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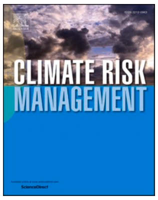

Spatial risk assessment for climate proofing of economic activities: The case of Belluno Province (North-East Italy)

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ABSTRACT

Recent advancements in spatial risk assessment methodologies, particularly those incorporating GIS and economic evaluations, have significantly enhanced our ability to assess and manage risks associated with natural disasters. Entrepreneurs, investors, and public administrations need information about climate change risks for effective planning and decision making. To move from generic global or national projections about climate change scenarios, towards more actionable information on climate risks for socioeconomic agents, the three dimensions of risk (Hazard, Exposure and Vulnerability) must be quantified and mapped with the involvement of stakeholders. In this study, spatial indicators, tailored to the social and ecological systems of interest and co-designed with the key stakeholders are aggregated into sectoral risk indexes quantified in economic terms. Climate risk indexes were calculated and mapped for the four key economic sectors of the study area of the Belluno Province (Italian Alps): summer tourism, winter sports and events, eyewear industry, and electricity supply. Stakeholders were involved during the assessment to share knowledge, data and needs and to provide expert judgments on intermediate and final results. Outputs include a series of maps and statistical summaries, highlighting future trends of climate related risks, their spatial variability within the area and the estimated levels of uncertainty. Estimates on expected changes of future damages with constant Exposure and Vulnerability, provided socioeconomic agents with simple and clear messages about how their activities could suffer or benefit from climate change in the future.

1. Introduction

The escalating threat of climate change is raising concerns among policy makers and economic agents such as entrepreneurs and investors. Social and economic actors are in search for tailored information about evolving climatic hazards, which can be provided by

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climatic models, but such information is affected by multiple sources of uncertainty, first of all internal model uncertainty and scenario uncertainties (Sanderson and Knutti, 2012; Hawkins and Sutton, 2009, Wilby and Dessay, 2010). Effective communication and information sharing are crucial for boosting preparedness, prompting adaptation strategies, and integrating anticipated climatic impacts into planning and decision-making (Lourenço et al., 2016; Iwaniec et al., 2020; Arnewell, 2022).

In general, climate change is considered as a source of risk together with others, such as financial or technological ones. Corporations are especially focused on physical risks from environmental hazards and transition risks deriving from the evolution of climate change policies, to be considered alongside financial risk for strategic planning and infrastructure design (Walenta, 2020).

This creates a demand for the scientific community to provide the best available information on future risks for human activities and assets. Here, the concept of “climate proofing” has emerged to identify risks to natural or human assets deriving from climate variability and change, and ensuring these risks are mitigated through long-lasting and environmentally sound, economically viable, and socially acceptable changes (ADB, 2005). Climate proofing is applicable at various levels of planning, project development and decision making, in different contexts, such as infrastructural or financial investments and public plans or programmes (Ricciardi et al; 2024; De Vivo et al; 2023a,b).

Climate proofing is often joined to “climate mainstreaming”, which in the case of adaptation indicates its integration into the preparation and implementation of sectoral policies, plans, and projects related to economic development, social progress, and/or environmental protection (ADB, 2005).

Many international institutions such as the UNDP,[1] UNEP,[2] UNWTO,[3] but also private investors such as ROBECO[4] are implementing these concepts at various levels as a means to take adequate consideration of impacts of climate change and to enhance the resilience and adaptive capacity of social and economic agents. Investment communities drive the interest for corporate climate risks for their effects on financial returns and the need emerges for methods and tools to disclose and evaluate those risks. However, the landscape of solutions is still quite varied and inconsistent and thus the provision of widely accepted guidelines and scientifically sound methods is increasingly urgent (Walenta, 2020).

In July 2021, the European Commission approved climate proofing guidelines for infrastructure projects, to assist institutional and private investors in making informed decisions which may be relevant for both mitigation and adaptation policies (EC, 2021).

Risk assessment involves considering the specific vulnerability of exposed assets (e.g. critical infrastructures) to climate hazards (e.g., floods, heat waves) within their specific environmental and socio-economic context, in light of the best available information about future scenarios (Diaz and Moore, 2017; Harrington et al., 2021). Transition from generic studies focusing on variables like temperature and precipitation, towards actionable information for socioeconomic stakeholders, requires the development of specific local-scale hazard indicators and conduct sector specific risk assessments. Advances in climate modelling have enabled the downscaling of climate scenarios, while increasingly detailed spatial data on exposed assets and socioeconomic factors now allows for creation of sets of indicator maps (Li et al., 2024). These maps can be used to inform the development of comprehensive risk indexes. This creates an opportunity to propose operational methods tailored to the informational needs of economic agents, leveraging the most detailed spatial and thematic information.

Spatial risk assessment, especially in the context of natural hazards such as landslides and floods, has evolved significantly over recent years. Researchers have increasingly employed Geographic Information Systems (GIS) and various analytical methodologies to improve the precision and applicability of risk assessments, particularly by integrating economic factors to better inform policy decisions.

In recent years, spatial risk assessment has advanced significantly, particularly with the integration of GIS to enhance the accuracy and utility of risk mapping. This approach has become essential for understanding and mitigating the impacts of natural hazards across diverse terrains and regions. Aligned with this approach, recent studies have explored various aspects of GIS-based risk assessments (Ricciardi et al; 2024). For instance, Van Westen et al. (2008) highlight the importance of precise spatial data for assessing landslide risks, while Cai et al. (2021) address the challenges of flood risk assessment in mountain cities using GIS and the Analytical Hierarchy Process. Similarly, Foudi et al. (2015) emphasise the need to integrate economic considerations into spatial risk assessments to better understand and manage flood impacts. Finally, Shi et al. (2020) advocate for a more interdisciplinary approach to disaster risk science, incorporating both physical and socio-economic factors.

Spatial analysis is multidimensional in nature and requires some sort of synthesis, which can be provided by concise indexes obtained by aggregating stacks of indicator maps. In climate studies, the index-based approach represents an operational solution for supporting hazard assessment, providing information on the expected variations, in terms of frequency, intensity, and persistence of weather-induced processes (such as floods, landslides, droughts, heat waves, and fires) (Amarnath et al., 2021). This approach is widely used in the literature to assess future changes in weather and climate extremes with respect to a reference period in a specific location (Christidis and Stott, 2016; Fioravanti et al., 2016; Dosio and Fischer, 2018; Hong and Ying, 2018; Reder et al., 2018; Rana et al., 2022; Tian et al., 2022). Selected hazard indicators describing the magnitude of the events (hazards) and their expected evolution under different future scenarios, are combined with other indicators assessing physical and structural factors of the exposed assets (exposure) and the local socio-economic factors (vulnerability) (IPCC, 2012). The combination of different indicators is performed through mathematical functions that calculate concise risk indexes, which typically express the potential damage for exposed

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[1] https://www.uncclearn.org/wp-content/uploads/library/unssc04.pdf.

[2] https://portals.iucn.org/library/sites/library/files/documents/2010–101.pdf.

[3] https://www.unwto.org/covid-19-oneplanet-responsible-recovery-initiatives/climate-proof-investments-guide.

[4] https://www.robeco.com/it/approfondimenti/2021/10/six-steps-to-climate-proof-your-investments.html#.

assets as a function of the magnitude of various extreme events (Beccari, 2016).

Index-based approaches are largely used also in the economic literature for supporting the assessment of climate impacts and the evaluation of risk, as well as for defining tailored adaptation strategies (EEA, 2018; Mysiak et al., 2018). In this field, several recent studies also consider the importance to tailor these approaches considering the specific local context (Rianna et al., 2017, Reder et al., 2018), but most of the studies focus on a single type of generic hazard (e.g. extreme rainfall), while instead risks are sector specific and derive from combination of extreme events (e.g. logistics being affected by combinations of heavy snowfalls and strong winds). Therefore, quantifying the risks induced by climate changes in a way that they can be beneficial for economic agents is still an open issue. In a review of the literature on quantitative assessment of climate change risk in urban areas, Ye et al. (2021) identify a series of research challenges to be dealt with, and ask for new efforts for improving the integration between economic and environmental models, the consideration of the relationships between variables such as exposure, sensitivity and adaptability, and the approaches for the aggregation of multiple dimensions to synthesise different risks faced by various receptors.

