THE URGENT CALL FOR TANGIBLE ACTIONS TO ADAPT REGIONS TO CLIMATE CHANGE IMPACTS: THE EXAMPLE OF IMPETUS MOUNTAIN DEMONSTRATION SITE

VALENTINA D'ALONZO[1], VALENTINA M. CITTATI[1], ELEONORA LEONARDI[1],
SILVIA COCUCCIONI[2], LIZ J. OLAYA CALDERON[2], PETRA PAGLIUGHI[3],
MATTEO RIZZARI[3], GIORGIA ROBBIATI[4] & NICOLÒ FRANCESCHETTI[5]
[1]Eurac Research, Institute for Renewable Energy, Italy
[2]Eurac Research, Center for Climate Change and Transformation, Italy
[3]Eurac Research, Institute for Regional Development, Italy
[4]BIM Sarca-Mincio-Garda, Italy
[5]Waterjade s.r.l., Italy

ABSTRACT

The IMPETUS project, funded in the EU Horizon 2020 Green Deal call has, as a main objective, to turn climate commitments into tangible actions developing and validating multi-level and cross-sectoral solutions for climate change adaptation. The project aims at building communities of local stakeholders able to support strategic decision-making processes within the seven project demonstration sites. A key element of the project is the combination of digital and human dimensions to implement durable adaptation pathways that can also be replicated in similar biogeographical regions. Valle dei Laghi (located in the Italian Alps) represents the mountainous biogeographical region. In this valley, climate change is generating water stress where water resources have been typically abundant, as water scarcity is recently identified as the more urgent climate risk. Different adaptation solutions are being developed in the area, which will be described in the paper focusing on the preliminary results and the stakeholders' engagement process: (1) Apply impact chains approach to break down risks into exposure, vulnerability, and climate hazard factors, pinpointing in which field adaptation measures need to be taken. (2) Identify and exploit the interconnected intangible and tangible components of cultural heritage that are an essential part of local identities and shared values, to detect triggers of behavioural change that can be applied in innovative climate change adaptation pathways. (3) Collaboration with insurance stakeholders for know-how and knowledge sharing to identify the best indices and forecast models that can support risk analysis and management for selected crops. (4) Development of a decision support system for improving the management of water under concurrent uses; this tool will allow better handling of conflicts among concurrent water users, i.e., energy production, human consumption, and irrigation. All these adaptation solutions will be implemented to foster and increase local authorities' and community's awareness and adaptive capacity.

Keywords: climate change adaptation, climate resilience, stakeholder engagement, decision-support tools.

1 INTRODUCTION

Human-caused climate change is an urgent global issue. In 2023, the IPCC reported that global surface temperatures reached 1.1°C above 1850–1900 levels in 2011–2020 due mainly to the continuous release of greenhouse gases in the atmosphere. This, together with 'unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production across regions' [1], is causing several impacts on nature and people. Physical water availability, agriculture/crop production, and key economic sectors are just a few of those fields that are damaged and will worsen in the future, considering that adverse impacts from human-caused climate change will intensify over time. The more time

www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/SDP240751

passes, the more urgent it becomes to address the effects of climate change and prevent future generations from experiencing a world in which it will be more challenging to live.

At the European level, the Green Deal commits European countries to reach an economic and social carbon-free system or climate neutrality by the year 2050. This means encouraging investments in renewable energy technology, renovation of buildings, sustainable industry, agriculture, and mobility, and protecting biodiversity, among others. As part of the European Green Deal, starting in 2023, the Fit for 55 package aims to reduce European gas emissions by 55% by 2030. The scientific community is engaged in designing projects to effectively and immediately address climate change effects. Different measures are needed to mitigate and adapt to the impacts of climate change, considering that they will aggravate existing regional differences [1], causing various consequences depending on the geographical features and potential (social) conflicts.

