Assessing Climate Change Adaptability and Risk in Italian Territories Using Open Data

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Abstract
This study evaluates climate adaptability and risk across Italy using two open-data-based indices: the Climate Change Adaptability Index (CCAI) and the Climate Change Risk Index (CCRI). The CCAI measures resilience by balancing climate exposure (e.g., heatwaves, droughts) with adaptive capacity indicators (e.g., tree cover, soil permeability). The CCRI combines similar climate hazards with socio-economic vulnerability. Results reveal strong regional disparities as northern Italy shows greater adaptability, while southern regions face heightened risk. The territorial disparities are visible as well since inner and peripheral areas consistently exhibit lower adaptability and higher risk, while intermediate and metropolitan zones show more mixed profiles. This dual-index approach integrates environmental and socio-economic dimensions, offering a replicable method for territorial assessments. Findings show the value of open data and cross-sectoral governance for guiding sustainable, resilient urban and regional adaptation policies.

Keywords: Climate change adaptability, climate change risk, territorial sustainability, open data, Italy

1. Introduction

1.1. Territorial challenges of climate risk and adaptability

Italy's geographical diversity and socio-economic disparities led to an uneven territorial exposure and responsiveness to climate risks (CMCC and Enel Foundation, 2021). These risks are accelerated by global climate change, particularly within the Mediterranean Basin, identified as one of the most climate-sensitive areas globally (Medri *et al.*, 2013)

Temperature increases and hydrological stress are key climate threats. Projections indicate a potential +5°C rise in average temperature by 2100 under high-emission scenarios (Representative Concentration Pathway, RCP8.5 (Riahi *et al.*, 2007), with corresponding increases in hot and dry days and the intensification of heatwaves and droughts, especially in southern Italy and small islands. Precipitation patterns are expected to become more erratic, but the trend underlines a general increase of the intensity of rainfalls both in the North and South of Italy and seasonal declines more pronounced in central-southern Italy during summer and increased rainfall in northern regions during winter. These changes exacerbate Italy's already stressed water resources, particularly during summer months when demand from agriculture, industry, energy, and tourism peaks (Spano D., 2020).

These changes in the climate conditions also worsen the hydrogeological risks affecting Italy's territory, particularly vulnerable to geo-hydrological instability, including floods, landslides, and soil erosion. Approximately 91% of Italian municipalities are already exposed to this kind of hazards, and 94% are classified as at risk because of both natural and anthropogenic factors (Spano D., 2020). The increasing frequency of short, intense rainfall events makes the instability of fragile areas worse, especially in the Alpine and Apennine regions (CMCC and Enel Foundation, 2021).

Exposure is another key challenge. Italy is one of the most exposed countries in Europe to flood-related hazards with potential infrastructure losses ranging from €1.5 to €15.2 billion annually under high-emission climate scenarios in the period 2071-2100. (Spano D., 2020). Sea-level rise further threatens coastal zones, particularly in the northern Adriatic, while critical sectors such as agriculture and tourism face declining productivity and revenue due to shifting climate conditions (Medri *et al.*, 2013).

The evolving concept of territorial resilience, as proposed by Brunetta et al. (2019), emphasizes a proactive, integrated, and co-evolutionary approach to spatial planning. It advocates for a shift from reactive risk mitigation to adaptive strategies that incorporate socio-ecological and technological systems (SETS), focusing not only on physical robustness but also on institutional capacity, social learning, and cultural assets (Brunetta *et al.*, 2019).

In this context, there is a growing need for more informed planning approaches that integrate data-driven tools to support climate risk mitigation. Such methods are essential for identifying vulnerable areas, prioritizing interventions, and guiding territorial policies that are responsive to evolving environmental pressures.

These territorial and climatic challenges must also be viewed through the lens of vulnerability and risk theory. According to the IPCC (Intergovernmental Panel on Climate Change (IPCC), 2023), vulnerability encompasses exposure, sensitivity, and adaptive capacity, combining both external pressures and internal system characteristics. According to Füssel and Klein (Füssel and Klein, 2006), exposure refers to the extent of hazard contact, while sensitivity and adaptive capacity define a system's ability to respond. Evolving assessment frameworks (Bruno Soares *et al.*, 2012; Peng *et al.*, 2024) increasingly adopt integrated approaches that consider both socio-economic and ecological dimensions. This study aligns with this perspective, emphasizing the need to address both environmental stressors and social fragilities when assessing territorial climate resilience.

1.2. Role of Open Data in climate assessment

Open data plays an increasingly vital role in climate assessment by enhancing the transparency, replicability, and scale of data-driven analyses. In the context of climate change, especially for countries like Italy with strong regional variability, open data enables localized, evidence-based planning while fostering participatory and inclusive decision-making (Grinspan and Worker, 2021).

Beyond their analytical power, open data initiatives support democratic and cross-sectoral engagement. They allow various actors, e.g., planners, researchers, NGOs, and local authorities, to interpret, validate, and reuse the data for both policy and advocacy purposes (Open Governmental Partnership, 2024). Initiatives like OS-Climate, the Net-Zero Data Public Utility, and Dataland have demonstrated how neutral and collaborative data platforms can fill information gaps while reducing reliance on proprietary datasets (United Nations Environment Programme, 2024). This kind of platforms promote integrity, accessibility, and neutrality along with values essential for effective climate governance.

Despite the big potential of open access dataset for describing climate conditions and trends, their accessibility and usability can be lacking for non-experts. Moreover, the comparison of environmental data with other context-related conditions, such as socio-economic and infrastructural ones, may be relevant for taking comprehensive and informed decisions, based on the development of composite indices able to interrelate data from these different domains. Open-access datasets allow for the integration of environmental, socio-economic, and infrastructural information, which is essential for developing composite indices like in this contribution.