Given these premises, the current work aims to enrich the literature on climate risk assessment for climate proofing and spatial planning, by integrating the outputs of high-resolution Regional Climate Model (RCM) data, into a system of spatial environmental and socioeconomic indicators with adequate spatial resolution, co-designed with local stakeholders. In particular, our work focuses on the application of GIS in mapping climate-related risks, while also incorporating economic assessments to provide a more comprehensive view of potential impacts. By positioning our research within this context, we contribute to the ongoing discourse on combining spatial data and economic evaluations to better inform risk management strategies and policy decisions, offering an integrated method that addresses the complexities of climate-related risks with high spatial resolution.

In this study we focus on the Alpine Region, one of the global hot spots where climate change has already shown remarkable effects in terms of temperature rise (close to 2 °C over the last 120 years) at a pace that is as much as twice the global average, with dramatic consequences in terms of glacier retreat and disappearance, but also extreme events of increasing magnitude (EEA 2009; Bergert and Frei, 2018). Future climate projections confirm the trend of the recent past and foresee further effects on temperature, seasonality of precipitation, relative humidity and frequency/intensity of extreme precipitation and floods (Gobiet et al., 2014). We focus in particular on the Belluno Province, where huge events, such as the catastrophic Vaia storm in 2018 (multimillion damages due to 18 million trees laid down by the wind) and the forthcoming Winter Olympic Games of Milano-Cortina in 2026 (multimillion investments for sport facilities and infrastructures), have raised awareness of local economic actors on the relationships between climate and economy and pointed out the critical need for climate proofing of current and future investments.

The collaboration with local stakeholders (association of local enterprises, utility companies, environmental protection agency, local administrations and alike), allowed for precise identification of the sectoral risks to be explored. In particular, a decision was taken to explore the risk deriving from downscaled future hazards on the current state of local vulnerability and exposure of the four main economic sectors. We excluded the elaboration of future socioeconomic scenarios, because we found that limiting future projections to the exploration of climate change impacts without any assumption about future socioeconomic scenarios, provides simpler, clearer and more effective messages for local economic actors and public decision makers, answering the question: “How can the evolution of climatic risks affect my activities in the Belluno Province?”.

The paper is organised as follows: Section 2 provides a detailed presentation of the methodology adopted, and how it was tailored to the needs of this application. Section 3 outlines the results of the risk assessment for each sector analysed (tourism sector, eyewear

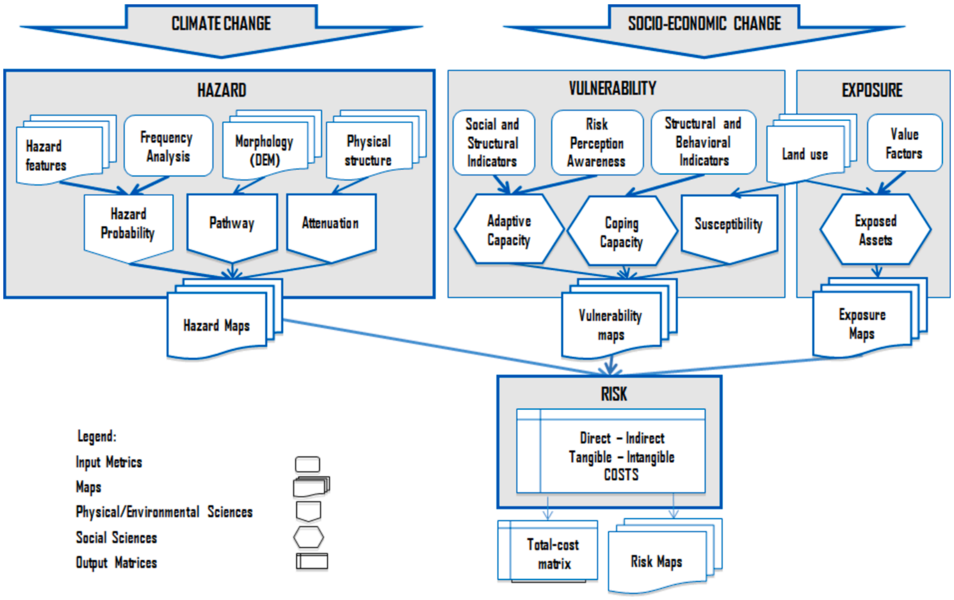

Fig. 1. General flow-chart of the SERRA methodological framework for risk assessment.

industry, electricity distribution system, and winter and sport events). Finally, the paper concludes with a discussion of the results, draws conclusions, and addresses the limitations of the study.

2. Methods

2.1. The SERRA methodological framework

The approach adopted herein derives from the Socio-Economic Regional Risk Assessment (SERRA) method developed by the EU Kulturisk Project (Giupponi et al., 2023), which focuses on three dimensions of risk, in accordance with a consolidated literature adopted also by the Intergovernmental Panel for Climate Change since the SREX Report (IPCC 2012) and in the following assessment reports (IPCC, 2014; IPCC, 2022):

- Hazard, i.e., "*the potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources*";
- Exposure, defined as the presence of receptors, i.e. "*people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected*" by hazard events;
- Vulnerability, i.e., "*the propensity or predisposition to be adversely affected*" by hazard events.

The SERRA integrated approach combines classical spatial risk assessment with socio-economic analysis, enabling the estimation of the damages associated with potential risks of different types and magnitudes (see Fig. 1), by combining the analysis of climatic hazards, exposed receptors and the vulnerability of the socio-ecosystem, to produce sets of descriptive maps and also quantitative – economic – estimation of the expected damages. The notion of risk, which is usually expressed by means of non-dimensional indexes, is here converted into a more concrete, understandable and useful quantification of the expected costs deriving from damages of different kinds (direct and indirect, tangible and intangible).

The application of the SERRA approach foresees a sequence of seven steps (adapted from Mojtahed et al. 2013), which have been implemented with reference to the methodological framework presented in Fig. 1 and adapted to the specific social, economic and geographical context of the study, depending on the selected receptors of climatic risk, i.e. in this case the four main economic sectors of the province the data availability:

1. selection of receptors directly and indirectly exposed to hazards, i.e. selection of the most important economic sectors exposed to climate change risks;
2. qualitative and quantitative description of the hazards, identified in collaboration with representatives of the most important economic sectors;
3. identification and description of the environment subject to the hazards considered, by collecting the most detailed spatial information available and storing them in a coherent a geographic information system (GIS) format;
4. identification of the spatial characteristics of susceptibility, coping and adaptive capacities mapped by means of indicators, which are subsequently aggregated into a vulnerability index for each type of receptor, i.e. for each economic sector;
5. identification of value factors for quantifying the economic magnitude of exposed receptors, by acquiring accurate spatial information about exposed assets and their economic values and their potential damages as consequences of various types and intensities of climatic hazards;
6. calculation of the risk from the combination of hazard, exposure and vulnerability maps;
7. reporting on economic risks in terms of aggregated expected damages and as thematic maps presenting spatial variabilities and hot spots.

This study is based on high-resolution RCMs, provided by the EURO-CORDEX (Jacob et al., 2014, 2020) program, largely used in the literature to assess the impact of the warming trends worldwide (Christensen et al; 2007), over Europe (Jacob et al; 2020) and finally over Italy (Spano et al., 2020). The adoption of the downscaled RCMs permits to involve in the risk analysis the use of spatial indicators taking into account the local characteristics of the area and of the hazards to be analysed. Even if at the moment EURO-CORDEX still does not include high-resolution scenarios derived from the Shared Socioeconomic Pathways (SSP) scenarios, it provides a robust foundation for evaluating climate risks and hazards (Jacob et al., 2020), as also supported by recent literature (Faggian et al., 2023; Ricciardi et al., 2024), and remains highly relevant within the Italian context, as it directly applies to the current National Adaptation Plan (MASE, 2023).

