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Socio-Ecological Systems for Sustainable Management in Mountain Areas: A Case Study in the Italian Alps

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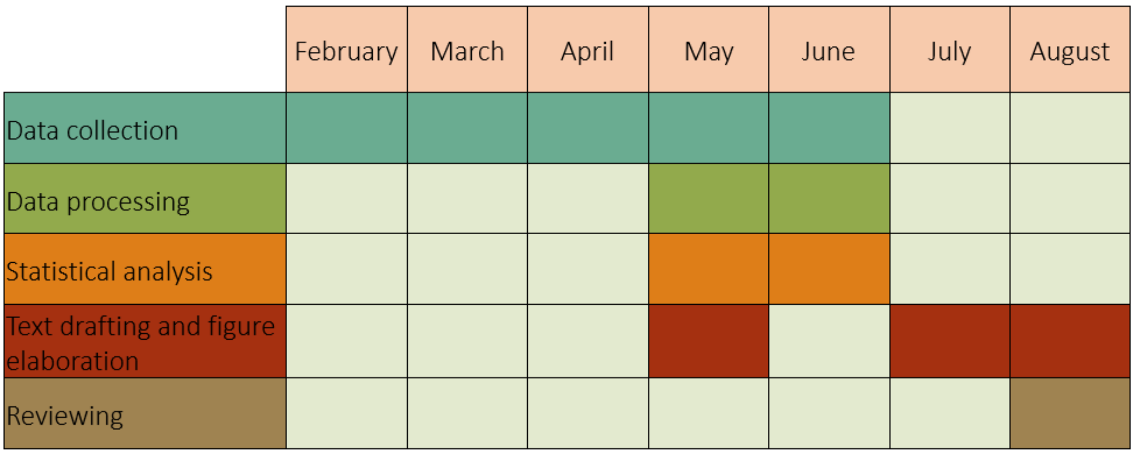

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Socio-Ecological Systems for Sustainable Management in Mountain Areas: A Case Study in the Italian Alps

Abstract

Mountains are highly complex systems exposed to multiple environmental and socioeconomic drivers and are thus better comprehended as Social-Ecological Systems (SES). We used piecewise structural equation modelling to quantitatively describe the interplay between water resources, biodiversity and human communities in the Lombardy region (Italian Alps). Our results show that (1) the current economic dynamics are characterized by the ongoing tertiarization and marginalization of traditional agriculture, and that (2) they severely impact water resources and biodiversity. Climate change scenarios will probably aggravate the pressures on the hydrological system and threaten the sustainability of winter tourism. We suggest that efforts to effectively promote employment in agriculture and to stimulate all-year-round tourism could help distribute the economic wealth among sectors and diminish external dependencies, as well as alleviate the pressures on water and biodiversity. Our findings highlight the importance of studying social and ecological factors holistically to improve sustainable resource management and the adequacy of applying a SES approach to the study of mountain ecosystems.

Keywords: *Social-Ecological Systems; mountain areas; climate change; sustainable resource management; biodiversity conservation*

1. Introduction

In the past century, significant ecological changes governed by climate have occurred in mountain ecosystems worldwide (Beniston et al. 1996). High mountain areas are possibly among the regions most affected by climate change (Beniston et al. 2018). Climate change in these locations impose additional stress on biota, which also suffers impacts derived from land use changes, direct exploitation, and pollutants (IPBES 2019). Climate change scenarios assuming a global temperature increase of 1.5ºC relative to pre-industrial levels, which have already occurred in some mountain ranges, estimate significant impacts on species abundance, community structure, and ecosystem functioning in high mountain areas (Hoegh-Guldberg et al. 2018).

The functioning of mountain ecosystems is vital for the provision of ecosystem services important to human communities within, nearby, and at a distance from mountainous regions. One of the most crucial ecosystem services is the availability and quality of water. Mountains have been referred to as the "water towers of the world" (Immerzeel et al. 2020). Variations in water supply has serious consequences for both downstream communities and the high mountain areas themselves. For instance, simulation results from a study in the Austrian Alps show that exceptionally warm and dry summers reduce groundwater recharge, thus decreasing its availability for human consumption (Vanham et al. 2009).

Mountain ecosystems are also considered biodiversity hotspots, as they harbour a great diversity of endemic, rare, and threatened species (Payne et al. 2020). In fact, mountain regions comprise nearly 30% of the terrestrial areas identified as Key Biodiversity Areas (KBAs), and a significant proportion of these areas are protected (Rodríguez-Rodríguez et al. 2011).