1.3. Aims and objectives

This study aims to develop a national-scale, open-data-based framework to assess climate change adaptability and risk across Italian territories. By utilizing datasets that are publicly accessible and easy to use for decision makers, researchers, as well as other professions who takes role in planning, we construct and apply two composite indices i.e., the Climate Change Adaptability Index (CCAI) and the Climate Change Risk Index (CCRI) to support spatialized, evidence-based planning. These indices were developed in a broader study under the framework of the GRINS (Growing Resilient, Inclusive and Sustainable) project, financed by the National Recovery and Resilience Plan (NRRP) in Italy. The objective is to identify regional and territorial patterns of exposure to climate-related hazards and adaptive capacity in order to underline climatic vulnerabilities that also consider other context-related variables, with the final aim of informing policy responses and prioritize place-based strategies.

More broadly, the study seeks to demonstrate how open data can be effectively operationalized in climate assessment, highlighting both the analytical potential and the structural limitations of this approach. In this framework, the research outcomes contribute to ongoing discussions on transparent, scalable methodologies for climate adaptation and territorial resilience planning.

The paper is structured as follows. Section 2 presents the materials and methods, including the GRINS main features and aims, open data sources, and the construction of the two composite indices i.e., CCAI and CCRI. Section 3 discusses the main results through a territorial lens, highlighting patterns of adaptability and risk across macro and micro typologies. It also includes a cross-index analysis to synthesize findings and identify most vulnerable areas related to climate conditions. The paper concludes by reflecting on the methodological strengths and limitations of the approach, emphasizing the value of open data in supporting spatially informed climate adaptation strategies.

2. Material and Methods

This study adopts a composite index approach to assess climate change adaptability and risk by integrating climate-related and socio-economic indicators. Moving from theoretical and empirical literature (Papathoma-Koehle *et al.*, 2016; Zhao *et al.*, 2020) key variables were identified that reflect either increased fragility (or risk) or adaptive capacity. Indicators such as temperature anomalies, duration of hot periods, and consecutive dry days capture exposure to climate hazards, while permeable soils and vegetation cover represent adaptive assets (Carter, 2018). Socio-economic conditions further influence local vulnerabilities and are embedded in the composite framework. The following subsections detail the taxonomy adopted (Section 2.1), open data sources and indicators (Section 2.2), and the structure of the indices (Sections 2.3 and 2.4).

2.1. **Territorial classification developed in GRINS project**

The project GRINS (Growing Resilient, Inclusive and Sustainable) (GRINS Foundation, n.d.) is part of an extended partnership funded under the National Recovery and Resilience Plan (Piano Nazionale di Ripresa e Resilienza, PNRR) by the Italian government and the European Union. It aims to create an open-access data platform supporting economic and financial sustainability of territories through research, policy analysis, and evaluation. GRINS is composed by nine spokes, conceived as sub-domains dedicated to address specific topics and produce related data. The present work was developed under Spoke 7 - Territorial sustainability, which aims to investigate and assess territorial disparities, vulnerabilities and gaps to orient more effective policies and actions.

Within Spoke 7 one important analytical output was the development of the "GRINS taxonomy", a methodological approach aimed at classifying Italian territories based on their functional and spatial characteristics. This taxonomy is developed by integrating multiple classification systems, including the National Strategy for Inner Areas (Strategia Nazionale per le Aree Interne,SNAI), the classification of metropolitan areas produced by the National Institute of Statistics (ISTAT), and the OECD Functional Urban Areas (FUAs) framework (Caramaschi *et al.*, 2024). The methodology used the municipal classification dataset of all Italian municipalities provided by ISTAT, which comprises population density and territorial boundaries, for dividing the municipalities into three main macro-classes as follows (see Figure 1a):

1. **Inner Italy** (Italia Interna), representing peripheral and ultra-peripheral areas identified by elaborating and enriching the National classification of inner areas given by SNAI (2014 and 2020).
2. **Intermediate Italy** (Italia di Mezzo), which encompasses territories that fall between inner and metropolitan areas. These include medium-sized cities, metropolitan fringes, and urban-rural continua.
3. **Metropolitan Italy** (Italia Metropolitana), including municipalities that are part of metropolitan areas or classified as Functional Urban Areas (FUAs).

Beyond these three macro-classes, the GRINS taxonomy foresees thirteen distinct sub-classes across the three macro-classes (see Figure 1b), providing a nuanced understanding of specific territorial differences and dynamics. These include:

- **Inner Italy**: 1.1.1 Inner, remote and sparsely populated area; 1.1.2 Inner and remote area with medium population density; 1.2.1 Sparsely populated inner area closest to a metropolitan area; 1.2.2 Inner area with medium population density closest to a metropolitan area.
- **Intermediate Italy**: 2.1.1.1 Sparsely populated mountain/inland hill urban-rural continuum; 2.1.1.2 Mountain/inland hill urban-rural continuum with medium population density; 2.1.2.1 Sparsely populated coastal and/or lowland urban-rural continuum; 2.1.2.2 Coastal and/or plain urban-rural continuum with medium population density; 2.2 Medium-sized city or non-FUA capital; 2.3 De facto or de jure metropolitan fringe.
- **Metropolitan Italy**: 3.1.1 De facto metropolitan centre; 3.2.1 De jure and de facto metropolitan area (not capital); 3.2.2 Metropolitan capital.

This classification system serves as the foundation for identifying socio-economic and environmental vulnerabilities, including climatic vulnerability, covering the whole Italian territory but providing data at municipal scale and across the different territorial classes. The final goal is to ease the definition of targeted territorial policies and sustainable development strategies.