Here, hazard is examined in terms of various types of extreme events, depending on the receptors (i.e. the economic sectors) considered for risk assessment. In the case of tourism, for example, extreme precipitation episodes can generate floods and thus damages on tourism receptive facilities, both in terms of direct damages on structural assets, such as flooded hotels, and indirect losses, such as interruptions of the road network impeding access to tourism destinations. Apart from short-term damages, events might have long-term economic impacts, for instance permanently affecting the viability of structures or infrastructures, or indirectly affecting the tourist attractiveness of an area.

Such approach follows the conceptual framework proposed by the Intergovernmental Panel on Climate Change (IPCC) in the fifth Assessment Report which, in turn, is in line with the prevailing literature on risk reduction (Disaster Risk Reduction – DRR) (IPCC 2012; 2014) and widely adopted references, such as the ESPON CLIMATE framework (ESPON, 2011), which has shaped our understanding of regional climate impacts and reinforced the need for tailored, region-specific assessments like SERRA. Moreover, it shows to be highly flexible and capable of analysing a wide range of risks, including complex and interconnected ones. It is particularly useful within the Italian national context, considering the current adaptation framework established by the National Adaptation Plan (MASE, 2023), with which it shares several elements, particularly in the quantitative use of climate indicators for hazard assessment. It provides a framework for supporting local risk assessments by leveraging methods and data that can be sourced from local stakeholders, thus providing a practical and effective tool that can be applied for studying local risks. Moreover, the methods adopted for the assessment of risk components and for multi-risk analysis are in line with the recent literature, including Simpson et al. (2021) and the IPCC AR6 WGII report (Kikstra et al., 2022). According to that literature stream, the three dimensions of risk previously defined (hazard, exposure and vulnerability) are quantified by means of case specific indicators from which the sectoral climate risk indexes are calculated and mapped with the following general formula:

$$Risk = f(Hazard, Exposure, Vulnerability)$$

In particular, in this work, that formula has been implemented with a combination of multiplicative and multi-criteria operators adapted to the four sectors assessed. The rationale of a multiplicative aggregation stands on the evidence that whenever one of the three dimensions had a value equal to zero, i.e. with no hazard, or nothing exposed, or no vulnerability, the risk would necessarily be null, or negligible (Blakie et al., 1994). Concerning the aggregation with multi-criteria operators, it has been applied for vulnerability, to aggregate its various dimensions measured by means of spatial indicators identified and co-designed in collaboration with the stakeholders involved. This participatory approach, as highlighted also in recent studies (Ricciardi et al., 2024), is particularly important, though still underutilised, in effectively supporting risk management monitoring systems, especially when integrated with the development of GIS tools, which also played a central role in our research. Active stakeholder involvement in all phases of the process is essential to ensure that the risk analysis results are not only technically accurate but also applicable and useful in practical risk management contexts. The literature strongly supports the idea that when stakeholders are actively involved in decision-making, they are more likely to support and adhere to the implemented measures, thereby building trust and ensuring that the strategies are scientifically sound, socially acceptable, and economically viable (Fleming et al., 2023; André et al., 2021; Te Boveldt et al., 2021). Furthermore, engaging stakeholders through a co-design process in climate risk analysis not only reinforces the relevance and robustness of the resulting strategies but also ensures that these strategies are tailored to the specific context and are practically implementable (Fleming et al., 2023; Becsi et al., 2020).

Stakeholders were involved in all critical phases of the process: from the definition of hazard indicators specific to different sectors, to the evaluation of the representation of results through the developed GIS platform, to the construction of the risk matrix. This involvement was carried out through various methods including questionnaires, periodic meetings, and workshops, which allowed us to collect continuous feedback and tailor the analysis to their specific needs. The COVID-19 pandemic, especially during its most acute phase (first stakeholder meeting in March 2020, at the beginning of the lockdown period) limited interaction opportunities, but we promptly switched from the original plans for periodic meetings in the study area, to online meetings. The research team met every second week with the grant provider ENEL Foundation and with the most relevant stakeholders for each of the project phases. Most of the meetings were attended also by representatives of electricity provider E-Distribuzione (a big issue for industrial activities in the area is the high frequency of short black outs) and other stakeholders through targeted online meetings. Besides the association of local entrepreneurs (Confindustria), who facilitated the connection with associates, the local office of regional Environmental Protection Agency of the Veneto Region (ARPAV), local administrations, and the main multi-utility company (BIM) who facilitate the targeting of the research, through the identification of current risks, the identification of specific indicators and their relative relevance through the elicitation of MCA weight vectors, and the discussion of preliminary and final results.

In order to have more robust and usable results and figures, in accordance with recent literature (Dottori et al., 2018), we focus on trends and relative changes, more than on absolute estimations of damages and losses and we limit the analysis to trends determined by climate change scenarios. Socio-economic variables are kept constant over the simulations for the reasons described above and discounting is not implemented.

Results are presented as sets of maps for highlighting the diversity of situations within the study area, and statistical summaries to provide concise information about how climate related damages are expected to change in the future. Statistics are also provided to communicate the uncertainty deriving from the different data sources considered, such as the multiplicity of climate models and scenarios, and the subjectivity inherent in some of the parameters adopted, such as the weighting of vulnerability indicators in multi-criteria analysis. In the case of historical risk, the uncertainty depends on the subjectivity of experts' weigh vectors for the aggregation of vulnerability dimensions. Concerning future climatic risk, the uncertainty depends not only on vulnerability weighting, but also on the climate models and on the scenarios considered. Maps of average risks and of coefficient of variation (%) are calculated per each time window (2012–2041, 2036–2065).

The following section describes the approach adopted to assess the three components of risk and its quantification in the territorial context of the Belluno Province.

2.2. Tailoring of the SERRA approach to the case study

2.2.1. Climate hazard

High-resolution hazard assessment is a fundamental step in the framework for the local climate change risk assessment for the social and economic sectors of interest. Climatic hazards are defined starting from a selection of climate indicators defining the expected change of specific weather extreme characteristic (mainly frequency and magnitude) and the probability that intense phenomena will occur within defined time frames, i.e. with various return periods. Below we report the main steps of the hazard process:

1. **Collecting observational data**: Data was collected from ARPAV,[5] using a network of meteorological stations distributed across the Veneto region. The observational data provided by ARPAV played a crucial role in calculating climate indicators to assess current climate conditions. The data used included:
    a. Daily cumulated precipitation (mm),
    b. Daily mean, maximum, and minimum temperatures at 2 m (°C),
    c. Daily mean wind speed and direction at 5 m (m/s),
    d. Daily maximum wind speed (based on 10-minute averages) at 5 m (m/s),
    e. Daily maximum wind gust speed at 5 m (m/s),
    f. Daily snow depth (mm).
2. **Definition and assessment of hazard**:
    1. Selection of climate indicators based on literature and stakeholders needs for a large overview of the climate hazard interesting the area.
    2. Calculating historical hazard indicators: hazard indicators were calculated for the reference period of 1981–2010 using the data in situ from ARPAV, for all points where in situ station data were available.
    3. Assessing climate variation: we assessed climate variation for all hazard indicators for the selected future periods and scenarios using an ensemble of high-resolution climate models data.
    4. Conducting risk assessments: only the indicators reported in Table 1 were used for the following risk assessment.