Another major change occurring in mountain ecosystems is the retreat of large glaciers and alterations in the cryosphere. The presence of snow, glaciers, and permafrost generally exerts strict control over the quantity, type, and biogeochemical properties of water flowing in mountainous areas (Hock et al. 2019). Changes in the cryosphere not only disrupt the availability of water for human consumption, but also affect other provisioning and regulatory services.

Alongside these ecological changes, mountain areas have undergone significant socio-economic transformations in recent decades. Following the gradual decline of traditional agricultural practices in the 20th century (Streifeneder et al. 2007; Schirpke et al. 2022), the past decades have witnessed a dramatic population decline (Bender and Kanitscheider 2012) and an increasing dependence on the tourism sector (Romeo et al. 2021). The agricultural sector has also undergone profound changes, from land abandonment to intensified production, resulting in severe social, economic, and ecological impacts. To adapt to such profound changes, mountain territories and the communities inhabiting them are undergoing a process of reorganization in multiple dimensions.

Since mountains are complex systems where multiple dimensions (social, ecological, and economic) are closely interconnected, an interdisciplinary approach is required to address the challenges of these territories. In this context, approaches such as Social-Ecological Systems (SES) are particularly useful as they allow for the integration of social and ecological perspectives. They provide a comprehensive understanding of the interactions between human communities and nature, as well as the drivers influencing them, within a common framework (Ostrom 2009; Virapongse et al. 2016). However, most studies using this approach tend to prioritize social variables over ecological ones, without achieving the necessary interdisciplinary integration. Rissman and Gillon (2017) showed that studies that incorporate the socio-economic and ecological dimensions are twice as likely to provide management recommendations compared to those that do not achieve this integration. Therefore, considering both dimensions is crucial for designing effective strategies for sustainable development.

Despite the great amount of research devoted to the Alps, studies that explore the relationships among socioeconomic and ecological elements in a socio-ecological context, are still missing. Hence, extending the research done in the Pyrenees by Zango et al. (under revision.*)*, we focus on the Lombardy region of the Italian Alps with the intention of analysing the interplay among social-ecological elements, aiming to understand the complexity of the current functioning of this mountain SES. By integrating socio-economic and ecological variables within a unified framework, our goal is to examine how changes in one variable can concurrently affect other variables through direct and indirect pathways, consequently impacting resource availability and system functioning.

Objectives

Through this integrated approach, we seek to elucidate the interconnections and mutual influences of these social-ecological variables and provide recommendations for potential adaptation strategies towards sustainable regional development. We aim at answering the following questions: (Q1) What is the primary economic focus of the region?; (Q2) How does the current economic structure influence water resources and biodiversity?; and (Q3) How are environmental variables link to the system and what do they represent?

2. Methods

2.1 Study area

The study area comprises two mountainous provinces in the Italian Alps in the Lombardy region, Brescia and Sondrio. Collectively, these provinces cover an area of ca. 7982 km^2. The region is home to five large alpine lakes (*Lago di Garda*, *Lago di Como*, *Lago d'Iseo*, *Lago d'Idro* and *Lago Maggiore*), that serve multiple purposes, including water consumption, recreational activities, and hydroelectric power generation (Enti regolatori dei grandi laghi 2023). The area is traversed by a network of rivers. The Adda and Como rivers are the most important ones in the Sondrio region, while in Brescia, it is the Chiese, Mella and Oglio rivers that hold the greatest importance. Additionally, the area includes several small alpine glaciers that have gradually decreased in size, such as the Ventina Glacier (Agenzia Regionalle per a la Protezione dell'Ambiente 2023).

The population in the region, especially in high mountain areas, has declined in recent decades, with people migrating to more industrialized areas at lower altitudes. The influx of immigrants, motivated by the thriving mountain tourism industry, serves as the primary factor mitigating the trend of depopulation (Bender and Kanitscheider 2012).

2.2 Elements of the Social-Ecological System

We employed the social-ecological framework developed by Elinor Ostrom (Ostrom 2009) to explore and organize the elements of our Social-Ecological System. This systematic selection of elements to study allows for targeted information gathering, ensuring that relevant components of the system are not overlooked (Delgado-Serrano and Ramos 2015).