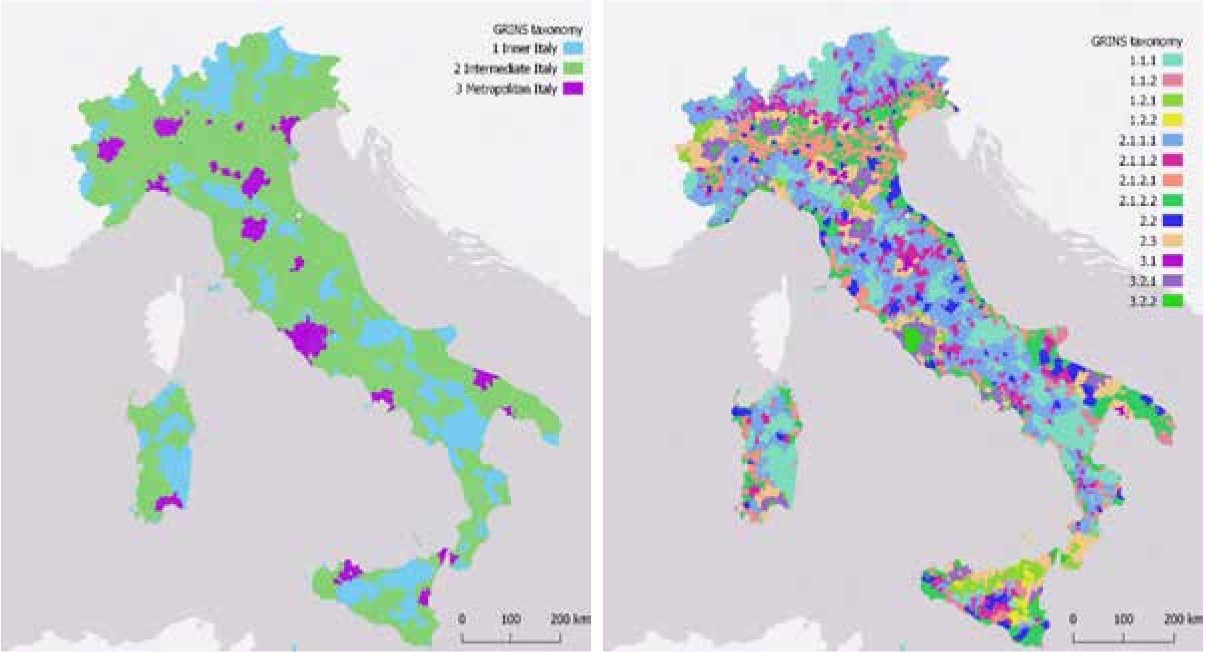

Figure 1. Taxonomy of Italian municipalities, developed within the GRINS project. (a) macro classes and (b) micro-classes. The classification system distinguishes three macro territorial categories (Inner, Intermediate, and Metropolitan Italy) and 13 micro-classes (produced after (Caramaschi *et al.*, 2024))

2.2. Open Data Sources and indicator Selection

The construction of both composite indices, i.e., CCAI and CCRI, relied on the selection of key indicators that are accessible, spatially detailed, and relevant to climate-related exposure, adaptive capacity, and socio-economic vulnerability. In order to develop robust and replicable indices, open datasets are prioritized with national coverage and adequate spatial granularity, preferably at the municipal (LAU) or provincial (NUTS3) level.

To ensure consistency and comparability, all data were pre-processed and harmonized. This involved normalization, imputation of missing values, and alignment of temporal and spatial resolutions. While most socio-economic indicators were available at the municipal level through ISTAT (Italian National Institute of Statistics), climate variables required further adaptation, often drawing from higher-resolution grid or provincial-level data.

The initial step was to identify the data needed and seek for the data sources. The most relevant datasets are identified ensuring high spatial and temporal resolution (see Tables 1 and 2) were sourced from national and international open databases including:
- ISTAT (Italian National Institute of Statistics): comprising many datasets for describing socio-economic data, including population density and income levels.
- Copernicus Climate Change Service: Climate-related variables, including temperature trends, heatwave duration, and precipitation data.
- EDJNet (European Data Journalism Network, i.e., a network of media organisations from across Europe, producing and promoting data-driven coverage of European issues, including environmental datasets): Surface temperature map of each municipality.

The sources of each datum, both temporal and territorial coverages, are provided in Tables 1 and 2.

While open data provides a transparent and accessible foundation for territorial analysis, their use introduces certain methodological considerations that required adaptation. The availability and quality of data were not uniform across all indicators and regions. For instance, some datasets, particularly climate variables like temperature trends and heatwave duration, were available at a high spatial resolution (provincial or grid-based), while socio-economic data from ISTAT often had a finer municipal-level granularity.

To address these challenges, the methodology was adapted by employing harmonization techniques to align indicators with differing spatial and temporal resolutions. For variables lacking high-resolution data, provincial-level indicators were aggregated or downscaled as proxies to ensure consistency within the composite indices. Despite these limitations, reliance on open data remains essential for fostering replicable and inclusive research.

2.3. **Climate Change Adaptability Index (CCAI)**

CCAI aims to provide a general measure of the level of response of environmental/anthropogenic factors to climate effects affecting a given territory, by adopting a balanced assessment between factors that are positive for adaptation to climate change and factors that hamper adaptation. The index has been calculated by considering the previous works (i.e., (Assumma *et al.*, 2019; Brunetta *et al.*, 2018) which was transposed in the climate domain, by considering indicators provided by different sources. Basically, the adopted method aims at calculating two synthetic indexes that respectively measure the exposure (E) of the socio-ecological system, and its adaptive capacity (A) by adopting a general perspective. This means considering climatic factors that might influence different spheres, such as the environment as well as the society. The index does not aim at being totally exhaustive in terms of indicators adopted (whose selection is influenced by data availability), however it is a valuable tentative to synthesize any vulnerabilities that can be further investigated.

Table 1. Indicators used to construct the Climate Change Adaptability Index (CCAI), including temporal and territorial coverage, units of measurement, and data sources. The composite index (I.1) is calculated based on five indicators (I.1.1–I.1.5).

Index	Code	Indicator Name	Temporal Coverage	Territorial Coverage	Unit	Data Source
1 CCAI	I.1.1	Consecutive days without rain	2021	Provincial (NUTS3)	n of days	ISTAT
	I.1.2	Duration of hot periods	2021	Provincial (NUTS3)	n of days	ISTAT
	I.1.3	Average temperature increase (1960-2018)	2018	Municipal (LAU)	°C	EDJNet
	I.1.4	Tree canopy density	2018	Municipal (LAU)	%	COPERNICUS
	I.1.5	Permeability	2018	Municipal (LAU)	%	COPERNICUS

The exposure component (E) is derived from the normalized values taking the municipal scale as base to have values between 0 and 1 of following indicators:

- **1.1 Consecutive days without rain**, i.e., maximum number of consecutive days in the year with daily rainfall less than or equal to 1 mm.
- **1.2 Duration of hot periods**, i.e., number of days in the year in which the maximum temperature is above the 90th percentile of the distribution in reference climatological period (1981-2010), for at least six consecutive days.
- **1.3 Average temperature increase from 1960 to 2018**, i.e., temperature variation occurred between the mean temperature values for the two decades considered (1961-1970 and 2009-2018).