In line with the attempt to meet the IPCC and Green Deal principles, the Horizon 2020 project IMPETUS (https://climate-impetus.eu/) aims to design an adaptation framework for supporting European regions toward a climate-neutral and sustainable economy. In particular, it intends to merge human and technological dimensions by promoting (a) a co-creation and co-design of climate-resilient adaptation solutions with relevant quintuple helix stakeholders; (b) a stakeholder engagement process to create a community through the so-called resilience knowledge boosters (RKBs); (c) a data collection to support decision and policymaking on suitable adaptation solutions. Moreover, the project uses qualitative and quantitative data to improve territorial governance towards a coordinated action to reduce climate change and its extreme effects. Thus, it aims to produce innovation packages for each demonstration site (DS) with risk assessment and cost–benefit analyses, guidelines on implementing and deploying RKBs, economic and social frameworks, and adaptation pathways with primary policy responses and solutions.

The DSs that will benefit from the innovation packages and adaptation pathways are seven European biogeographical regions involved in the project, namely continental (Germany), coastal (Spain), Mediterranean (Greece), Atlantic (The Netherlands), Arctic (Norway), boreal (Latvia) and mountainous (Italy).

This paper focuses on the latter region, specifically the mountain area of Valle dei Laghi, located within the Trento Province in northern Italy. It presents the ongoing activities that local partners are carrying on, namely Eurac Research, BIM Sarca-Mincio-Garda, and Waterjade s.r.l., designed on its mountain region’s features.

Among the ecosystems impacted by climate change effects, mountain areas are expected to be subjected to significant changes and mass loss of large glaciers by the end of the century [2]. Moreover, high mountains are also experiencing a reduction in snow cover [3] and migration of animals and plant species from their original habitats [4], [5]. As mountain elements and resources run low, transformations also jeopardize downstream regions, impacting other sectors such as water availability, tourism, and agricultural production [6]. This situation leads humans and ecosystems of worldwide mountain areas to adjust according to climate change impacts with practical solutions. For instance, Georgia decided to revitalize ancient wines whose deep roots would prevent land erosion and the increased risk of landslides. At the same time, Rwanda restored forests and biodiversity and introduced silvopastoral approaches to reduce climate change pressure on lands and the overexploitation of natural resources [7].

In European mountain areas, some suggested changing cropping systems and cultivation cycles and shifting vineyard altitude to cope with profound alterations in temperature and ecosystems [8]. Others highlighted the importance of developing new irrigation systems to support plant cultivation in high-latitude conditions [9]. However, the importance of dealing with human adaptation and, particularly, investigating governance, decision-making, and decision-support tools when addressing climate change effects and extreme events has been pointed out as well.

The following sections explain in detail the mountain DS of Valle dei Laghi (Italy) by presenting the main climate issue(s) addressed locally, the method/approach applied, and the stakeholder engagement process. Finally, a section shows the preliminary results and their potential transferability/replicability on other mountain regions.

2 MOUNTAIN DEMONSTRATION SITE

The Valle dei Laghi area is located within the province of Trento in the Italian Alps. The area has an abundant water supply and a very fragmented population, with small villages and municipalities with less than 5,000 inhabitants. Agriculture and food production (in particular, wine production), hydropower production, forestry for wood fuel and slow tourism are the main economic activities (Fig. 1).

Figure 1: Picture of the Valle dei Laghi area and its location within the Italian Alps. *(Source: Photo credit: LeDo lab. Map: Eurac on OpenStreetMap.)*

The Alps, and mountains in general, are recognised hotspots for climate change, with temperatures rising far beyond the average and more frequent extreme weather events. Also, in the Valle dei Laghi area, recent rapid climate change impacts are leading to the increase of conflicts in water and land usage. For this reason, within the IMPETUS project, local partners are seeking to promote participatory approaches in decision-making to ensure a rapid transition to sustainable and integrated water management, biodiversity conservation, and disaster risk reduction.

In the mountain DS, ambitious goals have been set for climate change adaptation and climate resilience increase, namely:

- Harmonise and build on existing solutions and initiatives to develop a multi-sectorial/ multi-systems innovation package for the region.
- Ensure local community 'ownership' of risk management solutions integrating risk analyses and management approaches with participation, communication, and co-creation.
- Setting the stage for a network of citizens and stakeholders for their long-term participation in the decision-making process.

- Demonstrate and test the developed solutions for wider uptake at provincial and higher levels as part of the Strategy for Climate Change Mitigation and Adaptation of the Province of Trento.
- Promote adaptation solutions uptake and transfer to other mountain communities engaging with national and international stakeholders.