Once the system elements were identified, an extensive search was conducted in public and private databases to obtain hydrological, climatic, ecological, land-use, and remote sensing variables, as well as socio-economic variables specific to the study area (see Appendix A – Data source and processing and Appendix B – Missing data imputation). This resulted in a total of 38 variables measured annually over a 22-year period, from 2000 to 2021 (Table 1).

2.3 Building the social-ecological network

First, we conceptualized a network structure using our 38 variables, hypothesizing a total of 72 possible relationships. We employed Structural Equation Modeling (SEM) to statistically test the hypothesized relationships, using the *piecewiseSEM* package (Lefcheck 2016) in the R software. This statistical technique utilizes path analysis, allowing for the incorporation of multiple variables and their relationships in the analysis. This enables us to construct a comprehensive network of connections and test the multiple hypotheses proposed all at once.

Furthermore, since in this type of analysis, variables within the network can act as both predictors and responses, it allows the quantification of both direct and indirect effects. A significant benefit of using piecewiseSEM compared to classical SEM is that it is based on local (rather than global) estimation (Lefcheck 2016), which provides great flexibility and power to the analysis (e.g., by enabling the specification of models with non-normal responses).

We specified and tested 23 individual models, one for each response variable (see Appendix C – Model Evaluation and Table C1 y Table C2*).* To test if our data fit the hypothesized network configuration, all the individual models for each response variable were joined into a single global model using the function *psem()* from the *piecewiseSEM* package (version 1.2.1). A d-separation test was run to find correlations among variables that were unaccounted for. Correlations that could have a potential causal link were included in the individual models when: 1) the model assumptions remained unaffected; 2) the model fit improved. All remaining relationships were specified as correlated errors in the model. Goodness of fit of the global SEM model was assessed using the test of directed separation using Fisher's C statistic and its associated p-value.

Due to the disparity in units and ranges between all included variables, the standardized estimates for each pairwise relationship from the model were used to create a matrix encompassing all interaction coefficients (Table 2). A quantitative social-ecological network depicting the relationships among all variables in our SES was represented using the *igraph* package (Csardi and Nepusz 2005) and edited using Adobe Photoshop WhiteRabbit for better visual appearance (Figure 1).

3. Results

We obtained a good fit between the data and the hypothesized network of relationships (Fisher's C statistic = 893.59, AICc = 840.441, df = 980, p-value = 0.977, with 490 independent claims). Out of 72 hypothesized relationships, 43 were significant (p-value < 0.05) and 7 were marginally significant (p-value < 0.1) (Table 2, Figure 1). Parameter estimates for all the individual hypothesized relationships, as well as model specifications for linear, generalized linear, and generalized least square models, can be found in Table C1 and Table C2 of Appendix C, respectively.

(Q1) What is the primary economic focus of the region?

Total GDP is heavily influenced by the *services GDP* (coefficient = 1.06, p-value <0.01), while *agriculture GDP* does not have a significant effect on it (coefficient = 0.14, p-value = 0.69). In turn, *services GDP* depends on *occupation in services* (coefficient = 0.22, p-value = 0.02) and on *second homes* (coefficient = 0.95, p-value = 0.03), whereas it is not directly affected by *tourism establishments* (coefficient = 3.07e-5, p-value = 0.97).

On the other hand, *agriculture GDP* relies primarily on *agriculture production* (coefficient = 0.96, p-value <0.01) and has in fact a negative relationship with *agriculture occupation* (coefficient = -0.20, p-value <0.01). The latter shows a negative relationship both with *agriculture salary* and *agriculture subsidies* (coefficient = -0.49, p-value = 0.03 and coefficient = -0.37, p-value = 0.08, respectively).

Services occupation is positively influenced by *total population* (coefficient = 8.87e-06, p-value = 0.01) and *tourism establishments* (coefficient = 1.28e-03, p-value = 0.03), which, in turn, depend positively on *summer* and *winter tourism* (coefficient = 0.16, p-value <0.01 and coefficient = 0.11, p-value <0.01, respectively). *Total population* is positively affected by *second homes* (coefficient = 0.04, p-value <0.01).

In summary, there are 4 indirect paths from the exogenous variables that lead to an effect on the *total GDP* of the region: 1) *Second homes* directly impacts on *GDP services* 2) *Second homes* also influences the *total population* and subsequently has an effect on *services occupation*, thereby affecting *services GDP*; 3) *Summer tourism* directly influences *tourism establishments* and this, in turn, affects the services *occupation;* and 4) *Winter tourism* has a direct effect on *tourism establishments* following the same path previously described.