The adaptive capacity component (A) is calculated from the normalized values of followings:
- **1.4 Tree canopy density**, i.e., tree cover density represents the percentage of a surface area covered by trees and vegetation in relation to the total surface area.
- **1.5 Permeability mean percentage value of permeable surfaces in a given area**, i.e., calculated by considering the complementary percentage of imperviousness provided by the HRL Copernicus dataset Imperviousness density.

CCAI, is calculated following the Equation through combining these two indexes:

$$CCAI = (A - E) / (A + E)$$

Positive values mean a prevalence of A; negative values mean a prevalence of E. Consequently, the more the negative value, the high the vulnerability.

2.4. **Climate Change Risk Index (CCRI)**

The Climate Change Risk Index (CCRI) captures the intersection of climate hazards and socio-economic vulnerability, highlighting regions where fragile socio-economic conditions are most impacted by increasing climatic extremes. As already anticipated climate risk is a combination of local hazards, exposure, and vulnerability and drought and warming represent the most critical challenges in Italy (Papathoma-Koehle *et al.*, 2016; Zhao *et al.*, 2020).

Therefore, the Climate Change Risk Index (CCRI) integrates exposure to those two climate-related hazards with socio-economic vulnerability to assess the overall risk faced by different territories. While CCAI aims to assess the above-mentioned climate hazards in relation to the adaptation response present in different contexts, CCRI aims to compare the climate hazards with the socio-economic vulnerability, in order to underline how the socioeconomic sphere is at risk in terms of climate change hazards. Therefore, climate change risk index indicates how much climate change hazards impact the socio-economic sphere of the territory, highlighting situations of greater risk and therefore more fragile situations. The index is calculated by averaging the combined exposure indicators with the socio-economic vulnerability index (SEVI), a composite indicator that captures the underlying susceptibility of communities to these hazards.

Table 2. Indicators used to construct the Climate Change Risk Index (CCRI), including temporal and territorial coverage, units of measurement, and data sources. The composite index (I.2) is based on three climatic stress indicators and one socio-economic vulnerability index (SEVI) (I.2.1–I.2.4).

Index	Code	Indicator Name	Temporal Coverage	Territorial Coverage	Unit	Data Source
2 CCRI	I.2.1	Consecutive days without rain	2021	Provincial (NUTS3)	n of days	ISTAT
	I.2.2	Duration of hot periods	2021	Provincial (NUTS3)	n of days	ISTAT
	I.2.3	Average temperature increase from 1960 to 2018	2018	Municipal (LAU)	°C	EDJNet
	I.2.4	Socio-economic vulnerability index (SEVI)	2019/2022	Municipal (LAU)	NA	Authors' elaboration

Formally, the index considers three exposure indicators and the socio-economic vulnerability index:
- **2.1 Consecutive Days Without Rain i.e.,** the maximum number of consecutive days in a year during which daily rainfall is less than or equal to 1 mm. Longer dry spells increase the exposure to drought conditions, impacting water availability and agriculture, and thus elevating climate risk.
- **2.2 Duration of Hot Periods, i.e.,** the number of days in a year where the maximum temperature exceeds the 90th percentile of the baseline climatological period (1981–2010) for at least six consecutive days. Prolonged heatwaves intensify exposure to extreme heat, posing threats to human health, infrastructure, and ecosystems.
- **2.3 Average Temperature Increase from 1960 to 2008, i.e.,** measures the **temperature variation** between two reference decades (1961–1970 and 2009–2018). An increase in average temperature signifies long-term warming trends, contributing to heightened exposure to climate-related hazards such as heat stress and altered precipitation patterns.

2.4 Socio-economic vulnerability index (SEVI), a composite indicator developed by the authors to capture territorial socio-economic fragility. It is calculated as the weighted average of four normalized variables: (1) old-age dependency ratio, (2) gross available income per capita, (3) employment rate (age 20–64), and (4) education level (lower secondary school attainment).

The result provides a comprehensive measure of the overall climate change risk, highlighting areas where climatic extremes intersect with fragile socio-economic conditions.

3. Results and Discussion

3.1. **Climate Change Adaptability Index (CCAI)**

The Climate Change Adaptability Index (CCAI) provides a measure of territorial resilience by balancing exposure to climate risks with the adaptive capacity. The results reveal significant disparities in adaptability across the national territory, with clear differences between northern and southern Italy, also confirming what was found in another recent study (Medri *et al.*, 2013).