3 ADAPTATION SOLUTIONS UNDER DEVELOPMENT

Different adaptation solutions are being developed in the area, which will be described in the following subsections focusing on the preliminary results and the stakeholders' engagement process:

- Combine impact chains and rapid risk appraisal methods, to break down risks into exposure, vulnerability, and climate hazard factors, pinpointing which field adaptation measures need to be taken (Section 3.1).
- Identify and exploit the interconnected intangible and tangible components of cultural heritage (CH) that are an essential part of local identities and shared values, to detect triggers of behavioural change that can be applied in innovative climate change adaptation pathways (Section 3.2).
- Collaboration with relevant insurance stakeholders for know-how and knowledge sharing to identify the best indices (climatic and non-climatic) and forecast models that can support drought risk analysis and management for selected crops (Section 3.3).
- Develop a decision support system (DSS) for improving the management of water under concurrent uses. This tool will allow better handling of conflicts among concurrent water users, i.e., energy production, human consumption, and irrigation (Section 3.4).

3.1 Improving integrated climate risk assessment and management through participatory approaches

Impact chains are conceptual models for risk assessment aimed at identifying and mapping out the causal relationships among various factors and processes contributing to specific climate-related risks [10]. Impact chains are based on the IPCC definition of risk and, therefore, encompass the key elements of hazards, vulnerabilities, and exposure, while also considering the cascading effects that occur as intermediate impacts. While the relationship between hazards and their resulting impacts is often clear and observable (e.g., heavy rainfall causing floods, leading to property damage), factors related to vulnerability and exposure are typically intricate, highly dependent on specific contexts, and often more difficult to quantify. Vulnerability encompasses a broad spectrum of factors, ranging from physical and ecological aspects to technical and institutional measures or capacities, such as the absence of flood-resistant infrastructure and inadequate urban planning. Exposure factors, on the other hand, refer to the presence, quantity, or density of assets and livelihoods that could potentially be affected by a given hazard. Impact chains are usually developed in a participatory process but can also be enhanced and improved through desk-based research. The final goal of impact chain development is identifying the entry points for improved risk management and climate change adaptation measures.

The development of impact chains is a collaborative effort involving stakeholders and experts, aiming to construct a shared understanding of the underlying causes of climate risks within a specific setting. This participatory approach facilitates the incorporation of local data and insights, ensuring that the impact chains accurately reflect the unique circumstances of the region or sector under consideration. Within IMPETUS, the mountain DS team conducted

www.witpress.com, ISSN 1743-3541 (on-line)

two half-day workshops with local stakeholders in May 2023, focusing on the agricultural sector (viticulture) and the built environment. 11 and 13 stakeholders took part in the workshop, respectively, covering different expertise and phases of risk management. Moreover, in 2024 interviews with local agricultural stakeholders were used to improve the viticulture impact chain, specifically to add missing vulnerability factors.

Thanks to the inputs of the two workshops, the main perceived hazards, direct and indirect impacts for both agriculture (mainly focusing on vineyards) and the built environment were identified, and two impact chains were developed. In particular, the main impacts related to the agriculture sector can be clustered into two groups: (i) those connected to water scarcity and to the resulting conflicts among different sectors that require water resources; and (ii) those connected to the reduction in quality and quantity of grapes and wine (e.g., due to a decrease in acidity), indirectly leading to an economic loss. The impact chain regarded the risk of loss of quality for wine products as a result of changes in wind patterns, temperatures, and hail.

On the other hand, the main impacts related to the built environment were connected to (i) physical damages to part of the buildings (e.g., roofs, facades, windows) or an increase of discomfort caused by extreme events; and (ii) the scarcity of water (e.g., for drinking purposes) or its opposite, the presence of too much water leading to pluvial flooding and to problems with the drainage system. The second impact chain focused on the risk of discomfort and increased costs for afterwar buildings due to heatwaves.

Subsequently, the impact chains have been built in Kumu (https://kumu.io, proprietary, commercial), a structured environment where the visual representation is supported by a table repository so that all elements and connections are systematically stored and can easily be accessed through the website.

