similarity between our maps and the regional cartography of degradation (RAPs), even though some areas identified by our procedure emerged as new hotspots. Starting from northern regions, the Piedmont RAP showed a partial overlap of the critical areas with both of the intercept-to-slope ratio maps, as these areas are mainly concentrated within the Po Plain around the major urban centers (see [97]), whereas the Emilia-Romagna RAP showed an appreciable correspondence with the 1960–1990 intercept-to-slope ratio map, identifying as vulnerable those areas located around the highways connecting the major centers of the region [98]. Regions belonging to Central Italy showed a scarce correspondence of critical areas, especially for Tuscany ([99]), whereas coastal areas of the Abruzzo Region were indicated both by the 1960–1990 intercept-to-slope ratio map and the relative RAP (see [100]). Studies concerning the southern regions indicated a large variety of correspondence. The work of Ladisa et al. [101] showed a geography of vulnerability for Apulia that does not match with our findings, neither with the local RAP (see [102]). A similar mismatch occurred for the RAP of Calabria and Basilicata regions (see [103,104]). The findings of the RAP of Basilicata proved to be aligned with other ESA-based studies [105,106]. Lastly, the RAP of Sardinia (see [107]) presented results partially overlapping with our map for the time frame 1990–2010 and with the map derived from an independent work, based on the integration of models and remote sensing data [67]. For Sicily, our 1990–2010 intercept-to-slope ratio map captured a large part of areas, identified as vulnerable by Giordano et al. [108] and by the last Regional Action Programme to fight desertification (see [109]).

At the same time, the results of this approach suggest how analyzing spatially explicit and refined data, such as the lattice constituted of 1 km^2 pixels adopted here, allows discrimination of complex processes that should be faced using differentiated tools, policies, and strategies [110]. The outcomes of local regressions additionally provided suitable indicators of convergence/divergence considering the most appropriate spatial scale for elaborating policies, i.e., administrative regions or provinces in Italy (respectively, NUTS-2 or NUTS-3 following European nomenclature of territorial units for official statistics). We have compared the same indicators at sub-regional scales (20 administrative regions and 107 provinces) consistent with the policy objective, i.e., reflecting homogeneous (polygon) areas representing the impact of Regional Action Plans (RAPs) or, eventually, Local Action Plans (LAPs), respectively. This exercise allows us to delineate the evolution of convergence (or divergence) processes characteristic of desertification risk in Italy, in line with the desired political instruments of the NAP.

From a methodological perspective, the novelty of this work lies in the application of a spatially explicit, local regression model to the topic of environmental convergence. This approach has been used for empirical analysis of some environmental variables (e.g., heavy metal accumulation, soil salinity, land use, ecological risk, and ground temperature [111–115]). Few studies have investigated land degradation/desertification issues by means of geographically weighted regressions [116]. In this way, we moved from global regression convergence models (providing homogeneous estimates on a country scale) to local estimation models, providing a spatially explicit result for each elementary unit. In our case, the territorial unit was represented by land pixels extending 1 km^2 each. The study area was divided into nearly 300,000 homogeneous pixels in which various factors have been evaluated and the ESAI has been derived at three different times (early-1960s, early-1990s, and early-2010s).

The results of this study are of interest both from a positive and normative point of view. From the former perspective, a statistically refined methodology is applied to an eminently local issue, which has been addressed for a long time with methodologies focusing exclusively (or mostly) on a global scale. At the same time, this approach has also evident regulatory implications, because policies should not be confined to outline country-scale strategies, but they should undertake concrete actions at both regional and local levels. The estimation of a local convergence model for desertification risk makes it possible to provide a significant information asset at a geographical scale of interest for policy, namely, the regional scale (reflecting the impact of regional action plans in Italy). This approach was also valid at the local scale thanks to the availability of a large set of information on homogeneous areas enabling a re-aggregation to the desired administrative scales most suitable for designing policy interventions—as we did in the descriptive analysis involving policy-relevant administrative units (Figure 5).

From this perspective, modeling results are meaningful both at the pixel scale (raster scale covering the whole study area) and at different (polygon) scales, basically reflecting the spatial articulation of administrative levels (NUTS-1, NUTS-2, NUTS-3, and NUTS-5, i.e., from regional to municipal level) representing possible policy targets for future actions to face desertification risk [117]. From an environmental accounting point of view, this system is also relevant because it translates stock use and the withdrawal of natural resources into a spatially explicit information flow. In this sense, the stock of natural resources is represented by the level of land degradation at time zero, assumed as a proxy of the level of land quality at an onset time. Obviously, this does not imply that the Italian landscape was pristine and healthy before the early-1960s; indeed, a massive use of agrochemicals began in parallel with the 1950s economic boom, and urbanization took an extraordinary turn [118–120]. In light of such evidence, the proposed model may be generalized to other socioeconomic contexts both in developed and in developing countries [121,122], shedding some further light on the intimate linkage between land degradation and sustainable development [123,124]. As a possible departure from paths of sustainable development, land degradation, especially in Mediterranean areas, reflects the complex interplay between socioeconomic and environmental dimensions [125,126]

5. Conclusions

The empirical results of our study highlight the effectiveness of interpretative models computing on spatially explicit data for complex environmental and socioeconomic issues over a relatively long time frame. They also suggest the importance of local econometric approaches controlling for spatial heterogeneity. In this regard, geographically weighted regressions produce outcomes that provide relevant information to design more effective policy strategies, assuming that local convergence holds—instead of (more traditional) global convergence mechanisms. The case of land vulnerability to degradation in Italy is significant when looking at the genesis of desertification hotspots in the country, namely, areas where risk levels increase rapidly compared with neighboring areas that show stable (or even improved) environmental conditions, because of local factors that are little known or poorly investigated. Capturing these hotspots means being able to concentrate local efforts on environmentally unsustainable areas, adopting the most appropriate mitigation and contrast policies, such as (i) favoring the restoration of abandoned areas, (ii) leveraging the new social demand for farming, and (iii) promoting specific actions to contain peri-urban expansion towards high-quality and fertile soils around metropolitan areas [78,127]. Together with remote sensing and field data, official statistics should directly contribute to this information challenge providing detailed information at an adequately fine-grain spatial resolution. Our approach can be easily generalized to more restricted (or larger) areas, not only in Europe, but also in other parts of the world featuring similar socioeconomic systems. Tools available for these studies are relatively simple and allow for a broad, low-cost application of environmental monitoring techniques in different geographical contexts where desertification risk appears to be an increasingly important issue, having climate change and human-driven landscape transformation as powerful drivers of change.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su141710906/su141710906/s1, Figure S1. (a) Total persistence map of NDVI (Normalized Difference Vegetation Index) trends for the period 1992-2003 obtained from 8 km GIMMS satellite dataset. The persistence index is expressed in number of years starting from 1992 for which the trend sign of the reference period 1982–1991 is preserved. (b) NDVI Trends of the reference period. (Figure readjusted from Simoniello et al. [87]). Areas of negative persistent trends (magenta) show patterns similar to the intercept-to-slope ratio derived from local regression results (1990–2010). Figure S2. Map of susceptibility to desertification obtained from the ESA procedure (Figure readjusted from https://esdac.jrc.ec.europa.eu/public_path/shared_folder/projects/DIS4ME/using_dis4me/dismed.htm, last accessed on 25 August 2022). The most vulnerable areas show patterns similar to the intercept-to-slope ratio derived from local regression results (1960–1990).

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