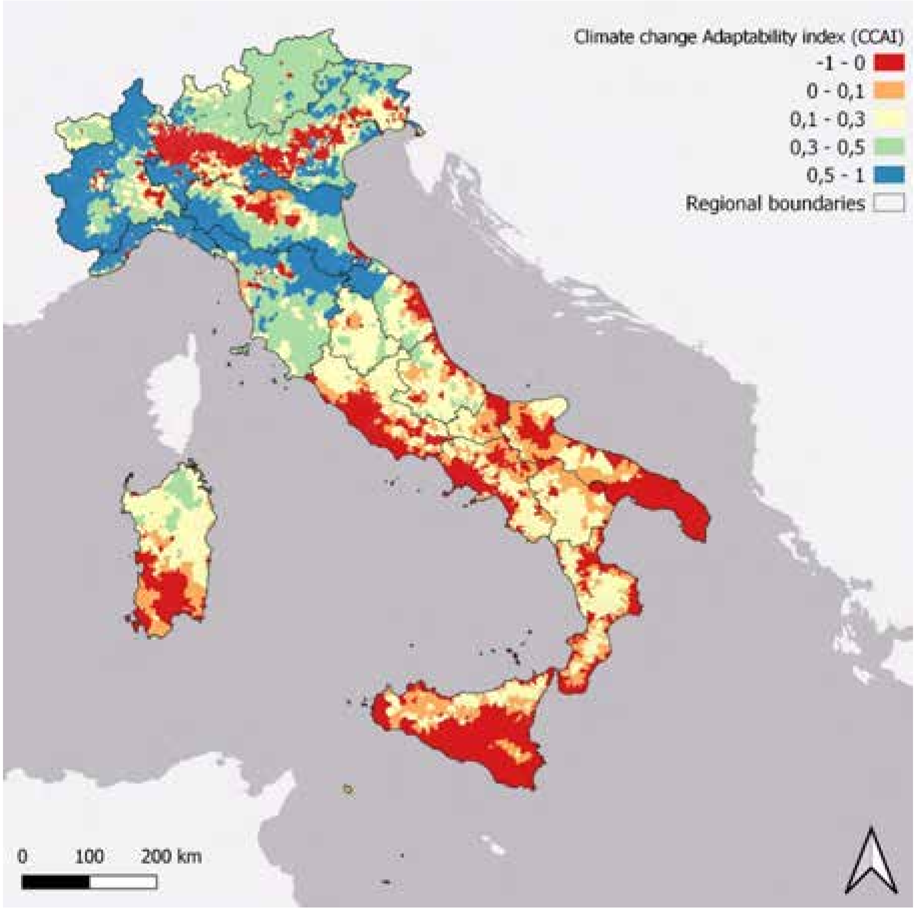

Figure 2. Climate change adaptability index (CCAI) across Italy. Higher index values indicate stronger natural and infrastructural capacity to buffer climate stress, particularly visible in northern and mountainous regions. Lower scores in southern and urbanized areas reflect limited adaptive assets and higher exposure to climatic hazards.

The spatial distribution of the CCAI scores, as presented in Figure 2, shows a clear contrast between northern and southern Italy. On one hand, territories with higher scores, primarily located in northern regions, exhibit favourable conditions such as dense tree canopy coverage and high soil permeability, which enhance natural climate resilience. These areas, including parts of the Alpine and pre-Alpine zones, benefit from robust governance and active climate action strategies, reflected in their positive index values. Conversely, regions in southern Italy and the islands show significantly lower scores due to prolonged droughts, higher exposure to heatwaves, and sparse natural buffers such as vegetation and permeable soils. Municipalities in regions like Sicily and Calabria recorded particularly negative index values, highlighting the urgent need for targeted interventions.

Table 3. Average values of the Climate Change Adaptability Index (CCAI) and its component indicators (1.1 to 1.5) across different territorial typologies in Italy. Values are shown for each typology and sub-typology, including inner, intermediate, and metropolitan areas.

Territorial Typology	1.1	1.2	1.3	1.4	1.5	CCAI
1 INNER ITALY	29	16	2.2	39	39	0.26
1.1.1 – Inner, remote and sparsely populated area	28	16	2.2	99	41	0.34
1.1.2 – Inner and remote area with medium population density	29	19	2.34	95	32	0.07
1.2.1 – Sparsely populated inner area closest to a metropolitan area	31	19	2.1	90	36	0.09

1.2.2 – Inner area with medium population density closest to a metropolitan area	29	15	2.07	73	40	0.05
2 INTERMEDIATE ITALY	25	12	2.07	94	29	0.19
2.1.1.1 – Sparsely populated mountain/inland hill urban-rural continuum	26	14	2.06	98	40	0.34
2.1.1.2 – Mountain/inland hill urban-rural continuum with medium population density	25	12	2.03	84	38	0.16
2.1.2.1 – Sparsely populated coastal and/or lowland urban-rural continuum	25	12	2	96	11	0.26
2.1.2.2 – Coastal and/or plain urban-rural continuum with medium population density	25	13	2.06	90	12	-0.13
2.2 – Medium-sized city or non-FUA capital	28	12	2.06	74	20	-0.11
2.3 – De facto or de jure metropolitan fringe	25	12	2.01	85	16	0.03
3 METROPOLITAN ITALY	28	14	2.2	85	23	-0.17
3.1.1 – De facto metropolitan centre	22	11	2.14	89	25	-0.17
3.2.1 – De jure and de facto metropolitan area (not capital)	24	12	2.21	85	23	-0.16
3.2.2 – Metropolitan capital	33	17	2.06	74	17	-0.44

When analysed through the territorial typologies, Inner Italy shows mixed results as it can be seen in Table 3. Inner, remote, and sparsely populated areas (1.1.1) have a relatively positive score of 0.34, benefiting from natural assets such as forests and low urban density. However, Inner areas with medium population density closest to metropolitan zones (1.2.2) record a score of only 0.05, reflecting challenges tied to urban pressure and limited natural buffers. Similarly, Intermediate Italy demonstrates variability, with sparsely populated coastal and lowland urban-rural continuums (2.1.2.1) scoring 0.26 due to moderate adaptive assets, while urban-rural plains (2.1.2.2) face negative adaptability (-0.13) due to land-use pressures. Metropolitan Italy, while economically strong, exhibits clear vulnerabilities. Metropolitan capitals (3.2.2) report the lowest adaptability scores (-0.44), driven by high exposure and urbanization. Overall, the findings confirm that the adaptive capacity plays a critical role in building territorial resilience to climate risks. Regions with natural assets such as forests and permeable soils demonstrate higher adaptability, while urban and coastal areas, particularly in southern and metropolitan contexts, exhibit negative scores driven by high exposure and limited adaptive measures. Targeted interventions such as reforestation, sustainable land management, and climate governance improvements are essential for reducing vulnerabilities, particularly in areas identified as high-risk zones.

3.2. **Climate Change Risk Index (CCRI)**

The Climate Change Risk Index (CCRI) captures the intersection of climate hazards and socio-economic vulnerability, highlighting regions where fragile socio-economic conditions are most impacted by increasing climatic extremes. Climate risk emerges from a combination of local conditions, including hazards, exposure, and vulnerability. In the Italian context, drought and warming represent the most critical challenges, necessitating the consideration of indicators such as temperature increase, duration of hot periods, and consecutive days without rain to assess both current conditions and future projections (Papathoma-Koehle *et al.*, 2016; Zhao *et al.*, 2020) While the CCAI previously assessed climatic hazards in relation to adaptive capacity, the CCRI focuses on how these hazards intersect with socio-economic vulnerability. This comparison highlights how territorial risks are magnified by fragile socio-economic conditions, such as low income, employment rates, and aging populations. Consequently, the CCRI underscores regions where climate change hazards exert the most significant pressure on the socio-economic sphere, identifying situations of heightened risk and territorial fragility that require urgent intervention.

