Climatic Change (2025) 178:41
https://doi.org/10.1007/s10584-025-03890-y

Review on climate change impacts on the Water-Energy-Food-Ecosystems (WEFE) Nexus in the North-Eastern Italian Alps

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Received: 3 October 2024 / Accepted: 17 February 2025 / Published online: 27 February 2025

Abstract
Mountains, such as the Trentino region in the North-Eastern Italian Alps, are highly vulnerable to climate change. Their intricate topography amplifies the interaction between local atmospheric processes and regional-scale dynamics, adding complexity to the assessment of climate impacts. To devise effective adaptation strategies, it is crucial to thoroughly understand the environmental and socio-economic sectors most affected in these distinctive mountain landscapes. This study explores the most significant documented impacts of climate change on the sectors within the Water-Energy-Food-Ecosystems (WEFE) Nexus in Trentino. It highlights their interconnections and the critical knowledge gaps that must be addressed to comprehensively understand the Nexus. The main aim is to provide a solid scientific basis for identifying high-priority climate risks in the region and to craft the most appropriate adaptation strategies. Our findings reveal that regarding individual sectors in Trentino, most studies focus on Ecosystems, followed by Water and Food. The least studied sector is Energy. Regarding the NEXUS, the Water Sector exhibits the majority of interconnections with other components. While the impacts of climate change on individual sectors have been analyzed to varying degrees, the strong interconnections between these sectors remain largely unexplored with important missing interconnections mainly between Energy and Food, and Energy and Ecosystems, as well as a comprehensive consideration of the impacts of energy on water and food on ecosystems.

Keywords Climate change impacts · Complex topography · Environmental and socio-economic connections · European Alps · Water resources

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1 Introduction

High mountain regions are one of the most sensible environments for climate change (Hock et al. 2019). They are being affected, and will likely be in the future, at a faster rate than other terrestrial environments (Hock et al. 2019; mou 2015; Palazzi et al. 2017; Rangwala et al. 2013) with cascading effects on a variety of sectors across multiple temporal and spatial scales (Aguiar et al. 2018). Climate change is already increasingly impacting both natural and social systems worldwide, profoundly modifying human activities and threatening human health and social security (Guisan et al. 2019; Steiger et al. 2022; Sugg et al. 2023; Beniston and Stoffel 2014). Among the most important sectors affected by climate change in mountain environments are water, ecosystems, energy, and food, which significantly influence and characterise almost all mountain socio-economic and environmental activities. The Water-Energy-Food-Ecosystem (WEFE) Nexus (Carmona-Moreno et al. 2019) has emerged in many different areas (e.g. Mediterranean De Roo et al. 2021; Lucca et al. 2023, Africa Botai et al. 2021; Kanda et al. 2023; Schlemm et al. 2024, Uzbekistan Song et al. 2023, India Jain et al. 2023) as a key framework to address these sectors' complex challenges (Bidoglio et al. 2019). This framework arises from the fact that water, energy, agriculture, and natural ecosystems are strongly interconnected. Considering them in a nexus approach can provide benefits to multiple sectors at once, while a separate, sometimes traditional sectorial approach, can jeopardise some sectors and pit one against the other.

As measures and plans for climate change adaptation are being developed at different governance levels (Lee et al. 2023), it is of paramount importance to have in-depth knowledge about climate change impacts and associated risks, in particular for the elements of the WEFE nexus and the nexus itself. This ensures that effective adaptation strategies can be developed for a complex topography region such as the Province of Trento (also referred to as Trentino). Trentino is a densely populated area in the North-Eastern Italian Alps and it contains all WEFE sectors in close proximity, thus enabling the in-depth study of WEFE components and interconnections. Its climate, topography, and socio-economy are representative of many other regions in the European Alps with implications that could potentially be transferred to other mountain regions of the world.

Furthermore, Trentino region adopted a work program for the development of a Provincial Strategy for Mitigation and Adaptation to Climate Change (https://www.appa.provincia.tn.it/Documenti-e-dati/Documenti-tecnici-di-supporto/Trentino-Clima-2021-2023) in 2021 and has been working since then mainly on the identification of climate risks and necessary adaptation measures for priority environmental systems and socio-economic sectors, with the support of local scientific institutions and with a multi-approach and collaborative pathway (Gretter 2024). This work program includes the development of future climate change scenarios for the region. These scenarios will be made publicly available online and are detailed in an internal Italian report (Matiu et al. 2024).

Understanding and highlighting the uncertainties and the gaps in our understanding of the main impacts of climate change on the components of the WEFE Nexus is of paramount importance for decision-makers, researchers, and climate service providers in order to enable collaborations aiming at improving the development and implementation of adaptation strategies and plans, and in order to understand possible future impacts on the nexus.

Consequently, the main aims of this review are:

- Identify the impacts of climate change on the WEFE nexus components in Trentino, as documented to Summer 2023;
- Identify knowledge gaps;
- Provide a solid and science-based foundation for the development of the provincial climate change adaptation strategy;

This review paper is organized into five main sections: Section 2 outlines the study area and the methodology employed; Section 3 presents the findings related to the components of the WEFE Nexus; Section 4 discusses the known impacts on the WEFE Nexus, and Section 5 provides the conclusions.

2 Study area and methods

The Trentino region is located in northern Italy and forms the southern portion of the Trentino-Alto Adige region, which is one of the 20 regions of Italy (Fig. 1). It covers approximately 6,214 square kilometers and is characterised by a diverse landscape of mountains, valleys, and rivers. The region is rich in water resources, featuring several major river basins, including the Adige, Sarca, and Noce rivers, and lakes such as Garda Lake. Its orography is predominantly mountainous, with rugged mountain ranges.

Climate change is profoundly affecting mountain environments, including Trentino where temperatures have risen significantly, with a sharper increase in the last 30-40 years, averaging 0.3-0.5°C per decade across the province, varying by elevation (Di Piazza et al. 2012; PAT and APRIE 2022; Tudoroiu et al. 2016). Urban heat islands (Giovannini et al. 2011), longer heatwaves (Di Piazza et al. 2012; Morlot et al. 2023), and shifts in precipitation patterns are notable impacts. These changes have led to reduced snow cover duration and snow depth at various altitudes, each showing distinct sensitivities to climate change (Marcolini et al. 2017). Orography plays a crucial role in extreme precipitation trends, with increases in sub-daily extremes from 1991 to 2020 (Dallan et al. 2022). For short precipita-

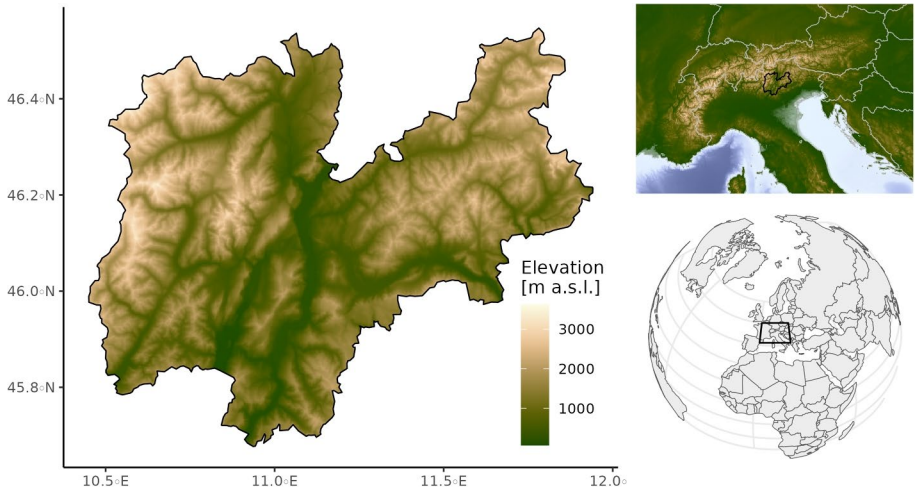

Fig. 1 Topography of Trentino, its location in the European Alps, and globally

tion events (under an hour), intensity decreases by 10-20% per 1000 m of elevation, whereas orographic enhancement is observed for events lasting over eight hours (Formetta et al. 2022).