The impact chain approach can be applied for risk assessment in any area and at different scales. In the future, the approach will be indeed replicated in the Carpathians in an area with similar characteristics to identify entry points for adaptation and foster knowledge transfer.

3.2 Activating CH to enhance climate resilience

Climate change is increasingly threatening territorial CH leading to the occurrence of adverse phenomena. The main relevant ones identified by local citizens and professionals of Valle dei Laghi are heatwaves, frost, water scarcity, extreme hailstorms, increased extreme rainfall events, and increased pathogens in agriculture. Among the consequences of these phenomena on the primary economic sector are an earlier general harvest, imbalances in the nutrients of the products, total or partial damage to crops, vineyards, and agricultural products with consequent partial or total loss of production and harvest, and finally, a general increase in hydrogeological instability. Climate change has a high impact also on the historical built environment – as a CH component. Temperature increases and heat waves result in overheating and the need for cooling systems for buildings. Increased extreme rainfall events may cause quicker building material degradation and issues with the hygrothermal behaviour of walls. Several studies have shown the importance of taking into consideration future climate scenarios for building retrofit strategies (e.g., Tootkaboni et al. [11], Bamdad et al. [12]). The adaptation and mitigation solutions undertaken to cope with these effects are the result of a process of connivance between tradition and innovation. Traditional knowledge is the basis upon which the help derived from innovative and technological tools is based, showing how CH is a process of continuous evolution.

In IMPETUS, the research methods used focused on one side on semi-structured qualitative interviews and a qualitative survey to investigate (i) the connection of people with local CH; (ii) the perceptions of the effects of climate change in one's area of profession or life and, at the same time; and (iii) the perception of the need to find adaptation solutions for safeguarding CH. The interviewed target groups include local stakeholders from farms, local winemaking industries, local agricultural and sectoral associations, representatives of local institutions, and citizens of the Valle dei Laghi DS. Among the results that emerged from the research conducted, there is widespread concern about the possible effects of climate change on local CH, particularly towards a probable future worsening. Citizens and local businesses are proving to be informed and interested in understanding the effects of climate change, and actively involved in supporting adaptation solutions. There is a widespread desire for greater participation and support from central institutions to implement adaptation measures more effectively, supporting small businesses and small municipalities economically and organizationally in dealing with emergencies.

On the side of the historical built environment, the first step has been the examination of the building stock across the various municipalities within the DS. This allows the recognition of recurring patterns in configuration and construction. Based on this analysis, the first representative building of the valley has been chosen: a residential building built in the first years of 1700 and presenting typical construction methods: stone walls, vaults in the cellar, wooden roof, attic round openings that were used to dry cereals. To propose useful adaptation strategies, building hygrothermal simulations are carried out. In the simulations geometry, building component stratigraphy, external climate, internal loads, and heating system are given as inputs and internal climate and energy are the outputs. This enables us to analyse the internal comfort and the energy consumption. These simulations are going to be carried out on two reference buildings (the second one is under selection) using the previous (original building envelope, original geometry, and original occupation) and current layout (including refurbishment and modifications in recent years) for the past and future climate (near future: 2050–2059 and far future: 2090–2099 for three scenarios based on the carbon pathways RCP 2.6, RCP 4.5 and RCP 8.5). Based on these results, some adaptation measures are going to be proposed and subsequently quantified through further simulations.

With respect to the possible adaptation solutions adopted in the agricultural and territorial field, the following emerge: (a) the tendency to move vineyards to higher altitudes to limit the effects of climate change; (b) the use of technological tools to monitor plant health and water stress; (c) the use of traditional anti-frost tools (even if they are still not very widespread in the Trentino area, while they are better known in neighbouring provincial areas); (d) the use of anti-hail nets to prevent damage and loss of crops; (e) the recovery of ancient irrigation canals to help the outflow of excess water and, at the same time, the orientation towards the construction of water collection and storage plants and the evaluation of methods for the efficient redistribution of water; (f) territorial planning that considers the recovery of abandoned terraces to favour agriculture, greenery, biodiversity, and to stem hydrogeological instability; and finally, (g) the evaluation and experimentation of resistant species in agriculture to be flanked by the varieties already present, to try to contain fungi and pathogens.