About item 1 and 2 of the step 2 (definition and assessment of the hazard), different indicators have been identified and evaluated allowing a general characterization of the variation of climate-related hazards potentially affecting the province of Belluno, using the high-resolution climate models provided in the framework of the EURO-CORDEX program under the RCP2.6, 4.5 and 8.5 scenarios, according to the IPCC's fifth assessment report (AR5; 2014a). The climatic variations were evaluated on both the annual and seasonal time scale, over two 30-year periods centred on 2026 (the year of the Olympic games of Milan and Cortina) and 2050 (2012–2041 and 2036–2065, respectively). Most of the climate indicators used in this study are defined by the Expert Team on Climate Change Detection and Indices (ETCCDI) (Sillman et al., 2013a, b) and are calculated by using temperature and precipitation data. Furthermore, they are integrated with those proposed in the framework of the European Climate Assessment & Dataset project (ECA&D) and also with those defined with the support of local stakeholders. All these indicators assessed for different periods and scenarios provide a good climate profiling of the area with useful information for the analysis of the spatial and temporal evolution of a specific climate-related hazard of interest. This extensive analysis of hazard indicators was very very useful for stakeholders' engagement, but only a small part of it was selected for the assessment of the following risk analysis phase. Initial discussion with the donor and local stakeholders, which drove to the identification of the sectors to study allowed also for the co-design to the set of hazard indicators to be extracted from the initial hazard analysis. As a consequence, the indicators adopted are rather innovative and specific for the four economic sectors (e.g. wet snow for risk assessment of electricity network), thus providing the best quantification of sources of hazard for wind, precipitation, snow and warm-related events, as reported in Table 1. Detailed information on hazard indicators are reported in 3.1.

2.2.2. *Exposure*

Exposure is analysed by focusing on four receptors, identifying the most important economic activities potentially suffering from climatic changes and extreme events in the province of Belluno and their main direct or indirect damages:

1. The **tourism sector** is by far the most important economic activity of the tertiary sector. It was analysed focusing in particular on the direct damages on the physical characteristics of the receptive facilities and the structural and infrastructural elements of the road networks that ensure accessibility to the area, and with reference to extreme precipitation events (Faturechi and Miller-Hooks, 2015). In line with the existing literature (e.g. Molinari et al., 2020), we applied a 15 % coefficient to the estimated monetary value of the tourism assets (cost of reconstruction or restoration in € per unit of exposed surface) to calculate the fraction that is exposed to extreme precipitations.
2. The **eyewear industrial sector** is the most important economic activity of the secondary sector of the province. Extreme events can limit or prevent the accessibility to production sites, affecting product deliveries and workers' access to production plants. Therefore, indirect damages from extreme precipitations were calculated for logistics and commuting, by locating exposed values at firm production sites. The market share of each firm is used as a proxy for the intensity of the shipping i.e. logistics, with a higher number of missed transactions in case of climatic extreme events deriving from higher shares. In the second case the economic value of exposure is given by the total hours worked by commuters. Exposure maps are calculated in monetary terms by summing up the results per firm at municipality level.

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[5] All ARPAV data are publicly available through the Open Data platform, accessible at the following link: https://www.arpa.veneto.it/dati-ambientali/open-data.

Table 1
List of indicators evaluated for each economic sector selected for the hazard evaluation in the framework of the climate risk assessment.

Climate indicator	Summer Tourism	Eyewear industry	Electricity distribution	Winter Sport and events
Precipitation-related indicator				
100 years return period for the daily precipitation (mm) (**Tr100pr**)	X (summer)	X (year)		
Snow-related indicators				
100 years return period for the **wetsnow2** (days)			X	
Snow reliability-related indicators				
Snow cover duration (days) **(SCD)**				X
Snow production days (days) **(SPD)**				X

3. The **electricity distribution service** plays a fundamental role for the province, not only because of its relevance in terms of production from hydroelectric plants, but also for its vulnerability to climatic risks. It was considered with focus on the consequences of "wet snow" events causing heavy ice loads on overhead line conductors and on trees along the lines. These events can have direct impacts on distribution grids and indirect impacts to critical services and businesses due to lack of electricity supply. Concerning direct damages, exposed assets consist of HV/MV (i.e. High/Medium Voltage) and MV/LV (Medium/Low Voltage) substations, overhead lines with relative supports and underground lines. Exposed values were assessed through the estimated monetary historical damages to power grids. Such information was used to develop a damage function for quantifying the increase in the monetary damage output associated with the increase in the frequency of the climatic conditions that determine individual hazardous events in the winter season, i.e. the average historical number of wet snow days. With regards to indirect damages, exposure consists in services, businesses and the local population which are affected by electricity outages. Expected indirect damages were calculated by comparing their historical magnitude in monetary terms (value of electricity not supplied to disconnected customers during outages of a standardised duration of 16 h), with the estimates for future climatic hazard events. For confidentiality reasons, data were aggregated at the municipality level.
4. **Winter sport activities and events**, was selected as the forth economic sector because of the forthcoming Winter Olympic Games of 2026. They were studied as an important economic sector very much exposed to climatic hazards. Exposed assets were identified as the areas for ski sports according to the current planning instruments and that include existing ski facilities and slopes as well as all other areas where new infrastructures for snow-based outdoor winter sports might be developed in the future. The map of exposed assets was used to calculate the risk in terms of expected changes in terms of snow cover days (SCD) determining the number of skiable days and the days suitable for artificial snow making (SPD). The economic valuation of damages was conducted by applying the average value added of a skiing day to the estimation of future decreases of the number of skiable days, over the ski areas of the Belluno Province.

Receptors are analysed within a geographic information system (GIS), with the production of one exposure maps per receptor, with the identification of relevant assets as points (e.g. the location of industrial plants), lines (e.g. road or electricity infrastructures) and polygons (e.g. sky areas, or municipalities).

2.2.3. Vulnerability

While the studies on climatic hazards and the identification of exposed receptors is consolidated, the third dimension – vulnerability – is much less developed and questioned by different authors and schools of thought (Rufat et al., 2015; Giupponi and Biscaro, 2015). Engineering studies typically focus on physical vulnerability, in terms of susceptibility, while others focus instead on the social dimension of population at risk (Koks et al., 2015). Here we adopt a vulnerability concept in line with the recent developments of the literature stream which refers to the IPCC reports and which originated in the SREX Special Report on vulnerability and extreme events (IPCC, 2012). Such concept is defined through three main dimensions and quantified by means of physical and socio-economic spatial indicators, determining the ability of mountain communities to face extreme climatic events:

1. **Coping capacity** is the ability of people, organisations and systems, through the use of available skills, resources and opportunities, to face, manage and overcome adverse conditions (IPCC, 2012).
2. **Adaptive capacity** is the combination of the strengths, attributes and resources available to an individual, community, company or organisation that can be used to prepare for and take action to reduce negative impacts, limit damage or exploit positive opportunities (IPCC, 2012).
3. **Susceptibility** is the probability that the receptors can be potentially damaged by any hazard due to their structural factors, types and characteristics (Giupponi et al., 2015).

In analogy to the assessment and mapping of hazard and exposure, vulnerability indicators were defined through the collaboration among researchers, stakeholders and the donor and the best compromise was found between the environmental and socioeconomic dimensions to be analysed and the availability of updated data with adequate spatial resolution. In the case of **summer tourism**, coping capacity was defined upon the minimum travel times necessary to reach each tourism structure from the rescue areas identified in the Provincial Civil Protection Plan. Statistical information such as international tourist stays were also considered, together with the number of available beds in relation to the peak of tourist stays and the number of people belonging to the weakest sections of the population. To estimate the adaptive capacity, structural socio-economic indicators were considered: employment and education levels, the distribution of income in relation to the resident population and the level of social inequality (Gini index). The physical susceptibility to extreme precipitation events was mapped upon the morphology of the territory, the sealing of the soil deriving from the degree of urbanisation and flood risk defined by previous studies.