2.1 Review methodology

In this review, we analyze the knowledge accumulated on the impact of climate change on the sectors that compose the WEFE nexus and the nexus itself until summer 2023 in Trentino.

As other previous review studies proceed (e.g. Lucca et al. 2023; Albrecht et al. 2018; Purwanto et al. 2021), in this work, the first important step was to identify the most significant issues for the territory under examination. The documents that helped in this first step were based on the Intergovernmental Panel on Climate Change and its reports (e.g. Hock et al. 2019; Lee et al. 2023), the National Adaptation Strategy to Climate Change (Castellari et al. 2014), the National Climate Change Adaptation Plan (PNACC 2018), and the South Tyrol Climate Report (Zebisch et al. 2018). Unlike previous review analyses, this work involved key experts from each sector, focusing specifically on Trentino, as well as other professionals from local research institutions, agencies, and public sector offices operating in relevant fields. A team of 48 experts contributed by recommending highly localized studies and analyses based on the keywords analysed. They also reviewed an initial draft of the review, offering their insights to identify gaps in the analysis and, more specifically, in the existing literature. Their suggestions were implemented before requiring a second final review. For the literature analysis, references were made to scientific articles, but also gray literature, such as results from research projects conducted in the territory, and technical reports produced by the local institutions. In cases where no scientific contributions specifically related to the Trentino region were identified, available information for a wider territory within the Alpine context was included after careful validity considerations. Recognized knowledge gaps were also clearly reported.

3 Impacts of climate change on the WEFE Nexus components

In this section, the impacts of climate change on the WEFE nexus components in Trentino are reported. Each sector is subdivided in multiple parts, as presented in Fig. 2. A general introduction is given per each sectors. This is then followed by the results of the reviewed literature for detailed aspects.

3.1 Water

One of the main effects of rising temperatures and the altered distribution of precipitation induced by climate change is to modify the hydrological cycle, by also increasing evapotranspiration (Mastrotheodoros et al. 2020), thereby disrupting the availability in space and time and quality of water resources. The impacts of climate change on the quality and quantity of water resources are increasingly evident throughout the Alpine region and are becoming a crucial concern for the planning and evaluation of policies and interventions for proper water resource management. Furthermore, despite its fundamental role at regional

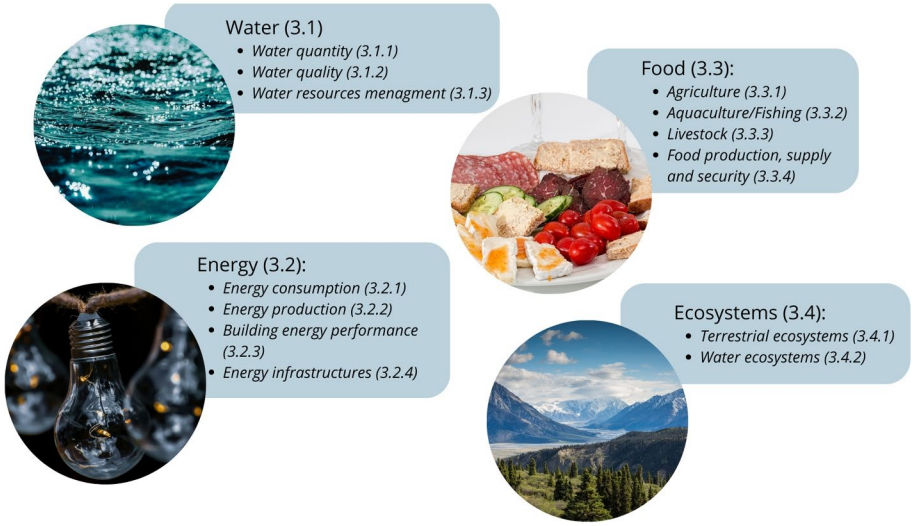

Fig. 2 The Water-Energy-Food-Ecosystems (WEFE) nexus: for each sector, the correspondent paragraph in this study is mentioned

level in terms of renewable energy production (ISPAT 2023), hydropower can contribute to exacerbating some effects of climate change, such as hydro and thermo-peaking (Hauer et al. 2017; Zolezzi et al. 2011).

Trentino is characterized by the presence of a rich and complex hydrographic network: the main basin in the region is the Adige River, the second-longest river in Italy, flowing from north to south, and covering more than a third of its total area. The hydrology of the Adige basin is strongly influenced by the dynamics of snow and glacier accumulation and melting in the small high-altitude basins. Precipitation and contributions from underground water, along with evapotranspiration, play a significant role in determining flows in the valleys, especially in the southern portion of the basin (Chiogna et al. 2016; Larsen et al. 2021). Moreover, Trentino is a territory characterised by a lot of different types of lakes, that are composed of deep mixing processes that influence the water quality (van Haren et al. 2021; Piccolroaz et al. 2019, 2021; Salmaso et al. 2018b, 2020; Amadori et al. 2018, 2020, 2021; Biemond et al. 2021) by redistributing nutrients, oxygen, and potential pollutants within the water body. In the Adige basin, the change in air temperature influences water surface temperature (Diamantini et al. 2018), and also lakes, whose surface temperature influences mixing and ecosystem function as shown for the entire region (Salmaso et al. 2014, 2018a). A global reconstruction from 1900 to the present, including the famous Garda Lake in Trentino, shows that lakes in temperate climatic zones, like most Trentino lakes, are the most thermally reactive (Piccolroaz et al. 2020). Moreover, glacier retreat also significantly affects the temperature of glacially-fed streams, with the change in temperatures delayed, as reported for the Careser glacier in Trentino (Lencioni et al. 2022).

To understand the impacts on this sector, it is crucial to consider changes in both water quantity and quality and the significant implications for the management of water resources in the region.