As said, climate change strongly influences the historical built environment, affecting energy demand and inhabitants' comfort. To meet the requirements of minimizing consumption and maximizing comfort in the future, renovation measures must be investigated with future climate, too. The main problems identified so far are the increased risk of summer overheating and the increased effect of driving rain. For this reason, measures such as shading, improvement of natural ventilation, and implementation of driving rain protection strategies should be considered within a renovation. However, some beneficial measures for the summer may increase winter energy demand. Studies show that the benefits of reduction of overheating in summer exceed the increase of winter energy demand in future climates [13].

The research approach used for historical building stock analysis can be transferred not only to the whole Trento province but also to other mountainous areas. Renovation measures must be developed taking into consideration climate change; only in this way the renovation will minimize energy consumption and maximize inhabitants' comfort also in the next years, resulting in saving of resources and materials. Similarly, the transferability of traditional knowledge and technical choices in agriculture adopted in Valle dei Laghi has proven to be exportable to other mountainous (and not) areas. Some of this knowledge has already been applied or is being applied in other contexts, as shown by terracing use in agriculture or traditional irrigation methods. Moreover, also the most innovative ones are easily exportable, as evidenced by the widespread interest in resistant varieties in several European regions, thus proving the universal value of CH.

3.3 Knowledge sharing to support risk analysis and management for selected crop

Insurance for the agricultural sector addresses a range of climate hazards that threaten farmers' livelihoods and food security. Within IMPETUS, the main climate hazard under consideration is water scarcity, as this is increasing competition over water resources, constituting one of the pivotal future risks for the Valle dei Laghi area. In particular, when it comes to grapevines, a prolonged decrease in water supply may lead to significantly lower grape yields, alteration in the sugar content and acidity as well as a general decline in the quality of the final product. Other climate hazards particularly compelling for the case study are extreme storms, hailstorms, and frosts. Whereas the formers can lead to significant direct physical damage and cause financial hardship due to the loss of crops, the latter can impact newly formed buds in the earlier stages of plant growth.

A literature review has been developed on the main insurance approaches to address the impacts of climate-related hazards on agriculture, especially concerning new forms of index-based insurance, the economic assessment of insurance performance, the combination of insurance with active protection strategies (such as hail nets), and a focus on grapevine phenology to evaluate the vulnerability of the wine-making sector to climate hazards. Furthermore, it has been analysed a dataset on losses and damages in agriculture caused by climate hazards. The data, provided by a local insurance company, is focused on northern Italy including Trento province, and covers the period from 2013 to 2022. This analysis aims to understand the spatial and temporal distribution of the impacts mentioned above and connect them with climate data. It will also identify patterns in the spatial distribution of damage and the influence of mitigation reduction measures taken to reduce losses. The results of these analyses will enhance the understanding of the climate impacts on agriculture in the region and provide insights into leveraging the insurance mechanisms by integrating climate data, moving towards parametric insurance.

Two types of stakeholders have been involved in this task. First, local agricultural consortia, whose activities are geared towards the active and passive defence of production (fruit, wine, olives, etc.) by registered members against damage caused by extreme events. They have taken part in thematic workshops as well as in a round of interviews to assess local governance structures. Secondly, the collaboration with a local insurance firm has been established for analysing data coming from insurance contracts and premiums to assess the impact of climate hazards in agriculture.

The analysis of the local insurance dataset focuses on a specific geographical and temporal scope, allowing for replication of similar analysis in the region. The use of statistical code to examine losses and damages in agriculture caused by climate-related hazards makes the analysis transferable. The goal is to link this data consistently with the climate data through a replicable method. Moreover, identifying spatial patterns and assessing mitigation measures for risk reduction may also apply to other areas. However, it is important to acknowledge that climate conditions, agricultural practices, and data collection methods for insurance vary across different regions. Therefore, the transferability of these analytical methods should be tailored to specific contexts.