The vulnerability of the **eyewear industry** was considered in terms of susceptibility of transport infrastructures. Two travel-cost analyses were thus performed to compute the cumulative time (in seconds) between the municipalities of workers' origin (for commuting), and the main highway gateways around the area (for logistics) and the locations of eyewear industries. Travel costs vary as a function of the length of segments susceptible to climatic hazards because of higher risk of flood and landslide in case of extreme precipitation, and because they cross wooded areas susceptible to tree falls in case of wind gusts. Coping and adaptive capacity indicators were considered not relevant for the specific risk.

Vulnerability was not considered as a relevant dimension of direct damages for **electrical infrastructures** because of the lack of detailed information about variations in the susceptibility of the infrastructural network to the specific risk of tree falls. Instead, vulnerability dimensions were included in the analysis of indirect damages, where susceptibility depends on the characteristics of power grids and on their interactions with territorial features. Coping capacity is defined through an indicator of the remoteness of infrastructures, calculated upon the travel time for the technical staff of electrical companies to reach damaged lines from maintenance facilities, for recovering the energy supply in case of electricity outages. Given the limited surface area of the Belluno Province, adaptive capacity, defined upon the financial support to structural investments for ameliorating and maintaining electrical infrastructures, was considered as invariant and then omitted from calculations.

The vulnerability of **winter sports** was examined in terms of susceptibility, i.e. by assessing the geographical features of the various ski areas affecting temperatures gradients and therefore the quantity and quality of snow at different altitudes. In order to improve the spatial mapping beyond the mere correlation between snow indicators and the elevation, we identified two suitable indicators: the *accumulation of solar radiation* on the ski slopes as a function of slope and aspect, through a "*hillshade*" operator, and a proxy indicator to include consideration of the *temperature inversion phenomenon*, typical of low-lying areas in winter, by means of geomorphological analyses. As yet, coping and adaptive capacity have been overlooked, because they were considered of secondary relevance for the specific purposes.

The procedure for mapping vulnerability starts with the selection of indicators for the three components and their spatial description with the maximum possible resolution. Sets of coherent raster layers were produced with 25 m resolution to facilitate multivariate analysis, even if several indicators were acquired at census units or at the municipality level. Indicator maps are normalised between 0 and 1to make them subject to aggregation. We adopted a min–max linear normalization, giving 0 for situations of absence of vulnerability, in which, whatever the entity of the assets exposed and whatever the magnitude of the hazardous event, the result in terms of expected damage (potential risk) is zero. On the opposite, value 1 indicates the situation of maximum vulnerability, in which the climatic event can determine the maximum possible damage.

The stack of indicator maps is aggregated through a spatial multi-criteria analysis, to produce the vulnerability map (Cian et al., 2018; Giupponi et al., 2023). Weights defined through an expert elicitation exercise are adopted to express the different importance of the various indicators in contributing to the determination of vulnerability. The inherently subjective weight vectors provided by the experts are subject to sensitivity analysis, to quantify the role of such subjectivity on the final results together with other sources of uncertainty, such as that deriving from the use of multiple climatic models and, as described below, different subjective attitudes to risk.

The algorithm adopted for multi-criteria aggregation of the indicators is the Order Weighted Averages (OWA) which allows for controlling the addictiveness of the aggregation procedure by applying a second set of ordered weights (Yager, 1988). With such method, different attitudes of decision makers can be represented with a vector of weights applied to the ordered values of each single cell of the map: a "risk averse" (or pessimistic attitude) can be represented by giving relatively high weights to those indicators that show relatively bad performances; a "risk taker" (or optimistic attitude) can be expressed by higher weights given to those indicators that perform better; a "balanced" attitude can be expressed by relatively high weights given both to good and bad indicators, with lower weights given to those with average performances. With such approach, an additional element of uncertainty is included in the uncertainty analysis, reflecting the possible variability of the decision-making approach to risk management. Supplementary Material 5 provides the details about the approach adopted for mapping vulnerability.

3. Results of risk assessment

3.1. Hazard scenarios and mapping

In general, the hazard indicators are identified by selecting sector specific output variables produced by climatic models and defined by calculating return periods, which can be interpreted as the value expected to be exceeded on average, once every return period, or with a probability of 1/(return time period) in any given year (Vezzoli et al., 2012).

The hazardous events of interest for **summer tourism** are **extreme precipitation events** that can generate flooding phenomena and damage buildings and infrastructure. These events can lead to inconveniences and safety problems linked to the nature of the emergency (for example, temporarily limiting the accessibility of the civil protection bodies or tourists themselves to the accommodation facilities in the area) and long-term economic impacts (direct impacts on the viability of the structures or indirect effects on the tourist attractiveness of a certain area). In particular, the selected hazard indicator it the extreme summer precipitation event with a return period of 100 years. Summer climatic variations show a general expected increase over all the investigated area for the 2036–2065 period analysed under both RCP4.5 and RCP8.5 scenarios, by using the ensemble mean of the regional climate models performed in the framework of the EURO-CORDEX program.

The hazardous events for **eyewear industry** are **extreme windstorm** and **extreme precipitation events** characterized by an intensity that can generate landslide and flooding phenomena, potentially limiting the accessibility to production plants. These events can lead to long-term economic impacts, i.e. indirect effects on economic activities of eyewear industries. Since climatic simulations showed no evident trends for extreme wind, only extreme precipitation events were considered, with a return period of 100 years on the annual time scale. Climatic variations show a general expected increase (in particular in the north-east area) for the future period analysed 2036–2065 under both the evaluated RCP scenarios (RCP4.5 and RCP8.5) by using the ensemble mean of the regional climate models performed in the framework of the EURO-CORDEX program.

The hazardous events of interest for **electricity distribution system** are **wet snow events**, which can cause ice accretion on electrical conductors, under particular atmospheric conditions of temperature, wind and precipitation, with a return period of 100 years. The most relevant consequence of a wet snow event is related to the accumulation of snow on bare conductors that may affect overhead medium voltage power lines causing their failure and the interruption of the power supply (Bonelli et al., 2011; Llasat et al., 2014). These events can have direct impacts on network infrastructures and indirect impacts to critical services and businesses due to lack of the electricity supply. A hazard indicator, called "wetsnow", is considered for this sector with two possible variants, i.e., *wetsnow1* (number of days with $0 <$ temperature < 1.5 °C and precipitation > 10 mm) and *wetsnow2* (number of days with $0 <$ temperature < 1.5 °C, precipitation > 10 mm and maximum wind speed < 5 m/s). The second indicator (hereafter simply referred to as "wet snow") is closer to commonly adopted analyses of electrical companies and is thus adopted for the risk assessment. The analysis focuses on the winter season (December, January and February) which returns the widest anomaly among all seasons. The analysis is carried out for extreme events with 20, 50, 100 and 150-year return periods but only the 100-year threshold is adopted for risk assessment and mapping, in analogy with the evaluation of the other economic sectors. The spatial distribution of the expected variation for the period 2036–2065 is characterized by a slight variation of the indicator with a clear signal pattern (positive in the northern part and negative in the southern part) in both the accounted RCP scenarios. Very weak variations are detected in the central area of Valbelluna.

The hazardous events considered for **winter sports and events** refer to **snow reliability** interfering with winter sports, with particular reference to the Winter Olympic Games of Milano-Cortina 2026. In the analysis of the winter sport activities and events sector, the climatic hazard refers to the lack of natural snow cover by considering two indicators: (i) snow cover duration (SCD), calculated as the number of days (from November 1st to March 31st of the following year) with snow depth greater than 30 cm, which might decrease in the future because of climate change (Durand et al. 2009; Marcolini et al. 2017); (ii) snow production days (SPD), calculated as the number of days from November 1st to December 31st with an average temperature lower than $-2.5°$ C. The SPD index has been defined in collaboration with local experts of ARPAV, aiming at representing the average trend of future winter seasons that stakeholders will face. The ensemble mean (2036–2065, RCP4.5 and 8.5) of EURO-CORDEX models shows the greatest and negative values in the northern-central part of the province, decreasing toward north-west and south-east. The same is detected for SPD climatic variations.