3.1.1 Water quantity

Long-term statistical analysis of annual flow values for five Alpine watercourses including the Adige revealed statistically significant and homogeneous negative trends in the study area, amounting to approximately -1.45 mm/year at the regional scale (Balistrocchi et al. 2021). In the Adige Valley, reconstructions of flows over the last 2000 years until 2012 identified numerous periods of drought and abundant precipitation (Formetta et al. 2022), but the role of climate change impacts in determining the observed trend and variability is not yet clear. Historical series of flow, precipitation, and temperature recorded in different sub-basins of the Adige have been analyzed by Mallucci et al. (2019): the observed decrease in summer flows affects the Adige plain from the 1970s, and it is attributed to both the reduction of winter precipitation and increased water use for irrigation. In contrast, winter flows have increased due to increased recharge of aquifers in the autumn, consistent with increased precipitation in the same period. These results reveal the varied impact of climate change on the Adige basin, which depend on the spatial scale of interest and strongly correlate with changes in water resource utilization. The melting of Alpine glaciers also has a strong impact on the changing runoff due to the combined effect of early snowmelt and the progressive reduction of glacier area (Zanoni et al. 2023).

Climate change impacts both surface and groundwater. Lucianetti et al. (2019) studied flows from three springs in Trentino during the extreme Vaia storm (2018) (Giovannini et al. 2021), finding that recently infiltrated meteoric waters increased winter base flow by up to 85%. Groundwater responses to intense precipitation depend on aquifer composition: high-altitude springs in fractured carbonate aquifers respond rapidly to rainfall, while springs at mountain bases exhibit delayed responses-key dynamics to consider as extreme events become more frequent.

Regarding water quantity future projections, Galletti et al. (2023) introduces a new interpretation of the hydro-meteorological drought index SPEI highlighting the complexity of the response to meteorological drought in the Adige basin, influenced by both the hydrological properties and the presence of water storage infrastructure. In this study, the westernmost area of the basin is indicated to be more susceptible to droughts in the mid-21st century. Moreover, the impacts of climate change on flows in the Noce and Brenta rivers were examined using emission scenarios RCP4.5 and RCP8.5 (PAT and APRIE 2022) revealing a general trend of decreasing annual flows in both basins, with the most noticeable effect of climate change being a shift in the seasonality of flows. Simulations indicated significant shifts in flow volumes from summer to the winter-spring period due to the increase in temperatures that has diverse effects based on a nivo-glacial or nivo-pluvial hydrological regime.

3.1.2 Water quality

Regarding the impacts on surface waters, Diamantini et al. (2018) evaluated, for the period 1990-2015, how numerous factors of both climatic and anthropogenic origin influence water quality in the Adige basin. It has been observed that air temperature significantly impacts surface waters, with negative trends in dissolved oxygen correlated to recorded increases in air temperatures. Diamantini et al. (2018) also report that another major driver of surface water quality alteration is flow variation: a decrease in flows during certain seasons directly

results in increased contaminant concentrations in water due to reduced dilution, a key behavior to consider in light of the changing climate. Rügner et al. (2019) further demonstrate how flow extremes are directly associated with significant mobilization of sediments and contaminants in some basins including the Adige. An additional cause of water quality alteration has been identified in glacier melting that can increase ecological risk for aquatic fauna (Rizzi et al. 2022; Wilkes et al. 2023).

The shift from snow recharge to rainfall recharge of a lake that is strongly influenced by underground springs increases its water temperature (Flaim et al. 2019). Studies conducted at Lake Tovel in Trentino have shown that lake ice cover is delayed by 5 days per decade (Flaim et al. 2020) strongly influencing the mixing and the oxygenation dynamics of the lake bed. In Lake Tovel, the annual average dissolved oxygen (% saturation) has increased from near anoxic levels to over 20% in the lower layer between 1937 and 2010. The progressive oxygenation of the deep layers is explained by a dual effect: the gradual rise in temperatures delays the formation of the surface ice layer, extending the period of autumnal mixing, leading to greater oxygen redistribution along the water column.

3.1.3 Water resources management

Water scarcity and water security are interconnected, not only through the direct effects of water scarcity on each user's access to water but also due to the conflicts that can arise in the presence of multiple uses of the resource (La Jeunesse et al. 2016). Future increases in temperature and changes in precipitation patterns induced by climate change will exacerbate water resource scarcity. These are issues that Mediterranean regions are already experiencing today. La Jeunesse et al. (2016) explored in the Mediterranean region, including the Noce River, whether local stakeholders (water users and managers) perceived climate change as a key issue for water resource use and supply security through interviews, meetings, and surveys. At the time, climate change was not identified as a primary concern. Instead, rising water demand in the Mediterranean was addressed by externalizing water resources, constrained by national boundaries and technological limitations-ensuring water security but through unsustainable practices. Notably, "climate change" was absent from stakeholder discussions in areas like the Noce basin (Trentino). Given recent severe water scarcity and conflicts (2022-2023), perceptions might differ today, underscoring the importance of raising awareness among local managers about climate impacts like water scarcity.

Water management in Trentino is based on the regional multisectoral water system that controls the entire supply and distribution network (Cirelli and La Jeunesse 2019). Referring to the Noce river basin in Trentino, Cirelli and La Jeunesse (2019) identified four criteria for evaluating water governance and drought-related challenges: diverse water uses, system management, conservation, and risk assessment. The study predicts that water issues will worsen, and conventional management approaches will be inadequate to meet future challenges. Integrated water resource management is thus needed-participatory, scientifically informed, and rooted in a bottom-up approach (Stanghellini 2010). In Trentino, a stakeholder analysis methodology was developed as a preliminary step to support their engagement in water management (Stanghellini 2010).

3.2 Energy

Climate change can profoundly impact the energy system, from production to consumption, particularly affecting renewable energy sources. Shifts in wind patterns may influence wind power generation, changes in runoff can alter hydropower output, and variations in cloud cover can affect solar radiation, impacting photovoltaic and solar thermal energy production. As energy systems increasingly rely on renewables, which are inherently intermittent and seasonally variable, understanding climate change's effects on the energy sector becomes critical to ensure resilience and reliability. As reported in PAT and APRIE (2022), In Trentino, electricity production is predominantly hydroelectric, with renewables contributing 83% of total production in 2016. Hydropower generated 4,321 GWh, far exceeding consumption (3,322 GWh), resulting in a 65% production surplus. Other contributions included photovoltaic energy (176 GWh), cogeneration from solid biomass for district heating (22 GWh), and biogas cogeneration (19 GWh). Gas cogeneration accounted for 951 GWh, primarily for industrial use and district heating. Trentino hosts approximately 15,000 photovoltaic systems with a combined capacity of nearly 180 MW, while small wind farms remain experimental. Thermal energy production from renewables is mainly derived from wood biomass, reflecting the area's reliance on domestic resources.

3.2.1 Energy consumption

Medium- and long-term energy planning at the regional level requires estimating future energy demand determined by the projected heating and cooling needs of buildings, taking into account the local impact of climate change and also considering recent European legislation on increasing energy efficiency of buildings. To support the development of the Environmental Energy Plan of the Province of Trento 2021-2030 (PAT and APRIE 2022), temperature projections provided by some of the regional climate models of EURO-CORDEX were downscaled to the local scale for 11 sites hosting provincial meteorological stations, at altitudes ranging from 0 to 700 meters above sea level, to estimate future values of a series of parameters commonly used to model building energy demand, such as Heating and Cooling Degree Days (HDDs and CDDs) (PAT and APRIE 2022). Historical data (1983-2019) show a comparable reduction in HDDs across stations at different elevations, averaging -10 HDDs per year, with signs of acceleration in recent years. Concurrently, CDDs have increased by less than 5 CDDs per year. Temperature projections indicate a continuation of these trends, with further reductions in HDDs and increases in CDDs. These changes suggest significant shifts in the seasonal energy demand for heating and cooling, with a particularly substantial relative increase in cooling energy needs.