3.4 DSS for the sustainable and integrated management of regional water resource

As previously mentioned, the primary climate challenges in the Valle dei Laghi DS are water scarcity and the increasing frequency of extreme storms. To tackle these issues, a more sustainable and integrated approach to water management across various uses (agriculture, drinking water, water retention in reservoirs, and urban areas) is essential. The primary focus is on agricultural water use, particularly for vineyards, as wine production is a significant economic activity in the region. In this context, specific project activities are being undertaken to develop a DSS to address these challenges and improve water management across concurrent uses, especially in agriculture, hydropower generation, and drinking water.

The DSS being developed utilizes customized hydrological models to accurately adapt to the complexities of mountain environments. It incorporates seasonal and climate projection scale operational climate services, considering climate variability and decadal climate change projections. This hydrological model leverages local-scale and satellite data, seasonal forecasts, and climate projections from Copernicus and project partners. By integrating machine learning and multi-criteria analysis, the DSS aims to support comprehensive water resource management plans in the target area where the anthropic effect is important (hydroelectricity, irrigation consortia). It is informed by projected long-term trends, enabling the creation of medium and long-term strategies for smart irrigation, ecosystem protection, and hydropower plant upgrades. The intended users of the DSS are local and provincial water management entities, such as provincial administrations and irrigation consortia.

Various stakeholder engagement activities are being conducted to co-create this tool with potential users and local stakeholders. In February 2023, the first workshop aimed to (i) enhance understanding of the current provincial decision-making process for managing water scarcity, facilitating the identification of issues in information flow; and (ii) gather insights for defining the DSS as an operational tool, including its features, potential users, and existing gaps. In April 2023, a second workshop focused on farmers and irrigation consortia, given the importance of agriculture in the DS area. This workshop aimed to (i) improve understanding of critical issues in irrigation water management and encourage the sharing of proposals to address these shortcomings; (ii) identify training needs from irrigation consortia for future activities; (iii) facilitate discussions among different stakeholders involved in irrigation water management at the valley level, such as local authorities and irrigation consortia; and (iv) raise awareness about efficient irrigation water use during water scarcity, offering tips and tools to improve irrigation techniques and soil water retention capacity. In December 2023, a third stakeholder workshop was held to present and test a mock-up of the river basin digital twin. During this interactive session, participants provided feedback on the usability of the tool, which will serve as the back-end of the DSS to support water management decision-making processes. Between these formal events, numerous bilateral and smaller meetings were held with various DS administrations and irrigation consortia. Notably, the April workshop spurred local irrigation consortia to initiate new projects and collaborations. Discussions focused on specific short-term adaptation measures, such as implementing monitoring systems, soil mapping, and recording consumption costs. There was strong support for enhancing the monitoring process to promote more sustainable water management in agriculture. As a result of these discussions, two additional meetings were held within the irrigation consortia to launch a joint project and establish new irrigation grants and licenses.

According to the feedback collected during the last workshop (December 2023) from the potential users of the tool, the digital twin structure has been revised and updated and now is under a validation process. Several new functions requested by the stakeholders are going to be implemented when the new structure is ready. From the feedback received, it was also possible to define the main user requirements, especially concerning the functionality to be implemented in the DSS. These functionalities will be developed and tested, again thanks to the interaction with stakeholders, in the coming months of development. In the meantime, the front-end interface is going to be developed and the connection between digital twin and the visualization dashboard is under discussion among DS partners.

The modular structure of the hydrological model and the flexibility provided by using different data sources allow the model to be reused in other areas with little effort. Some work remains to be done in terms of model calibration, which must in any case be carried out by specialized technicians. For what concerns the proposed approach, it is highly replicable in other mountainous regions where water management is affected by issues due to climate change and where the main water usages are irrigation, energy production, and drinking use. Moreover, the application of the hydrological forecasting model to the Valle dei Laghi DS represents an innovative adaptation solution addressing water scarcity in the agricultural sector; it can be transferred to the whole provincial context and has a high potential of replicability on a local, regional and alpine scale.

4 CONCLUSIONS AND OUTLOOK

The previously mentioned adaptation solutions will be incorporated into the development of alternative adaptation pathways for the Valle dei Laghi area. These pathways consist of a sequence of adaptation measures that can be progressively implemented to address various impacts of climate change, based on future climate developments. Initially conceptualized with diverse approaches and contexts at both local and regional scales, adaptation pathways have evolved significantly. They are now increasingly recognised as tools to promote transformative approaches to adaptation and to support stakeholder engagement in the decision-making process [14].