Supplementary Material 1 presents the hazard maps (variation of the climate indicators) used in risk analysis:

- Figure S1-2: 100 years return period for the daily precipitation (mm) for summer period (June, July, August JJA) for summer tourism;
- Figure S2-2: 100 years return period for the daily precipitation (mm) for eyewear industry risk analysis;
- Figure S3-2: 100 years return period for the wetsnow2 (days) for electricity distribution risk analysis;
- Figure S4-2 and Figure S4-3: Snow Cover duration and Snow production days for winter sports and events.

3.2. Risk assessment and mapping per economic sector

3.2.1. Summer tourism

Exposure analysis shows that the highest expected values of assets at risk and thus the highest exposures are located in the municipality of Cortina d'Ampezzo in which the highest unitary property values coincide with a concentration of numerous tourism facilities. The total value of facilities potentially exposed to the damages deriving from extreme precipitation amounts to 427,960,494 € over the whole Belluno Province. Figure S1-3 in Supplementary Material 1 presents the map of exposure.

The higher values of vulnerability are found in the valleys, flat areas near the hydrographic network, specifically in the areas of Ampezzano, Agordino, Cadore, Valbelluna and Feltrino, with local variability depending on the weighting scheme. Figure S1-4 in Supplementary Material 1 presents the vulnerability map at 25 m resolution, showing the average trend of all possible combinations of weights and decision-making attitudes.

The multiplicative intersection of the hazard, exposure and vulnerability maps provided the risk map and the estimation of the proportion of the total value of the assets exposed at risk for the extreme precipitation events, with reference to a 100-year return period. From the stack of 216 risk maps (generated from all possible combinations of weight vectors, climate models and scenarios), summary maps are then produced to present the average trends and the uncertainty associated with their calculation (see Table 2 and

Figure S1-5 and S1-6 in Supplementary Material 1 for geographical details). Higher levels of risks are located in the areas where tourism activities are concentrated and where are the higher unitary values of real estate properties; in this area the municipality of Cortina d'Ampezzo pops up as the area where the risk is higher. An inset in Figure S1-5 of Supplementary Material 1 shows the results of the calculations made building by building, which were subsequently aggregated at the level of municipality.

3.2.2. Eyewear industry

The *commuting* phenomenon in the Belluno Province is estimated in monetary terms, considering the average gross hourly wage according to official statistics.[6] The number of commuters is estimated at municipality level, by combining Veneto Region geodata on commuting with sector-specific information from ANFAO (the association of eyewear producers), including firm addresses and number of employees. With regards to *logistics*, the market share of each firm is used as a proxy for the intensity of the shipping, which translates into higher number of missed transactions in case of climatic extreme events. Data from ANFAO on yearly revenues are used to provide a monetary estimation. Figures S2-3 to S2-6 in Supplementary Material 2 present the maps of exposure and of vulnerability. They show that the municipalities of Longarone, Sedico, Agordo and Cencenighe Agordino exhibit exposure values that tend to be much higher than the surrounding areas, being headquarters of the most important production sites in the Belluno Eyewear District. Other clusters of firms can be found in Cadore and Basso Feltrino, and in general in the south-eastern half of the Belluno Province. The estimated potential exposure amount to 2,705,280 €/day for logistics and to 872,927 €/day for commuting, over the whole Belluno Province. With regard to vulnerability, in the case of logistics, it generally shows an increasing south-to-north trend. For the combination extreme precipitation/logistics, the greatest vulnerability is denoted in the Ampezzano while Cadore/Comelico and Agordino have higher values depending on the adopted weighing scheme. In the case of commuting, vulnerability generally shows a local pattern, given that main flows of commuters are limited to 14 municipalities but 4 of them host the main production sites. Among these, the greatest vulnerability is denoted in the municipalities of Agordo and Longarone.

Risk maps are produced per each combination of hazard and exposed asset; i.e. extreme precipitation/logistics, extreme precipitation/commuting, wind gusts/logistics and wind gusts/commuting, under a return period of 100 years, resulting in a stack of 288 maps. Summary risk maps are then produced to present the average trends and the uncertainty associated with their calculation (see Figures S2-7 to S2-10 in Supplementary Material 2 for geographical details), in which is evident that those municipalities where plants are located (Sedico, Longarone and Agordo), are also those exhibiting the greatest flows of commuters, therefore presenting a higher climatic risk. By aggregating historical and future risk maps over the whole Belluno Province, we found up to 17.1 % increase in the climate risk for extreme precipitation events with a 100-year return period, in the 2036–2065 time window (Table 3).

3.2.3. Electricity distribution system

Concerning the spatial analysis of exposure, in the case of direct damages, the exposure term is represented by the historical monetary damage to distribution power grids estimated for hazardous events under specific return periods (provided by the electricity distribution provider). In a similar way, in the case of indirect damages, the exposure term is given, according to the Energy Authority (ARERA) del. 668/18,[7] by the estimated monetary value of the electricity not supplied to disconnected customers (12 €/kWh for domestic customers, 54 €/kWh for non-domestic customers for an average electricity consumption in the Belluno Province), during outages of a standardized duration, i.e. 16 h. Vulnerability mapping is carried out only for indirect damages as, beyond grids' morphology and aggregated statistical records, detailed information about electrical infrastructures is not available. All vulnerability maps to indirect damages show an increasing south-to-north trend, both in the case of direct and indirect impacts, with a minor local variability depending on the adopted weighing scheme. Such trend depends on the northernmost half of the Belluno Province whose municipalities are the farthest from the maintenance facilities of the distribution system operator, and those with the highest woodland cover intersecting the road network. Figures S3-4 to S3-6 in Supplementary Material 3 present the maps of exposure and of vulnerability.

For the analysis of this sector, the hazard map represents a frequency (days) that is multiplied by the monetary map of exposure to generate an estimation of the expected damages over a time span (winter season), which can be reduced when the vulnerability of the area in which the assets are located is lower than 1. From the stack of risk maps (168 in the case of direct damages while 134 maps for indirect damages) a series of summary maps are then produced to present the average trends and the uncertainty associated with their calculation (see Figures S3-7 to S3-10 in Supplementary Material 3 for geographical details). By aggregating historical and future risk maps over the whole Belluno Province, we found up to 6.2 % increase in the direct climate risk and 10.2 % increase in the indirect climate risk, for wet snow events in the 2036–2065 time window.

3.2.4. Winter sports and events

For the winter sports and events sector, the exposed assets are given by all state-owned properties (in Italian "aree demaniali") in the Belluno Province, that include existing ski facilities and slopes and all other areas where new infrastructures for snow-based outdoor winter sports might be built in the future. Vulnerability map pattern depends on the adopted weighting scheme, showing more vulnerable areas at high elevation, where temperature inversion cannot occur, and/or on mountain slopes exposed to south. Figure S4-4 and S4-5 in Supplementary Material 4 present the maps of exposure and vulnerability.

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[6] Average worker wage provided by the Italian Institute for Statistics (ISTAT) for economic activities with ATECO code 32 "*altre industrie manifatturiere*" (other manufactural industries).

[7] https://www.arera.it/atti-e-provvedimenti/dettaglio/18/668–18.

Table 2
Projections of variations in economic risk due to extreme precipitation events with a 100-year return period (€/event) for the summer tourism sector in the 2012–2041 and 2036–2065 time windows, over the whole Belluno Province.

Extreme precipitation						
	Estimated damage 2012–2041	Difference with current risk		Estimated damage 2036–2065	Difference with current risk	
Average values	9,642,939 €	363,405 €	3.92 %	9,902,107 €	622,572 €	6.71 %
Uncertainty ranges	2,253,476 €	–	–	2,314,262 €	–	–

Table 3
Projections of variations in economic risk due to extreme precipitation events and wind gusts with a 100-year return period (€/event) for the eyewear industry sector in the 2012–2041 and 2036–2065 time windows, over the whole Belluno Province.