Moreover, changes in the quantity of snow and its duration on the ground (Matiu et al. 2020), especially at lower altitudes, lead to impacts on energy consumption mainly in the skiing environment, on which the Italian Alpine countries are most dependent (LEGAMBIENTE 2023). Monitoring snow depth and reservoir water temperatures has become particularly important, alongside identifying best practices to reduce cooling activities, optimize snow production, and thereby decrease energy consumption (Viesi et al. 2023).

3.2.2 Energy production

Climate change will cause alterations in flow regimes in the Alpine region, with potentially significant consequences for various socio-economic sectors, including hydropower production, as cited in Section 3.1.3. Changes in water availability are reflected in the hydropower potential of the basin with a general decrease in production in Trentino (PAT and APRIE 2022), with conflicting production trends in the short term (2021-2050) between the two emission scenarios (RCP4.5 and RCP8.5), and aligned trends in the second period (2041-2070) (PAT and APRIE 2022). The expected changes in water availability directly affect the estimate of the hydroelectric production potential of the hydrographic basin, which differs depending on season (PAT and APRIE 2022), but also on the location of the production plant (Majone et al. 2016). In general in Trentino, a potential increase in hydroelectric production is expected in the short-medium future linked to the expected increases in water supply for hydroelectric plants located at higher altitudes (Majone et al. 2016). The effects of climate change also impact the dynamics of lakes, such as the water currents, and thus the energy production that will be exploited during different times of the day (Stucchi et al. 2023). Moreover, the expected increased frequency and intensity of prolonged drought events and water scarcity, especially in the summer season, may potentially induce greater conflict situations among competing water uses (see Section 3.1.3). This can lead to periods of lower hydropower production due to the scarcity of water accumulated in the reservoirs and the higher priority given to other uses through emergency-mandated releases. Climate change also involves a variation in water temperature (see Section 3.1) even in reservoirs for artificial snowmaking (see Section 3.2.1), which will require dedicated cooling systems, thus increasing energy demand.

Despite the wide uncertainty associated with future climate projections, the Trentino seems to be located in an area in which a decrease of wind is predicted by the end of this century as in all the Mediterranean area (Carvalho et al. 2017) and it is not particularly favorable for wind production by its nature, primarily due to morphological causes (Giovannini et al. 2013, 2014). Moreover, the complex terrain poses significant obstacles to the preparation of necessary infrastructure and the accessibility of hypothetical facilities.

Photovoltaic solar energy plays an essential role in decarbonizing the European energy system in general and the energy system of Trentino in particular (PAT and APRIE 2022). However, climate change may influence surface solar radiation components and therefore directly affect future photovoltaic energy generation. In Trentino, Laiti et al. (2014) mapped and assessed solar global radiation at annual and monthly scales, analysing and comparing estimates of hourly mean diffuse radiation fractions from global radiation data with observations from a local weather station. However, no studies have yet examined future projections or the potential impacts of climate change on cloud cover and solar radiation inputs in the region.

Fermentable biomasses are exploitable for energy mainly through anaerobic digestion processes and subsequent biogas production. The availability of studies addressing the effects of climate change on the availability of energetically exploitable biomass is very limited in Trentino and none is available for the Italian territory, for instance, compared to studies on the effects of biomass utilization on climate change (Poudel et al. 2011; Laanaia et al. 2016). Regarding the zootechnical sector, which is considered the most strategic for biogas production from organic waste in Trentino, at national level a reduction of the national pro-

duction of excreted material is expected (see Section 3.3.3) and thus a negative effect on the national biogas production capacity cannot be excluded also in this area. Indeed, mountain regions may be less affected by the above-mentioned effects, but not entirely excluded.

3.2.3 Building energy performance

Building materials vary in characteristics, affecting the energy efficiency of buildings. Indeed, many factors influence thermal conductivity, such as temperature, moisture content, and bulk density (Pásztory et al. 2021). Other factors such as thickness, airflow velocity, pressure, and aging also influence thermal performance. Understanding the quantitative relationship between effective thermal conductivity and influencing factors of insulation materials is crucial for determining building envelope heat, mass transfer, and energy consumption. No studies have been done in Trentino, but knowing that variation in temperature is the aspect that most affect energy consumption (Pappaccogli et al. 2020) with increase of value of thermal conductivity with increasing temperature (Pásztory et al. 2021), and thus lower overall building energy efficiency in winter and less insulation in summer (Pásztory et al. 2021), can help in understanding how the building energy performance will be in future in the area.

3.2.4 Energy infrastructures

The expected increase in the frequency and intensity of extreme weather events could affect the security of energy infrastructures, due to the impacts on them Patt et al. (2013); Carraro (2021), and directly the energy generation (Carraro 2021) (e.g changes in the mechanical and structural properties of the soil could impact pipelines; dry and hot climatic conditions tend to favor the initiation and propagation of fires, which can cause significant damage to infrastructures; river floods can lead to structural damage; large dimensions of hailstones and the consequent impact velocity make most solar panels vulnerable; etc...). Rising temperatures significantly impact energy systems, as highlighted by Carraro (2021). Higher air temperatures reduce the efficiency of cooling systems, energy products, and electricity generation while impairing heat dissipation due to elevated nighttime temperatures. Conversely, cold spells can lead to the formation of snow and ice sleeves on transmission and distribution lines, risking structural collapse and disrupting energy supply. Besides affecting the reliability of electricity supply, there could also be increased difficulties in the operational management of energy infrastructures, for example, due to possible demand spikes in certain periods and/or difficulties in their implementation, as well as variations in the efficiency of production plants.

3.3 Food

Agriculture, aquaculture/fishing, livestock, and food production depend heavily on climate (Epa 2017). The increase in global temperatures could enhance the yield of certain crops, and to achieve these benefits, production must be supported by appropriate levels of, for example, nutrients, soil moisture, and water availability. Changes in the frequency and severity of droughts and floods could also pose a challenge for farmers and livestock breeders and threaten food security (Epa 2017). In general, climate change could make it

more difficult to cultivate, raise animals, and fish in the same ways and in the same places as we have done in the past (Epa 2017). The effects of climate change must be considered alongside other evolving factors influencing agricultural production, such as changes in agricultural practices and technology.

3.3.1 Agriculture

The impact of climate change can have different effects on agriculture as a socio-economic sector, with repercussions on income, agricultural production choices, natural capital, and ecosystem services, with outcomes varying by location (Fezzi et al. 2014). Studies in Italy have examined how climate will affect agricultural land values and productivity, revealing geographically heterogeneous impacts. In particular, more severe climate scenarios are projected to have increasingly harmful effects on land values and agricultural productivity across the country (Bozzola and Ravetti 2017; Bozzola et al. 2018).