(Q2) How does the current economic structure influence water resources and biodiversity?

While most socio-economic variables primarily connect with other variables of the same class, *total population* has a direct impact on *water consumption* (coefficient = 2.19e-5, p-value = 0.02), thus indirectly affecting hydrological variables. *Water consumption* exerts a negative influence over *summer flow* (coefficient = -0.09, p-value = 0.07). Furthermore, *total population* and *tourism establishments* have a direct and positive effect (coefficient = 1.28e-5, p-value <0.01, coefficient = 7.99e-4, p-value <0.01, respectively) on *urban,* which indirectly affects *bird diversity* through its positive relationship with *roads*. As a result, socio-economic variables end up reaching not only *total GDP*, but also environmental and biodiversity variables (Figure 1).

Urban acts as a bridge between economic and biodiversity variables, whereas the other land use variables act as drivers of change for the biodiversity and hydrological variables. A*gricultural land*, which has been considered as an exogenous variable due to its complex causal characteristics, negatively impacts *bird abundance* (coefficient = -0.68, p-value = 0.03) and *meadows, bushes, fields* (coefficient = -0.53, p-value <0.01). This *agricultural land* is also connected to the hydrological part of the system due to its negative effect on both *winter* and *summer flow* (coefficient = -0.24, p-value = 0.02 and coefficient = -0.28, p-value <0.01, respectively). Forested areas, which are likewise seen as drivers due to their global expansion (Palmero 2021) have a dual influence on biodiversity. On the one hand, they positively impact *bird diversity* and *bird richness* (coefficient = 3.62, p-value = 0.04 and coefficient = 3.09, p-value = 0.08, respectively), but on the other hand, they negatively affect *meadows, bushes, fields* (coefficient = -1.20, p-value <0.01) which, in turn, have a positive effect on *bird richness* and *bird diversity* (coefficient = 1.98, p-value = 0.01 and coefficient = 2.28, p-value <0.01, respectively).

(Q3) How are environmental variables link to the system and what do they represent?

Max summer and winter temperatures solely have a direct effect on the *summer snow* (coefficient = -0.39, p-value = 0.04 and coefficient = -0.42, p-value = 0.03, respectively) *and winter snow*, (coefficient = -0.62, p-value < 0.01), while *local* and *regional precipitation* influence hydrological variables (i.e., *winter* and *summer flow* and *lake height*). *Regional summer precipitation* also influences *summer NDVI* (coefficient = 0.02, p-value = 0.02), as well as *maximum summer temperature* (coefficient = 0.03, p-value = 0.01). *Local winter precipitation* has a positive effect on *summer ET* (coefficient = 0.44, p-value = 0.08). Additionally, *summer ET* is affected by *forests* (coefficient = 0.64, p-value = 0.02). (Pereira et al. 1999; Wang et al. 2004; Kingston et al. 2009; Zhao et al. 2012; Beniston et al. 2018)

While *glacier* is not explained by *max summer* and *max winter temperature*, it exhibits a negative relationship with *the summer and winter lake height* (coefficient = -0.28, p-value <0.01 and coefficient = -0.24 p-value <0.01, respectively).

4. Discussion

The socio-economic dynamics

The dominance of the service sector in driving the total GDP underscores its significance as a key contributor to the regional economy. This aligns with the trend observed in many alpine territories where services are increasingly playing a pivotal role in economic growth and development (Cantiani et al. 2016), i.e. a "tertiarisation" of the economy (Dominiak and Weltrowska 2022). *Services occupation* is one of the drivers of its economic importance and relies both on tourism and *total population*. Traditionally, tourism in alpine regions has focused on winter sports, mainly skiing, and has thus been centred in ski resorts (Dornier and Mauri

2018). Over the last decades, climate change, along with social changes, has led to a diversification of the touristic offer and to a pattern shift (Pesaro 2003). Even though the Sondrio province counts with a greater mountain territory than Brescia, the touristic model is similar in both places. It is highly seasonal, with a peak of overnight stays from June to September (Provenzano and Volo 2022), and it is characterized by summer activities like trekking and mountaineering, rural tourism, tourism related to the historical and cultural heritage and winter sports (skiing and alpinism, mainly). Such a model, as well as the consequent territorial and natural environmental impact paths, are common to most Alpine territories (Pesaro 2003).