Logistics – Extreme precipitation						
	Estimated damage 2012–2041	Difference with current risk		Estimated damage 2036–2065	Difference with current risk	
Average values	139,734 €	9,861 €	7.59 %	151,894 €	22,021 €	16.96 %
Uncertainty ranges	7,563 €	–	–	8,215 €	–	–
Commuting – Extreme precipitation						
	Estimated damage 2012–2041	Difference with current risk		Estimated damage 2036–2065	Difference with current risk	
Average values	55,635 €	4,077 €	7.91 %	60,384 €	8,826 €	17.12 %
Uncertainty ranges	3,502 €	–	–	3,804 €	–	–
Logistics – Wind gusts						
	Estimated damage 2012–2041	Difference with current risk		Estimated damage 2036–2065	Difference with current risk	
Average values	307,603 €	1,397 €	0.46 %	305,064 €	−1,142 €	−0.37 %
Uncertainty ranges	15,614 €	–	–	15,489 €	–	–
Commuting – Wind gusts						
	Estimated damage 2012–2041	Difference with current risk		Estimated damage 2036–2065	Difference with current risk	
Average values	120,852 €	627 €	0.52 %	119,825 €	−400 €	−0.33 %
Uncertainty ranges	7,299 €	–	–	7,238 €	–	–

In this sector, the hazard map represents a frequency (number of days) that is multiplied by the vulnerability, to generate an estimation of the expected SCD and SPD (snow cover duration and production days). The result is masked over exposed ski areas as the exposure map does not provides a spatial estimation of monetary damages but only information concerning the location of sites potentially at risk. From the stack of risk maps (36 in the case of SCD and 72 maps for SPD) a series of summary maps are produced to present the average trends and the uncertainty associated with their calculation (see Figures S4-6 to S4-9 in Supplementary Material 4 for geographical details).

By aggregating historical and future risk maps over the ski areas of the whole Belluno Province, we calculated the risk of experiencing 9.5 % decrease in the SCD and 37.9 % decrease in the number of SPD, in the 2036–2065 time window (Table 4). Based upon current figures in terms of revenue per skiing day (data are provided by the local association of ski lift operators), the decreases of SCD values would generate losses of around 3 M € in the first time window and more than 9 M € in the 2036–2065 period. Such decreasing trend depends on the hazard variations, which are stronger in the northern part of the province, where most of the ski facilities are located. As a consequence, ski areas at lower latitude and elevations (e.g. Alpe del Nevegal), which are already in sub-optimal conditions, are expected to experience rather limited effects by medium term climate change. On the contrary, ski facilities in the northern part of the province, which currently have adequate numbers of SCD, are expected to experience higher significant impacts on the depth and quality of the snowpack, raising concerns about the sustainability of ski resorts and investments.

3.2.5. Multi-risk aggregation

The sectoral sets of maps and tabular synthesis presented above allow for providing private and public decision makers with extensive documentation to be considered when strategic decisions have to be taken for investments and strategic planning. As a final processing of the output produced with the sectoral risk assessment, we developed a final multi-risk map, aimed at identifying the various combination of risk typologies and levels for the four most important economic sectors of the province, combined with information about risk exposure of road infrastructures. Fig. 2 shows the results of the multi-risk analysis carried out by using an ISODATA cluster analysis technique (Iterative Self-Organizing Data Analysis Technique), which is a consolidated k-clustering method used for identifying land classes from stacks of multiple images in remote sensing studies (Johnson and Wichern, 2007; Richards, 2013).

The map of ISODATA clusters provides a synthesis of multivariate spatial variability of the combination of 6 risk maps (linearly normalized between minimum and maximum values) produced for the study area. The SPD map was omitted, because of its very high

Table 4

Projections for the winter sports and events sector in terms of (a) economic performances deriving from the number of skiable days (SCD) and (b) the number of days with suitable conditions for the production of artificial snow (SPD) in the 2012–2041 and 2036–2065 time windows, over the ski areas of the Belluno Province.

SCD (November to March)						
	Estimated values 2012–2041	Difference with current values (revenues of winter season)		Estimated values 2036–2065	Difference with current values (revenues of winter season)	
Average values	89.44 days	−2,919,855 €	−4.42 %	84.65 days	−6,298,140 €	−9.54 %
Uncertainty ranges	1.03 days	–	–	0.97 days	–	–

SPD (November to December)						
	Estimated values 2012–2041	Difference with current values (snow-making days)		Estimated values 2036–2065	Difference with current values (snow making days)	
Average values	20.34 days	−5.45 days	−21.14 %	16.01 days	−9.78 days	−37.92 %
Uncertainty ranges	0.21 days	–	–	0.16 days	–	–

correlation with SCD. The multi-risk map can be considered as a support for policy makers in the identification of a series of different zones characterized by relative internal homogeneity, thus requiring different approaches in terms of policies and measures for risk management. Results show that some areas have combinations of multiple risks at higher levels, which should be carefully considered in planning. These are the cases of key areas for eyewear production (Longarone, Sedico, Agordo), where risks for winter sports are also present. Even more relevant is the combination of high risks for summer tourism, with moderate to high risks for both electricity distribution and winter sports in the area of Cortina.

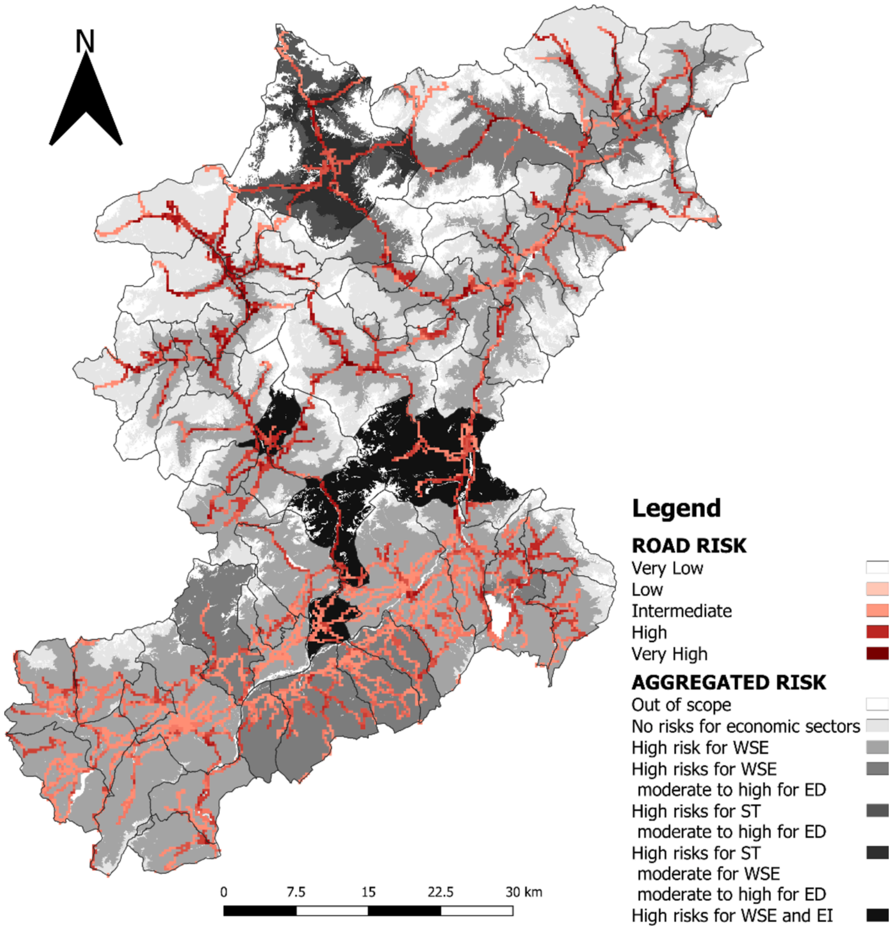

Fig. 2. Final map with the identification of areas with similar types and levels of risks of the economic sectors in the Belluno Province (EI=eyewear industry; ED=electricity distribution; ST=summer tourism; WSE=winter sports and events).