The likely increase in the intensity of extreme events has led and will potentially lead to greater damage to agricultural production in Trentino (Eccel et al. 2012). The advancement of phenological phases modifies the timing of sowing, treatment, pruning, harvesting, and other operations carried out by farmers for the care of different crops (Alikadic et al. 2019). The variation in the quality of musts changes the quality of wine products and modifies winemaking techniques. Similarly, the quality of berries declines during warmer and drier periods, altering production levels. Changes in thermal sums can also affect the flowering and production of different fruit species, and optimal cultivation areas may shift to higher elevations, leading to the abandonment of some areas or expansion into new areas (Eccel et al. 2016). Changes in water demand for irrigation, driven by modified seasonal precipitation and water flows, as well as more frequent droughts, may intensify conflicts over water resources (see Section 3.1.3). The earlier flowering due to climate change can lead to an increased risk of late frosts causing damage to flowers/fruits. Moreover, climate change is predicted to have direct and multiple effects on the epidemiology of plant diseases (Burdon and Zhan 2020; Lahlali et al. 2024) impacting seriously the agricultural production.

Globally, Drosophila suzukii (an invasive alien insect that significantly damages the agro-ecosystems and whose development and maintenance of the species is favored by milder temperatures Langille et al. 2017) is impacting both directly and indirectly the economy of the territory mainly fresh markets, frozen berries, and fruit export programs due to the limited availability of effective insecticides (Tait et al. 2021). Besides global studies, the economic impact of this parasite on the red fruits industry, one of the most important industries for Trentino, has also been evaluated on the territory highlighting different approaches based on the insect population pressure (De Ros et al. 2015; Del Fava et al. 2017).

Understanding how farmers perceive risks related to agriculture and how they behave in contexts of uncertainty is essential for shaping effective policies, awareness programs, and insurance tools. In Trentino, a significant portion of farmers is concerned about climate change (Menapace et al. 2015): the main challenge is not raising awareness about climate-induced agronomic risks but providing support in identifying effective adaptation solutions, including economic ones. From an economic point of view, it has been confirmed through a study on apple producers in Trentino that agricultural producers are risk-averse (Menapace et al. 2013). Farmers' perceptions of future damages vary depending on the beliefs and experience of the farmer, the crop, or the risk considered.

3.3.2 Aquaculture/Fishing

Unlike fishing, aquaculture relies on external inputs for over 70% of its sustenance, making it less affected by changes in ocean primary productivity. Although climate change represents a global risk to food production, these factors will not affect aquaculture in the same way, as, unlike any other agricultural practice, the sector is confined over time, space, and dimension and therefore has a considerable degree of maneuverability (De Silva and Soto 2009). The severity of the risk will vary depending on geographical or climatic zones, the environment, the species farmed, production systems, and scale, but also based on national economies (Maulu et al. 2021).

Aquaculture is an activity deeply rooted in Trentino for over a century with changes in temperatures that could lead to increased stress-related mortality at certain stages of the animal's life cycle and could also influence the incidence of major diseases. The possible reduction in water flow rates in watercourses (Van Vliet et al. 2013) could lead to a drastic reduction in water turnover in facilities, resulting in oxygen deficiencies and increased catabolites, with repercussions on production due to stunted growth and increased mortality. The issue of dry periods could also be exacerbated by competition for water, in the case of multiple uses. Furthermore, it should be noted that, compared to other uses, aquaculture releases almost all the water it withdraws.

As introduced in Section 3.1, rivers and lakes are directly affected by environmental changes, with consequences for invertebrate communities. As a result of these changes, it is expected that the spatial position or altitudinal and/or latitudinal limits of fish species will change. The most likely response is a shift in fish distribution towards higher altitudes or latitudes, especially for cold-water species (Comte et al. 2013). Lake Garda, in Trentino, has been studied and monitored for decades. The European project ClimeFish (Climfish 2020) focused on studying the effects of climate change on fishing and aquaculture on a European and local scale, with Lake Garda as one of the case studies. According to the project's results, the temperature increase in Lake Garda could lead to a decrease in animal growth rates and this temperature change can affect the survival of larval stages of some species. The main risks identified in the project concern wild stocks, including decreased natural recruitment for whitefish, reduced biomass for various species, lower productivity, and the rise of more invasive species better adapted to the changing environment. Risks directly related to fishing activities include the potential extension of the winter fishing ban, a reduction in the number of fishing licenses, and decreased catch efficiency.

3.3.3 Livestock

Global warming has significant effects on the diversity of farmed animal species and food security (Bernabucci 2019). A growing concern for the thermal comfort of farm animals is present, moreover, animal production will need to increase in the coming decades to meet the growing demand for animal-origin foods, thus it is expected that livestock systems will be increasingly influenced by climate change (Bernabucci 2019) with differences between intensive and extensive livestock (Rust 2019).

A warm environment negatively affects the health of farm animals, directly and indirectly (Lacetera 2019). Directly on livestock health by causing metabolic alterations, oxidative stress, reduced feed intake, and immune suppression, leading to increased susceptibility

to various diseases due to changes in temperatures (Lacetera 2019). The repercussions of heat stress are not only immediate but also long-term, such as decreased fertility (Wolfenson and Roth 2019) and increased incidences of hoof and skin diseases. Heat stress negatively affects milk and meat production, both qualitatively and quantitatively (Bernabucci et al. 2014; Bernabucci 2019). Regarding milk production, for example, heat stress has a more significant effect on high-quality products such as protected designation of origin cheeses in many European countries (Summer et al. 2019), while concerning meat, beef cattle are usually considered less sensitive to heat stress than dairy cattle due to their lower metabolic rate and lower heat production (Summer et al. 2019). However, beef cattle also compensate for increased body temperature with homeostatic mechanisms and behavioral changes, effects that are responsible for lower growth rates and reduced fertility in both males and females (Summer et al. 2019). Regarding pigs, the main economic losses associated with heat stress in the swine industry include reduced and inconsistent growth, decreased feed efficiency, decreased carcass quality, poor sow performance, decreased fertility, and increased mortality (Mayorga et al. 2019). The indirect effects of a warm environment are those related to alterations in feed availability and quality.

3.3.4 Food production, supply and security

Climate and weather instability will affect food supply levels and access, altering social and economic stability and regional competitiveness (Altieri et al. 2015). Climate change can influence food safety hazards at various stages of the food chain, from production to consumption impacting socioeconomic aspects at the base of food security (Tirado et al. 2010; Miraglia et al. 2009). There is a need for new metrics to assess food security in local and regional contexts, considering not only food availability and price but also the effects of climate change and agricultural prices on household incomes (Hertel 2016). Food access and utilization may also be indirectly affected by impacts on incomes, drinking water access, and health (Wheeler and Von Braun 2013).