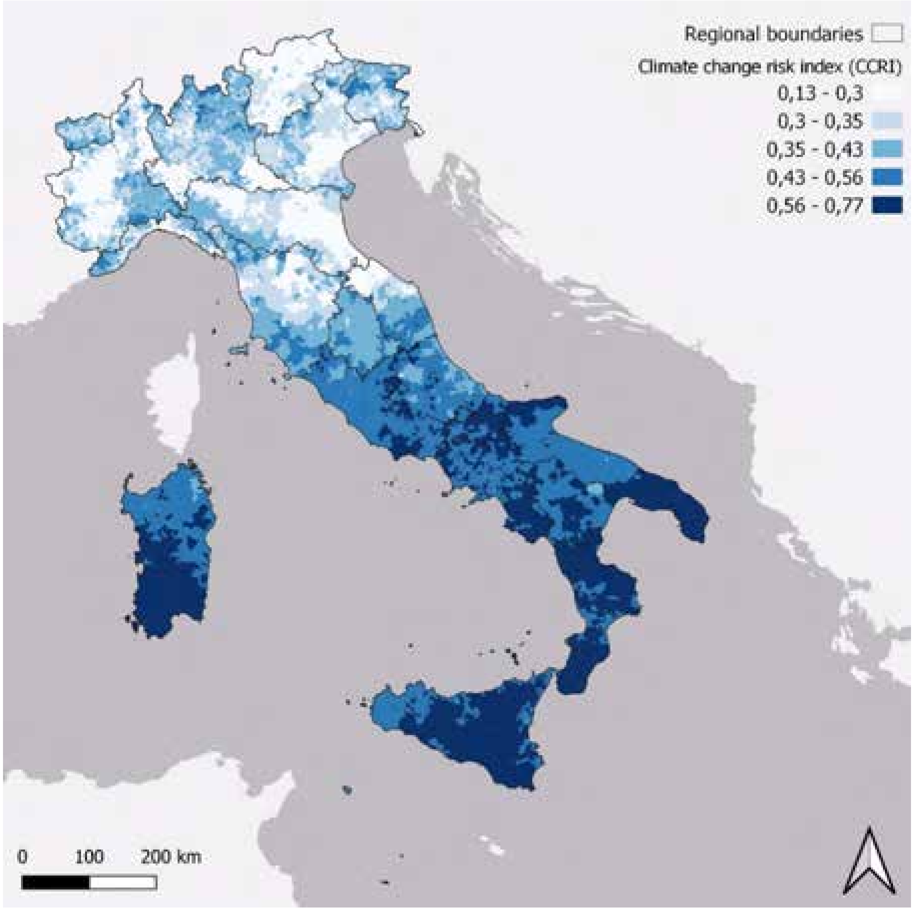

Figure 3. Climate Change Risk Index (CCRI) across Italy. Higher risk scores are concentrated in southern and rural regions, where climatic stressors coincide with fragile socio-economic conditions. Lower risk is observed in more resilient northern and metropolitan areas, though local hotspots remain due to uneven vulnerability patterns.

As Figure 3 shows, the southern regions, particularly Calabria, Sicily, and Apulia, exhibit the highest CCRI scores, exceeding 0.56. This pattern is primarily driven by prolonged exposure to extreme climatic events, such as extended consecutive days without rain (40.60 in inner areas) and duration of hot periods (22.40 days in certain areas). These regions also face socio-economic challenges, such as lower income levels and higher demographic pressures, which further amplify vulnerability. For example, inner remote areas show a SEVI of 0.54, exacerbating the region's inability to cope with climatic stressors. This pattern aligns with findings from another study (Mysiak *et al.*, 2018), which developed a Climate Risk Index for Italy to support national adaptation planning. While their approach relies on high-resolution gridded data and multi-model climate projections from EURO-CORDEX to simulate future scenarios (2021–2100), the present study focuses on recent observational data from open-access national sources to construct two present-day indices. A key methodological distinction lies in the composition of the indices: the Climate Risk Index incorporates a broader set of variables, including manufactured, natural, social, and economic capital, while the present study uses a more streamlined and spatially detailed set of indicators, emphasizing biophysical features (e.g., canopy cover, soil permeability) and socio-economic vulnerability.

Table 4. Average values of the Climate Change Risk Index (CCRI) and its component indicators (2.1 to 2.4) across different territorial typologies in Italy. Values are presented for each typology and sub-typology, including inner, intermediate, and metropolitan areas.

Territorial Typology	2.1	2.2	2.3	2.4	CCRI
1 INNER ITALY	28.97	16.48	2.2	0.52	0.5
1.1.1 – Inner, remote and sparsely populated area	28.27	15.56	2.2	0.54	0.49
1.1.2 – Inner and remote area with medium population density	28.65	19.27	2.34	0.45	0.49
1.2.1 – Sparsely populated inner area closest to a metropolitan area	31.21	18.74	2.1	0.49	0.52
1.2.2 – Inner area with medium population density closest to a metropolitan area	40.6	22.4	2.13	0.45	0.47
2 INTERMEDIATE ITALY	25.1	11.92	2.06	0.49	0.43
2.1.1.1 – Sparsely populated mountain/inland hill urban-rural continuum	25.94	14.29	2.06	0.49	0.43
2.1.1.2 – Mountain/inland hill urban-rural continuum with medium population density	22.54	10.89	2.03	0.38	0.37
2.1.2.1 – Sparsely populated coastal and/or lowland urban-rural continuum	25.29	7.82	1.94	0.34	0.38
2.1.2.2 – Coastal and/or plain urban-rural continuum with medium population density	25.17	12.86	2.15	0.35	0.43
2.2 – Medium-sized city or non-FUA capital	28.2	15.74	2.02	0.42	0.39
2.3 – De facto or de jure metropolitan fringe	25.38	12.1	2.01	0.39	0.36
3 METROPOLITAN ITALY	28.23	14.33	2.2	0.31	0.4
3.1.1 – De facto metropolitan centre	22.18	10.59	2.06	0.3	0.36
3.2.1 – De jure and de facto metropolitan area (not capital)	28.23	14.34	2.21	0.31	0.4
3.2.2 – Metropolitan capital	32.82	16.79	2.06	0.35	0.42

Table 4 summarizes the numerical findings separated by territorial typologies. In inner Italy, sparsely populated areas close to metropolitan regions demonstrate CCRI values of 0.52, driven by a combination of exposure indicators such as 31.21 consecutive dry days and moderate socio-economic vulnerabilities. These results emphasize that rural and remote areas remain disproportionately affected due to limited adaptive capacity, aging populations, and weaker economic conditions.