Given the relevance of road infrastructures to cope with natural hazards, we overlaid the road network with colour coding deriving from the results of the analyses of exposures to landslides, flooding and tree falls. At this regard, it is worth to underline that in many cases critical situations of the road network coincide with areas with relatively high levels of multiple risks, or are located on the most important corridors to access to most peripheral areas.

3.3. Summary of findings in terms of future economic damages from climatic risks

The results of the risk assessment for the Belluno Province highlight the region's vulnerability to various climate-related hazards, with significant implications for multiple economic sectors. The findings reveal the complexity of risk distribution across different industries, underlining the importance of sector-specific and multi-risk approaches in disaster management and planning.

In the summer tourism sector, Cortina d'Ampezzo is identified as the most exposed area, with high property values and a dense concentration of tourism facilities. The total economic exposure to extreme precipitation is approximately €428 million for the entire province. Vulnerability is particularly high in valleys and flat areas close to water sources, with Cortina d'Ampezzo showing the highest risk. Economic damage from extreme precipitation is projected to increase from €9.64 million for the period 2012–2041 to €9.90 million for 2036–2065, representing a 6.71 % rise from current risk. This indicates a growing need for targeted risk management strategies in high-risk areas.

For the eyewear industry, significant exposure is concentrated in Longarone, Sedico, Agordo, and Cencenighe Agordino, with logistics exposure estimated at €2.71 million per day and commuting exposure at €873,000 per day. The risk maps show that municipalities with major production facilities and high commuter flows, such as Sedico, Longarone, and Agordo, face higher climatic risks. Projected damage from extreme precipitation is expected to increase by approximately 17 % for both logistics and commuting in the 2036–2065 time window compared to current risk levels.

In the electricity distribution sector, direct damage is assessed based on historical data, while indirect damage is estimated from the monetary value of electricity lost during outages. Vulnerability increases from south to north in the province, with higher risk in northern areas due to greater distance from maintenance facilities and more woodland cover. The risk associated with wet snow events is projected to rise by up to 6.2 % for direct damages and 10.2 % for indirect damages in the 2036–2065 window.

For the winter sports and events sector, the assessment focuses on state-owned properties used for skiing and other snow-based activities. Vulnerability patterns indicate higher risks at high elevations and south-facing slopes. The analysis predicts a 9.5 % reduction in snow cover duration (SCD) and a 37.9 % decrease in snow production days (SPD) in the windows 2036–2065, compared to current levels. This reduction translates into financial losses of approximately €3 million for the earlier period and over €9 million for the later period. The northern part of the province, where most ski facilities are located, is expected to experience more pronounced declines in snow quality and depth, raising concerns about the sustainability of these resorts and future investments.

4. Conclusions

The concept of risk is crucial for decision-makers to understand the potential adverse impacts of climate change and exploring appropriate response options (IPCC, 2020). Assessing the potential damage that areas may suffer due to extreme weather events is a fundamental issue that requires a strict collaboration between scientists and stakeholders. Scientists should offer tools to convert outputs of models into meaningful and sector specific indicators, stakeholders should identify the most significant ones to be adopted for risk assessment. In this case, the numbers of involved stakeholders was relatively small (from a handful of representatives to a few dozens depending on circumstances), but justified by the focus on local entrepreneurs and institutional actors.

To be practical for local stakeholders, a high level of precision and granularity of risk assessments are essential, but high spatial-resolutions pose a challenge in climate impact studies, which are currently mainly constrained by the grid size of regional climate models (Hofmann et al., 2022). Another big challenge is currently in the definition of methods for multi-risk assessment (Schmidt, 2011). This work targeted those two challenges and offered operational solutions usable for both private actors and investors (sectoral risk maps with monetary estimation of damages, in particular) and for policy makers (sectoral and also multi-risk maps). In both cases, the economy and the public administration, the produced maps and quantifications of expected economic damages can provide the basis for further, even more local, studies that can benefit not only of the synthesis maps presented herein, but also of a huge amount of information related to different models, scenarios, etc.

The availability of detailed information about economic activities and the development of tailored indicators of climate hazard, both with high spatial resolution, allowed for investigating how climate risk may evolve in the future for the most important sectors in the various parts of the Belluno Province. The focus of the analyses was not on the absolute quantification of risks and expected damages, but on the estimation of future changes, thus providing messages to local actors that are easily factorable into climate proofing investment and spatial planning decisions; for example, the expected increment of damages due to lost working hours for the eyewear industrial sector. Focusing only on climatic scenarios and avoiding the joint consideration of socio-economic ones allowed for providing stakeholders with simple and clear messages about the magnitude of expected changes in comparison to their direct – past and current – experience with climatic hazards. Further studies can be conducted to explore combined future scenarios including hypotheses about local social and economic developments.

The literature concords in recommending high levels of engagement and participation to improve the efficacy of climate change risk management and adaptation (Huges and David, 2020). In this study, feedback from local entrepreneurs and other stakeholders confirms that the proposed approach increased local awareness of risks and their expected magnitude in economic terms. For example, concerning winter sports, the results provided quantitative information concerning the shrinking of the time-window for snow making in preparation of the ski season and for the duration of the skiing season itself, together with estimates of the expected economic impacts. The communication of uncertainty deriving from the unavoidable subjectivity of weights for multi-criteria aggregation was appreciated by stakeholders, but it appears to be still an open issue in terms of effective communication.

The current work is not exempt from limitations. Firstly, limitations are in the use of simplified damage functions, as well as in the current level of granularity of some of the inputs. Enhancing the spatial resolution of climate models and improving the spatial and thematic detail of economic information would significantly improve the accuracy of the analysis.

Moreover, the integration of hydrologic and hydraulic models should be considered to allow for a shift from assessing intense precipitation hazards to providing more precise estimates of flood risk and expected damages. Running sequential simulations of a wide range of events with varying return periods could also yield estimates of expected annual damages by risk type. Finally, as mentioned above, the economic analysis could be further refined by incorporating integrated scenario analyses of local relevance, defined with additional interactions with stakeholders. Those scenarios would require the adoption of suitable socioeconomic models, thus providing a deeper understanding of how exposed assets and vulnerabilities may evolve in response to future socioeconomic and demographic changes.

To conclude, more detailed models and scenarios would support improved precision of damage estimations, and they could still benefit from the analysis of the whole province provided here that allows for the identification of critical areas and hot spots, but they would require a stronger and formal involvement and acknowledgement by public administrations, to increase the opportunities for the adoption of outcomes in local planning.

Author contributions

CG coordinated the research, designed the methodological framework and directed socio-economic analyses of risk; GB and PM provided climate modelling and identified the hazard indicators; VL developed economic analyses; CP and CZ contributed to the definition of the objectives and to the interaction with stakeholders; MZ developed the code and ran integrated assessment and mapping; GV provided the expertise for risk assessment of electricity supply services. All the authors share the responsibility of the text.

CRediT authorship contribution statement

Carlo Giupponi: Conceptualization, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Giuliana Barbato:** Data curation, Formal analysis, Writing – original draft. **Veronica Leoni:** Data curation, Formal analysis, Writing – original draft. **Paola Mercogliano:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Carlo Papa:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Giovanni Valtorta:** Data curation, Investigation. **Michele Zen:** Data curation, Formal analysis, Software, Writing – original draft. **Christian Zulberti:** Funding acquisition, Investigation, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Availability of results and algorithms

Hazard, exposure and vulnerability spatial indicators and risk maps are available within the climate service DATACLIME (www.dataclime.com) by consulting the climate product “Visualize climate data - Province of Belluno”. The data processing algorithms coded in R are available upon request to the corresponding author.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2024.100656.

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