The potential impact of climate change is less clear on a regional scale, but climate variability and changes are likely to mostly aggravate food insecurity in areas currently vulnerable to hunger and malnutrition (Wheeler and Von Braun 2013). In Trentino, the sociocultural and economic value of a series of positive functions of alpine agroecosystems was analyzed in a context of simultaneous intensification and abandonment processes by Faccioni et al. (2019): it was found that all local stakeholders have a positive opinion of the outcomes of the mountain dairy farming system, where, however, regulation services were found to be the most valuable for societal well-being. However, these could be subject to variations in the future due to ongoing climate change. Considering food production in Trentino, an Urban Food Strategy has begun to be evaluated (Andreola et al. 2021), an approach that aims to address the various challenges presented by the shortcomings of the food system, while also involving the existing network of grassroots initiatives.

3.4 Ecosystems

Trentino is an area of diverse ecosystems, ranging from mountainous terrestrial environments to aquatic habitats. The terrestrial landscape is dominated by a wide range of flora and fauna, similarly, numerous lakes and waterways offer a thriving aquatic ecosystem. The

combination of these ecosystems makes Trentino a region of extraordinary biodiversity. Globally, climate change is driving significant alterations in ecosystem structure and functionality, with certain habitats, such as alpine environments, proving particularly vulnerable (Verrall and Pickering 2020). This vulnerability arises not only from climate change but also from a combination of factors, including anthropogenic pressures such as the reduction or loss of open-area habitats which are essential for maintaining the balance of mountain ecosystems (Ceresa et al. 2023; Tattoni et al. 2011; Ciolli et al. 2012; Tattoni et al. 2017). Additionally, excessive tourism in wintering areas exacerbates this fragility (Arlettaz et al. 2013). Changes in the ecological mosaic, as well as the quality and extent of forest cover, further disrupt ecological connectivity and faunal composition (Brambilla et al. 2020a, 2021).

3.4.1 Terrestrial ecosystems

High-altitude habitats in the Alps are highly vulnerable to climate change, with even small increases in average annual temperatures causing significant changes in alpine and nival communities (Verrall and Pickering 2020). It is crucial to implement long-term monitoring protocols for high-altitude flora and fauna as bioindicators of these changes and to protect areas that serve as climate refuges from anthropogenic alterations (Brambilla et al. 2022).

In the Trentino Dolomites, changes in the phytosociology of plants could be sometimes prevented by topographic barriers (Bertol et al. 2021), and the changes in plant species number, frequency, and composition along an altitudinal gradient can most likely be attributed to the effects of climate warming and competitive interactions (Erschbamer et al. 2009). A clear upward trend of treeline in Trentino has been found (Gobbi et al. 2019; Zatelli et al. 2022): the spatially explicit reconstruction of forest landscape changes can be related to many aspects of climate trends in Trentino, including those of animal populations and the distribution of plant species. Explanations further include an ecological and population point of view and a genetic one. Both in Monte Baldo (Dainese et al. 2017) and Lobbia Alta (Prosser et al. 2023) a clear upward trend has been reported with a difference between native and non-native species (Dainese et al. 2017): non-native species are spreading upward at a rate about twice that of native species because the pool of non-native species is already strongly biased towards species with traits that facilitate spread. A large percentage of both native and non-native species seems to be able to spread faster than the current rate of climate change. Most native species and the vast majority of alien species were adapted to warmth (Geppert et al. 2023), but only alien species showed a great competitive ability to thrive in disturbed and resource-rich environments (Geppert et al. 2023). Multiple environmental pressures, including climate change, land use change, and intensification likely drove the rapid upward shifts of native species' rear edges (Geppert et al. 2023). Research by Marini et al. (2009) found that the richness of exotic plant species in Trentino is primarily influenced by temperature and human population density. Future environmental changes are expected to elicit a stronger response from alien species compared to native ones, particularly in warm, urbanized, low-altitude areas, while cold, high-altitude regions with low population density are likely to experience less impact.

A particular interest in Trentino is the situation of orchids (Geppert et al. 2020) where local extinctions were more likely for small populations. Declines were most pronounced for rear edge populations, likely due to multiple pressures such as climate warming, habitat alteration, and mismatched ecological interactions. In general, range loss occurred at lower

elevations, while gained and stable areas are located at higher elevations highligthing the important role of topographic heterogeneity in maintaining climatic microrefugia.

Glaciers are the most significant and visible expression of the ongoing effects of climate change (Gaudio and Gobbi 2022), and as they retreat, they leave behind areas whose substrates are rapidly colonized by multiple forms of life. The ice-free areas resulting from this retreat, known as proglacial plains, represent an experimental system for understanding plant species colonization patterns, community formation, and dynamics (Losapio et al. 2021; Ficetola et al. 2021). As presented by Prosser et al. (2022) and Erschbamer and Caccianiga (2017), no environment is better suited for studying vegetational successions than proglacial plains. Multiple factors can accelerate or slow down the colonization rate such as granularity, pH, soil organic matter content, and thermal gradient from the glacier front to deglaciated sites (Gobbi et al. 2014). Moreover, Losapio et al. (2021) demonstrated, analyzing the vegetation present along the proglacial plains of four Alpine glaciers in Trentino, that plant communities termed "pioneer" plants are found near the front of a glacier and about 50% have a spatio-temporal distribution influenced by glacier retreat.

In Trentino, climate change will affect not only flora but also animal species, as their distribution is largely determined by factors such as altitude, vegetation cover, thermal gradients, and their dispersal capacity (Gobbi et al. 2014). Future projections indicate a progressive decrease in the distribution range and connectivity for several alpine species (Brambilla et al. 2017; Scridel et al. 2021) and an increasing overlap of suitable areas for these species with those suitable for winter recreational activities (Brambilla et al. 2016). Climate change may also have direct effects on alpine species, influencing their survival (Strinella et al. 2020), movement strategies (Resano-Mayor et al. 2020), and social interactions (del Mar Delgado et al. 2021). Preserving suitable conditions in areas that will serve as climatic refuges is fundamental for the conservation of these species and their habitats (Brambilla et al. 2022).

It has been demonstrated in the Dolomites of Brenta (Trentino) that some cryophilic species have been pushing towards higher altitudes, as the conditions of their current habitats become microclimatically less favorable (Panza and Gobbi 2022). Climate change can influence the avian communities across various altitudinal zones: while on one hand, forest species will benefit from the general increase in forest cover, on the other hand, new dynamics are emerging within the forest community that may favor some more generalist species at the expense of others. For example, Brambilla et al. (2020b) studied the future distributions of four cavity-nesting bird species in the European Alps finding that climate change will affect both individual species and community dynamics by altering the overlap of their ranges in terms of proportion and extent. Inter-species interactions will play a key role in shaping species presence and community composition.

For the ungulate in mountains, the occurrence of migration varied among populations and within them but especially depended on the severity of winter and topographic variability (Cagnacci et al. 2011). Alpine large herbivores have developed physiological and behavioral mechanisms to cope with climate fluctuations and resource availability, which may become maladaptive in the case of climate warming. The direct impact of climate change has been analyzed through the study of female Alpine ibex (Capra ibex) movements and activities in the Marmolada massif (Trentino) by Semenzato et al. (2021) finding that in summer ibexes move higher up, and their diurnal activity sharply decreases above a threshold temperature of 13-14°C. This critical temperature will be reached in the future

according to climate change projections, so the altitudinal extension of the area will limit the available habitat for thermal shelter. The variability in the average spatial distribution of roe deer in Europe reflects the interaction between local weather-climatic and seasonal conditions, providing valuable insights into the limiting factors affecting this large herbivore under contrasting conditions (Morellet et al. 2013).