Conversely, northern and central Italy, particularly in metropolitan areas, show lower levels of climate change risk. Metropolitan regions like Lombardy and Veneto report CCRI scores as low as 0.36–0.40, reflecting favorable conditions, including shorter dry spells (22.18 consecutive days) and stronger economic resilience, evidenced by socio-economic index values as low as 0.31. However, even within metropolitan Italy, capital cities demonstrate slightly higher risk values (0.42), indicating localized challenges associated with urban heat and socio-economic disparities.

The results for intermediate Italy present a nuanced picture. Sparsely populated mountain and inland urban-rural areas report CCRI scores around 0.43, with lower exposure indicators but socio-economic vulnerabilities, such as aging populations and reduced employment rates. Areas with medium-sized cities demonstrate slightly better resilience, but exposure to warming trends still highlights the need for targeted adaptation measures.

Overall, the CCRI underscores the territorial patterns of climate risk across Italy. Southern and rural areas face the most significant challenges, where prolonged dry periods, rising temperatures, and economic fragility combine to amplify vulnerability. In particular, Calabria region and some parts of Sicily score high both on climate exposure and socio-economic vulnerability with SEVI values exceeding 0.50. In contrast, northern and central metropolitan areas demonstrate lower hazard exposure and stronger socio-economic resilience. Intermediate Italy reflects a mixed picture: while some subtypes benefit from natural buffers, socio-economic fragilities in sparsely populated or mountainous areas contribute substantially to overall risk levels.

Addressing these disparities requires region-specific strategies that improve both adaptive capacity and socio-economic conditions, particularly in high-risk areas, through investments in green infrastructure, economic development, and climate-responsive policies.

Despite lower average CCRI values in several territorial typologies, approximately 27% of municipalities exhibit high climate risk due to socio-economic fragility as well. For example, many are located in urban-rural continuums or sparsely populated inner areas, demonstrate CCRI values above 0.50 and SEVI scores exceeding 0.50, placing them among the most vulnerable within otherwise more resilient typologies. These cases illustrate the importance of disaggregated assessments and reveal "outlier municipalities" (see Figure 4) that may be masked by broader territorial averages, as well as showing the impact of SEVI in CCRI. Recognizing such outliers is critical for ensuring that adaptation strategies are not only regionally targeted but also attentive to intra-regional inequalities.

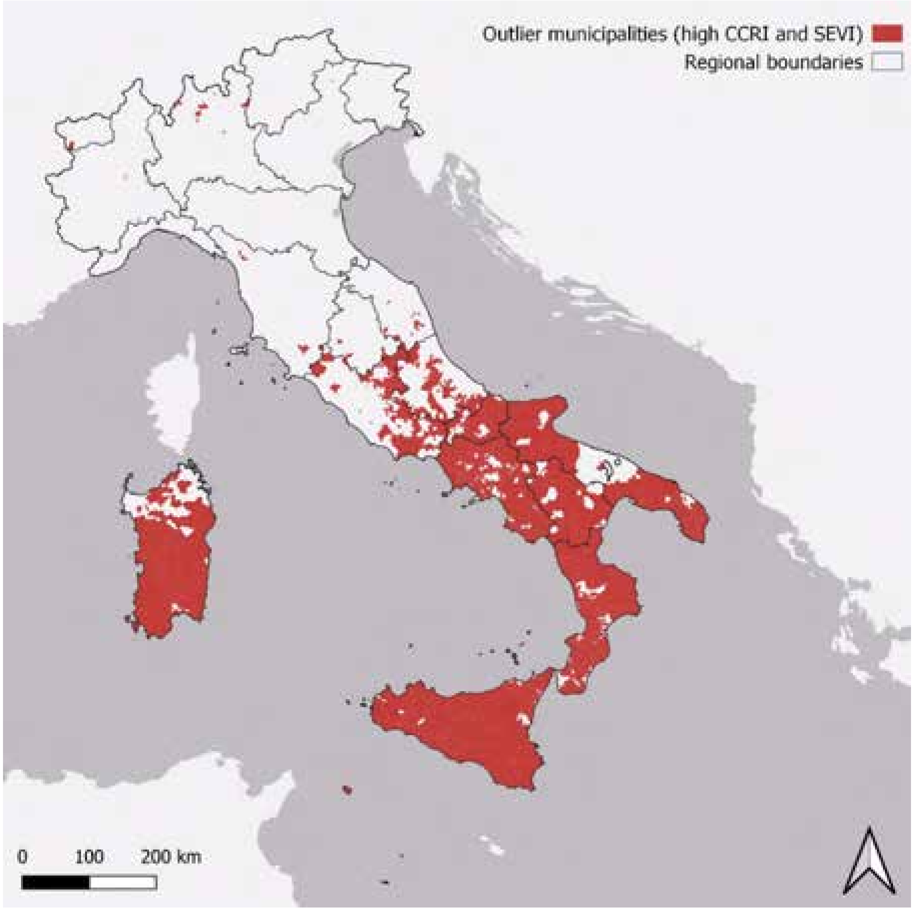

Figure 4. Municipalities with both CCRI and SEVI values above 0.50, identifying territorial climate resilience patterns.