Second homes are a major socio-economic force contributing to the regional development in many Alpine areas (Sonderegger and Bätzing 2013). This is reflected in our model by the influence of *second homes* on two key elements of the network*, total population* and *services GDP*. Last decades have seen an increase in urban dwellers investing in mountain second homes, using them not only during holiday seasons, but also for shorter periods of time. This second homes tourism model may generate a higher impact on the territory and on the structures than other accommodation forms. Second home development can generate conflicts between second home users and local residents, and within the local rural population (Rye 2011). Even though, it also has a positive influence on both the economy and the prevention of depopulation in these areas (Bender and Kanitscheider 2012; Sonderegger and Bätzing 2013), as suggested by our model. The political, social, and economic impact of second homes becomes even more complex when considering their ecological effects. They have, for example, a particularly significant impact on the water resources of mountainous areas (Hiltunen 2007), which are often insufficient to meet the needs of the entire seasonal population. However, our model does not reveal a relationship between water consumption and second homes, probably due to the lack of better data to explain water consumption, such as type of constructions, leaks in the net, etc. Furthermore, second homes often contribute to new urban development, sometimes separated from local population centres and resulting in significant impacts on land use (Couch et al. 2008). Our model shows how the expansion of second homes has an indirect effect on urban development via its influence on *total population*, ultimately impacting on the biodiversity of the area. For all these reasons, the phenomenon of second homes is commonly referred to as “both a blessing and a curse” (Rye 2011).

The comparison of the relative importance of the service sector *versus* the agricultural sector in the regional economy reflects a profound socio-economic change that has occurred in the Italian Alps and in most economically developed mountainous areas (Streifeneder et al. 2007). This transformation is based on a gradual shift from traditional agro-pastoral activities to predominantly tourism-related activities in mountainous regions and their surroundings. Although different parts of the Alps have experienced this transformation at different times and rates (Streifeneder et al. 2007), it is a widespread phenomenon that is reflected in our model. The influence of agriculture on the region's total GDP is negligible. We can observe how employment in the agricultural sector curiously has a negative effect on the sector's GDP, while agricultural production does have the expected positive effect. This may be indicative of the impact of technological advancements in the primary sector. The abandonment of traditional mountain practices in favour of intensive agriculture in lower areas promotes higher production but is often accompanied by lower employability in the sector (McEldowney 2020). It seems evident in our model that the social and economic causes underlying this situation go beyond the local effects that subsidies or salary increases may have (Kirwan and Roberts 2016). The marginal role of the primary sector in this region and other mountainous regions, coupled with the growth of tourism and the service sector, promotes a dependency of the local society on external elements of the system, primarily tourism, which are subject to different socio-economic dynamics.

Threats to water resources and biodiversity

Hydrological dynamics in mountain systems are complex and have a significant influence on downstream ecosystems. Our model shows how key hydrological variables, such as flow rate and lake volume, are influenced by other elements within the socio-ecological system. This influence is reflected in the negative impact of *water consumption* on *summer flow*. Water consumption is enhanced in our model by *total population* but is probably not only driven by population size itself, but also by the increased demand associated with a higher water consumption lifestyle (Hubacek et al. 2009), since the population increase happens at the same time as the GDP of the area and the tourism sector do. The fact that the influence of water consumption on winter flow rates, in contrast to on summer flow rates, is not significant, suggests the vulnerability of these systems to water scarcity during the summer season, as has been stated by other authors (Terzi et al. 2021). However, changes in hydrological dynamics and, particularly, increases in water consumption during the winter period, could potentially imply a greater impact on winter flow rates in the future.

The hydrological system is also connected to land use through the percentage of agricultural land, which exerts a negative influence on both winter and summer flow rates. In the Lombardy region, irrigation land accounts for the 20% of the national irrigation surface (Beteta 2021). Since the available water consumption data primarily focuses on domestic usage, our model cannot fully reflect the influence of agriculture on water consumption, but its impact on flow rates is clear.