In addition to changes in migration range, climate change indirectly impacts the body size of alpine mammals: in recent decades, climate and environmental changes have led to widespread changes in body size, particularly reductions, in a range of taxonomic groups, which could have substantial impacts on ecosystem functioning. As reported by Mason et al. (2014) with a study on the body mass in young Alpine ibex (Rupicapra rupicapra) within three neighboring populations in Trentino, most studies to date suggest that temporal trends in sizes are indirectly derived from climate change altering resource availability and quality, influencing individuals' ability to acquire resources and grow. This could be due to increased competition intensity and decreased foraging time due to high temperatures.

3.4.2 Water ecosystems

High-altitude waters represent the last reserves of uncontaminated water for the future. In the scientific world as well as in the political, economic, and public opinion spheres, awareness has been raised about the fact that the health and survival of alpine aquatic ecosystems are seriously threatened by the numerous direct and indirect impacts of human activities, including climate change (Schirpke and Ebner 2022), which for some time now have also affected the most remote areas of the planet (Wilkes et al. 2023). Lakes with low suitability for human use are mostly influenced by large-scale factors such as climate change (Ebner et al. 2022), while lakes with high suitability for human use are more often affected by pressures related to changes in local water use (Ebner et al. 2022). Among the most extreme and inhospitable environments for flora and fauna are streams fed by glacial meltwater, characterized by very low temperatures (below 4°C), highly unstable riverbeds, turbidity, high flow rates, and highly variable current velocities during the day in summer and low or no flow in winter when the streams can freeze in the substrate (Castella et al. 2001). In the sections near the glacier front, there is a low richness of species, plant organisms are generally absent, and animals are represented only by some highly specialized insect species (Trenti et al. 2022). Overall, these ecosystems are highly sensitive to environmental and climatic changes, and their study over time can be an excellent tool for monitoring the effects of such changes on biological communities in periglacial environments (Lencioni et al. 2018). Trentino has over 320 different lakes varying in size, geological substrate, altitude, and trophic status, and they represent the majority of physicochemical types of temperate lakes (Hansen and Flaim 2007).

Using future glacier projections along with hydrological routing methods and species distribution models, Wilkes et al. (2023) quantified the variable influence of glaciers on the distribution of the population of 15 species of alpine fluvial invertebrates throughout the entire Alpine arc, including Trentino, forecasting their presence and abundance until 2100. This study predicts that the influence of glaciers on rivers will steadily decrease. Glacial species are expected to conquer higher elevations following retreating glaciers until they become extinct with them highlighting that not all species have the same vulnerability and not all will have the same fate. The modes and timing of response of invertebrate communi-

ties to global warming in alpine streams in Trentino have been analyzed by Debiasi et al. (2022) and Lencioni et al. (2022), where the authors evaluated the effect of global warming on high-altitude invertebrate communities using data from the Careser glacial system. A warmer climate has been observed, and the invertebrate community showed a delayed response of about 13 years to water warming. In watercourses fed by glacial meltwater, taxonomic and functional diversity changed more consistently than at the glacio-rhithral site due to the arrival of taxa previously absent upstream and bearing completely new functional traits. The number of individuals of Diamesa steinboecki, known as the glacier fly, a cold-adapted insect, decreased (Muñiz-González et al. 2023) as did community structures in glacier-fed streams (Lencioni et al. 2018).

4 WEFE Nexus in Trentino

Mountainous regions, such as Trentino, are already facing the impacts of climate change on the components of the Water-Energy-Food-Ecosystem (WEFE) nexus. These impacts are strongly influenced by seasonal variations in weather and hydrological variables and elevation, as reported in the previous chapters. As an example, the alterations of the hydrological cycle necessitate adaptations in water resource management to mitigate potential socio-economic impacts. Climate change is also reshaping agriculture and food production, energy systems, and ecosystems, further amplifying the complexity of the nexus.

As noted by Lucca et al. (2023), water-energy interdependencies are particularly significant within the Mediterranean region, including Trentino, which lies at the interface between regions with Mediterranean and Continental climates. This is largely attributable to the energy-intensive nature of water abstraction and distribution systems needed to meet drinking and irrigation demands prevailing in densely populated lowland regions. At the local scale, Trentino exemplifies these dynamics, with hydropower representing the main water use as many other mountain areas. However, Trentino's context diverges from the broader Mediterranean setting in some key areas. The Water-Ecosystems and Water-Food interconnections are prominent in this mountainous region, at the base of both environmental and socio-economic stability. For instance, in Trentino, fish farming and agriculture are the second and third largest water-use sectors after hydropower, while mountain ecosystems are among the most biodiverse globally. These interconnections are twofold: the Water-Food nexus depends on water availability, which directly influences agricultural outputs, while climate-driven shifts in crops and livestock may alter water demand. Additionally, as outlined in Section 3.1, rising temperatures due to climate change directly affect evapotranspiration rates, thereby increasing plant water demand. Fish farming, a significant activity in Trentino, is also impacted: as water temperatures continue to increase in the region, as reported in Sections 3.1 and 3.4.2, the sector faces a higher demand of water to maintain optimal conditions for trout farming, as more frequent water renewal is required to regulate temperatures. Similarly, the Water-Ecosystems nexus reflects a reciprocal relationship: ecosystems rely on water availability, but changes in biodiversity, algal blooms, organism distributions, and consequently the capacity of water purification by dilution and consumption of nutrients, can also significantly affect water quality (see Section 3.1.2). Over time, these dynamics may lead to conflicts between strategic sectors, especially under conditions of unsustainable water use and continuing climate change. Another crucial issue in Trentino

is the link between Ecosystems and Food. Climate-driven biodiversity shifts, including species population changes, pose challenges for agriculture and livestock sectors, emphasizing the intricate dependencies within the WEFE nexus.

Numerous other potential interconnections appear to have either not been analyzed in this area or there has been no quantitative assessment of their strength, particularly in comparative terms: impact of Energy on the Water sector, Energy-Food nexus, Energy-Ecosystems nexus, and impact of the Food sector on Ecosystems. Understanding these links is essential to fully assess the potential impacts of climate change on the WEFE Nexus and could provide valuable insights into mountain communities.

5 Conclusions

Climate change necessitates profound human habits and governance adaptations in mountainous regions like Trentino, where Water, Energy, Food, and Ecosystems are deeply interconnected. These adjustments represent significant challenges for national, regional, and local authorities, demanding robust adaptation policies tailored to the physical, environmental, socio-cultural, and economic characteristics of the area.