3.3. **Cross-Index Analysis of Adaptability and Risk**

Bringing together the Climate Change Adaptability Index (CCAI) and the Climate Change Risk Index (CCRI) enables a more nuanced understanding of territorial resilience and fragility in Italy. While the CCAI reflects the capacity of local systems to withstand climatic stress through natural and infrastructural buffers, the CCRI reveals where climate hazards overlap with socio-economic vulnerability. Viewing the indices together highlights critical intersections where resilience strategies are most urgently needed.

Both CCAI and CCRI are unitless composite indices derived from normalized data, which allows their spatial patterns to be jointly visualized.

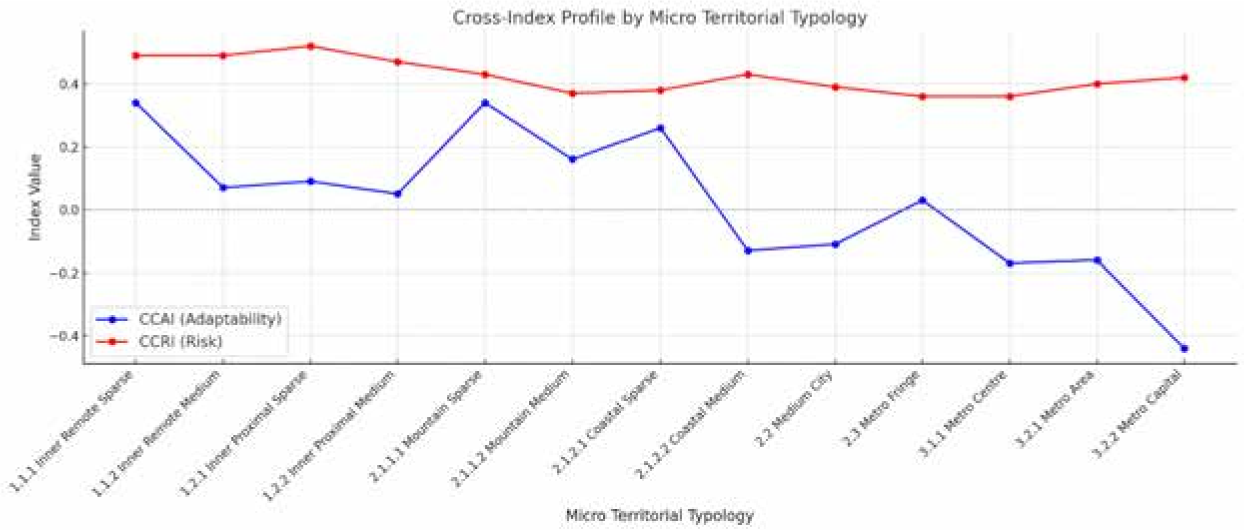

Figure 5. Climate Change Adaptability Index (CCAI) and Climate Change Risk Index (CCRI) across Italian micro territorial typologies. The figure highlights the inverse spatial relationship between adaptability and risk, with notable disparities across inner, intermediate, and metropolitan areas.

Figure 5 illustrates a cross-index plot showing the distribution of scores across micro territorial typologies. A striking feature of the plot is the consistent and steep drop in CCAI scores for metropolitan capitals (3.2.2), which contrasts with their moderate CCRI values—revealing a scenario where high exposure and environmental stress are somewhat offset by socio-economic robustness. Conversely, inner areas (e.g., 1.2.2) show moderate adaptability yet relatively high risk, illustrating the amplifying role of social vulnerability in rural or peri-urban contexts.

This combined perspective reinforces key findings from the previous sections: while natural conditions (e.g., canopy density, soil permeability) offer a degree of climate resilience, socio-economic disparities can override these advantages. At the same time, some urbanized areas with stronger institutions and services demonstrate the capacity to absorb risk, even when ecological adaptability is low.

The cross-index view supports the argument that place-based climate policies should not rely on environmental indicators alone. Instead, they must account for compounded vulnerabilities by aligning ecological investments (e.g., nature-based solutions) with social policy interventions (e.g., education, employment, and health infrastructure). In this way, the combined use of CCAI and CCRI offers a replicable framework for guiding adaptive strategies across diverse territorial contexts.

4. Conclusions

This contribution has presented a national-scale assessment of climate change adaptability and risk in Italy through the development of two open-data-based composite indices: the Climate Change Adaptability Index (CCAI) and the Climate Change Risk Index (CCRI). By integrating environmental and socio-economic indicators across a spatially detailed territorial taxonomy, the analysis reveals stark disparities in both adaptability and risk across Italian territories. The use of open data and a replicable methodological framework enhances the transparency, scalability, and policy relevance of the findings, offering a practical tool for spatialized climate planning. Such technical foundations are crucial for developing robust composite indicators like the CCAI and CCRI introduced in this study, which depend on integrating open datasets from multiple institutions and spatial scales. Without clear standards and shared conventions, the operationalization of territorial climate assessments becomes fragile, limiting both their analytical reliability and policy relevance.

Despite the strengths mentioned above, the analysis also faces limitations linked to data availability, spatial resolution, and indicator harmonization, which may affect comparability across regions. Despite these constraints, the study demonstrates the potential of open-data-driven approaches for supporting place-based adaptation strategies and guiding informed territorial policy.

The analysis highlights specific regions (e.g., Calabria, Sicily, Apulia) and territorial typologies (particularly inner, remote, and sparsely populated areas) priority zones for climate adaptation. These areas consistently exhibit low adaptability and high climate risk due to limited ecological buffers and compounded socio-economic vulnerability. By contrast, some metropolitan and intermediate areas show greater resilience, yet still face localized pressures that warrant targeted planning. These findings support the need for differentiated place-based strategies tailored to the specific challenges and capacities of each territorial context.

Addressing climate risk and fostering adaptability in Italy requires tools that reflect territorial specificities and local-scale heterogeneity. National-level strategies must be grounded in spatialized assessments capable of identifying not only where risks are highest, but also where adaptive capacity is weakest. This highlights the importance of developing and applying robust, data-driven methodologies that integrate climatic and socio-ecological dimensions at appropriate scales. Such approaches are critical for informing place-based adaptation strategies and ensuring that policy responses are both equitable and effective across diverse territorial contexts.

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