Within the IMPETUS project, each DS is setting specific objectives, performance metrics, thresholds, and strategies to manage the uncertainties caused by climate change. They will assess adaptation tipping points under increasing emission scenarios to design a corresponding series of adaptation measures. This process involves collaborative work with DS partners who are implementing adaptation solutions across various biogeographical regions of Europe. Additionally, all activities depend on stakeholder engagement to ensure that adaptation pathways are developed through a co-creation approach. For the Valle dei Laghi DS the main objective of the adaptation pathway to be developed is the increase of efficiency in usage and storage of water, in particular for agriculture and aquifer recharge.

ACKNOWLEDGEMENTS

The IMPETUS project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Grant Agreement No 101037084.

REFERENCES

[1] IPCC, Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Core Writing Team: H. Lee & J. Romero (eds)). IPCC: Geneva, Switzerland, 184 pp, 2023. https://doi.org/10.59327/IPCC/AR6-9789291691647.

[2] Beniston, M. et al., The European Mountain cryosphere: A review of its current state, trends, and future challenges. *Cryosphere*, **12**(2), pp. 759–794, 2018.

[3] Diaz, H.F., Eischeid, J.K., Duncan, C. & Bradley, R.S., Variability of freezing levels, melting season indicators, and snow cover for selected high-elevation and continental regions in the last 50 years. *Climatic Change*, **59**, pp. 33–52, 2003.

[4] Engler, R. et al., 21st century climate change threatens mountain flora unequally across Europe. *Global Change Biology*, **17**(7), pp. 2330–2341, 2011.

[5] Freeman, B.G., Lee-Yaw, J.A., Sunday, J.M. & Hargreaves, A.L., Expanding, shifting and shrinking: The impact of global warming on species' elevational distributions. *Global Ecology and Biogeography*, **27**(8), pp. 1268–1276, 2018.

[6] Hock, R. et al., High mountain areas. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, Cambridge University Press: Cambridge, pp. 131–202, 2019.

[7] UN Environment Programme, Mountain adaptation solutions: Turning challenges into opportunities. UNEP, 2022. https://www.unep.org/news-and-stories/story/mountain-adaptation-solutions-turning-challenges-opportunities. Accessed on: 22 Apr. 2022.

[8] Pérez, FL., Viticultural practices in Jumilla (Murcia, Spain): A case study of agriculture and adaptation to natural landscape processes in a variable and changing climate. *AIMS Agriculture and Food*, **1**, pp. 265–293, 2016.

[9] Peltonen-Sainio, P., Jauhiainen, L., Palosuo, T., Hakala, K. & Ruosteenoja, K., Rainfed crop production challenges under European high-latitude conditions. *Regional Environmental Change*, **16**(5), pp. 1521–1533, 2016.

[10] Zebisch, M., Terzi, S., Pittore, M., Renner, K. & Schneiderbauer, S., Climate impact chains: A conceptual modelling approach for climate risk assessment in the context of adaptation planning. *Climate Adaptation Modelling*, eds C. Kondrup, et al., pp. 217–224. Springer: Cham, 2022.

[11] Tootkaboni, M.P., Ballarini, I. & Corrado, V., Analysing the future energy performance of residential buildings in the most populated Italian climatic zone: A study of climate change impacts. *Energy Reports*, **7**, pp. 8548–8560, 2021.

[12] Bamdad, K., Cholette, M.E., Omrani, S. & Bell, J., Future energy-optimised buildings: Addressing the impact of climate change on buildings. *Energy and Buildings*, **231**, 110610, 2021.

[13] Liyanage, D.R., Hewage, K., Hussain, S.A., Razi, F. & Sadiq, R., Climate adaptation of existing buildings: A critical review on planning energy retrofit strategies for future climate. *Renewable and Sustainable Energy Reviews*, **199**, 114476, 2024.

[14] Werners, S.E., Wise, R.M., Butler, J.R.A., Totin, E. & Vincent, K., Adaptation pathways: A review of approaches and a learning framework. *Environmental Science and Policy*, **116**, pp. 266–275, 2021.