The present review underscores a marked disparity in the depth and breadth of scientific studies across the components of the WEFE nexus in Trentino. Research focusing on ecosystems is relatively well-developed, whereas socio-economic impact studies remain limited, highlighting the need for enhanced knowledge in this domain. Key WEFE components and WEFE Nexus requiring further research include:

- Water Sector, in which limited studies address the impacts of climate change on groundwater, springwater resources, and the surface temperatures of lakes and rivers. Furthermore, a critical area of concern is the uncertainty of how climate variations, particularly during drought periods, will affect water distribution and availability, directly impacting water resource management.
- Energy Sector, where research is lacking on the impact of climate change on cloud cover and solar radiation, which are vital for evaluating the potential of photovoltaic solar energywhich now experiencing more rapid growth in the region. Studies on the availability of climate-impacted biomass for energy production are also insufficient, especially compared to the relatively extensive research available on the reverse relationship-how biomass utilization affects climate change. Also lacking are comprehensive studies examining building energy performance. Despite evident heating and cooling needs in Trentino (see Section 3.2.1), further investigation is needed as this is one of the most significant climate adaptation topics in the region.
- The WEFE Nexus in Trentino primarily lacks the Energy-Food (e.g., use of renewable energy to produce food (Nadal et al. 2017; Xydis et al. 2021), and use of anaerobic digestion of agro-industrial by-products to produce renewable energy (Valenti et al. 2020) and Energy-Ecosystems (e.g., use of renewable energy to preserve the environment Rahmane et al. 2021) connections, as well as a comprehensive consideration of the impacts of energy on water and of food on ecosystems. This gap hinders a comprehensive understanding of the interconnected dynamics within the Nexus, as well as the impact of climate change on it, which is the primary focus of this study. Additionally, research on

hydropower production under changing climate conditions remains limited to a few watersheds of the entire territory of the Province, which represents a critical link between Water and Energy that requires further exploration.

Addressing these gaps is essential for improving our understanding of the WEFE nexus in Trentino, especially in quantitative terms, and for developing effective, region-specific targeted adaptation strategies in response to climate change. Moreover, where studies are available, it is essential to update scientific information and datasets to ensure that our understanding of climate change impacts remains current over time. Future efforts in Trentino, and generally in mountainous regions, should focus on understanding the nexus' components, their complexities due to the orography, and their interdependencies to better anticipate and mitigate the challenges posed by climate change.

Acknowledgements In the framework of a collaboration agreement with the Provincial Agency for Environmental Protection (Agenzia Provinciale per la Protezione dell'Ambiente, APPA), the public authority in charge of coordinating the development of the Provincial Strategy for Mitigation and Adaptation to Climate Change, we chose a team of more than 48 experts belonging to both local scientific institutions and Provincial Departments, based on their scientific expertise in the field of interest, completed or ongoing research projects within the Autonomous Province of Trento, and roles of responsibility held within the Provincial Departments. The authors thank all the experts who helped actively in the review process by helping in the collection of fundamental information for each sector here presented and/or reviewing them: Gianfranco Anfora (Università di Trento - Centro Agricoltura Alimenti e Ambiente (C3A)), Fabio Antonelli (Fondazione Bruno Kessler (FBK)), Alessio Bertolli (Fondazione Museo Civico di Rovereto), Chiara Bettega (Museo delle Scienze (MUSE)), Mattia Brambilla (Università di Milano), Maria Cristina Bruno (Fondazione Edmund Mach (FEM)), Marco Ciolli (Università di Trento - C3A), Antonella Contrini (Provincia Autonoma di Trento (PAT) - Agenzia Provinciale per le Risorse Idriche e l'Energia (APRIE), Nicola Curzel (PAT - Agenzia provinciale per la protezione dell'Ambiente (APPA), Carlo Detassis (PAT - Servizio politiche sviluppo rurale), Valentina D'Alonzo (EURAC research), Emanuele Eccel (FEM), Filippo Faccenda (FEM), Braian Farneti (FEM), Maurizio Fauri (Università di Trento - Dipartimento di Ingegneria Civile, Ambientale e Meccanica (DICAM)), Alessandra Gattolin (PAT - Unità di Missione STrategica (UMST) Agricoltura), Alberto Giacomoni (PAT - Servizio politiche sviluppo rurale), Raffaele Giaffreda (FBK), Lorenzo Giovannini (Università di Trento - DICAM), Mauro Gobbi (MUSE), Alessandro Gretter (FEM), Heidi C. Hauffe (FEM), Claudio Ioratti (FEM), Valeria Lencioni (MUSE), David Macii (Università di Trento - DII), Romano Masè (PAT - APPA), Catia Monauni (PAT - APPA), Andrea Mustoni (Parco Naturale Adamello Brenta), Ulrike Obertegger (FEM), Francesco Parrino (Università di Trento - Dipartimento di Ingegneria Indistriale (DII)), Erika Partel (FEM), Paolo Pedrini (MUSE), Ilaria Pertot (Università di Trento - DICAM), Sebastiano Piccolroaz (Università di Trento - DICAM), Filippo Prosser (Fondazione Museo Civico di Rovereto), Gregorio Rigotti (PAT - UMST Agricoltura), Paolo Rocca (Università di Trento - DII), Silvia Silvestri (FEM), Sara Stemberger (FBK), Stefano Terzi (EURAC), Monica Tolotti (FEM), Luca Tomasi (FEM), Michela Troggio (FEM), Sara Verones (PAT - APRIE), Diego Viesi (FBK), Roberto Zorer (FEM), Fabio Zottele (FEM), Nadia Zorzi (PAT - APRIE). The authors would like to thank all the other experts from DICAM, EURAC Research, FEM, FBK, PAT, APPA, APRIE, MUSE, Fondazione Museo Civico di Rovereto, Università di Padova, and C3A, who, though not necessarily specialists in the specific fields reported in this study, are experts in related areas (such as Snow, Glaciers, Permafrost, Risk, Air, and Agroecosystems). Their insightful discussions helped the authors gain a deeper understanding of the various topics and their interconnections.

Author contributions All authors contributed to the study conception and design. The review was performed by Anna Napoli. Anna Napoli wrote a first draft of the manuscript with the help of Michael Matiu, and all authors contributed to subsequent modifications that led to the final submitted version. All the authors approved the final version of the paper.

Funding Open access funding provided by Università degli Studi di Trento within the CRUI-CARE Agreement.
This research received financial support from the project "Sintesi degli studi sui cambiamenti climatici e i loro impatti ed elaborazione di scenari climatici di riferimento per il Trentino" funded by the Agency for Environmental Protection (Agenzia provinciale per la protezione dell'ambiente, APPA) of the Autonomous

Province of Trento, Italy. Anna Napoli has been supported by "Fondazione CARITRO" (Cassa di Risparmio di Trento e Rovereto) within Bando Post-Doc 2022 and 2023. This research acknowledges the Italian Ministry of Education, Universities and Research (MUR), in the framework of the project DICAM-EXC (Departments of Excellence 2023-2027, grant L232/2016). B. M., D. Z. and Alberto Bellin also acknowledge support from "iNEST (Interconnected Nord-Est Innovation Ecosystem)" project funded by the European Union under NextGenerationEU (PNRR, Mission 4.2, Investment 1.5, Project ID: ECS 00000043).

Data availability Not applicable

Code availability Not applicable

Declarations

Competing interests The authors have no competing interests to declare relevant to this article's content.

Ethics approval Not applicable

Consent to participate Not applicable

Consent for publication Not applicable

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