The cryosphere, represented by variables related to snow and glacier cover in our model, is closely linked to the hydrological system, particularly in high-mountain ecosystems (Mir et al. 2023). The loss of glacier surface area leads to an increase in mountain lake reservoirs water (Beniston et al. 2011); however, the progressive melting of glaciers has significant impacts on mountain ecosystems and the planet as a whole, given that glaciers are major freshwater reservoirs (Huss 2011) and have a significant albedo effect on climate (Dumont et al. 2012). Additionally, the height of lakes is influenced annually by both liquid and solid precipitation. In the context of climate change, with earlier snow-melt and rainfall variation, inter-annual run-off and, consequently, water storage in reservoirs, are changing, resulting in less water during the summer but more water during the winter (Beniston et al. 2011; Beniston et al. 2018; Terzi et al. 2021). A negative relationship between maximum temperatures and glacier cover would be expected (Hock et al. 2019), but our model does not reflect it. However, glacier dynamics are complex, and a broader analysis beyond the 22-year scope of our study would be required to fully understand it. It is easier to observe patterns in the snow cover, which changes annually and more drastically with air temperature and rainfall (Beniston et al. 2018), than in large glacier masses. In our model, *winter snow* and especially *summer snow* clearly reflect this tendency acting as early indicators of cryosphere changes due to the climate change. These findings point to a change in the hydrological dynamics of the region.

Biodiversity in the area has been expressed through bird indicators due to their reliability and accessibility, but a broader taxonomic coverage would provide more informative insights into the biodiversity of the area and its vulnerabilities. Our biodiversity indicators are primarily affected by land use variables, as observed in other systems (Jaureguiberry et al. 2022). Land use variables related to human expansion, urban areas and road infrastructures, connect the socio-economic system to biodiversity, exerting a strongly negative effect on *bird diversity*, measured as Shannon's index. While roads may have positive effects on certain bird communities by providing foraging habitats, nesting sites, and hunting perches (Morelli et al. 2014), in general, roads are indicative of habitat loss and fragmentation (Dri et al. 2021; Jaureguiberry et al. 2022)

A natural phenomenon occurring in European mountain ecosystems is forest expansion due to agricultural land abandonment and climate change (Ameztegui et al. 2021). In a process of plant succession, abandoned fields are gradually colonized by shrub vegetation and later by dense forests. Our model reflects this phenomenon through the negative interactions that occur between *meadows, bushes, fields* and *agricultural land* and *forests.* Both *agricultural land* and *forests* have been considered exogenous variables due to the complicated processes governing their dynamics. The relationship between agriculture and biodiversity is highly complex (Dudley and Alexander 2017), as open areas and crops may benefit some species (Fahrig et al. 2011). However, intensive agriculture leads to landscape homogenization and has negative effects on the avifauna (Dudley and Alexander 2017). In our study area, agriculture is concentrated in the lowlands of the province of Brescia, where intensification of agriculture is more likely to take place, which could explain the relationships found. On the other hand, *forests* and *meadows, bushes, fields*, negatively correlated, have complex effects on *bird diversity* and *bird richness*. Both variables are positively related to these biodiversity indicators, as each of them favour a different avifauna community. However, *forests* also exerts a negative impact on *bird diversity* and *bird richness* through its relationship with *meadows, bushes and fields.* The displacement of shrubland areas due to forest expansion, with the consequent loss of this environments, leads to ecosystem homogenization and, in the long term, a loss of biodiversity (Ameztegui et al. 2021).

Environmental indicators

The evapotranspiration is the sum of water vapor fluxes from soil evaporation, wet canopy evaporation and plant transpiration at the dry canopy surface. It is used to estimate water balances and to estimate water availability and requirements (Pereira et al. 1999). The forest biomass is among the major regulators of forest evapotranspiration, although there is still an ongoing debate regarding how global evapotranspiration will change in the future accordingly to the current “greening” of the Earth, as many interactive factors may play a role (Jaramillo et al. 2018). In our model, evapotranspiration is predominantly linked to local precipitations and forested areas but not to the maximum summer temperatures, as could be expected. This environmental variable can function as an indicator of how drought and water balance will evolve in the near future if the forested areas continue to expand as it is expected.

The NDVI is another environmental proxy used to describe plant productivity. In our model, the NDVI is linked to the *regional summer precipitation* and to *forests*, as expected (Yang et al. 2019). However, it does not predict the bird abundance well, which may be due to the fact that vegetation productivity is not as strongly correlated to bird abundance at such a small scale, unlike larger scales such as continental or regional extents (>100km) (Ribeiro et al. 2019).

Recommendations for a sustainable management of resources

Mountains are particularly subject to rapid and sustained environmental changes (Gobiet et al. 2014). Warmer winters, earlier snow-melt, changes in rainfall patterns and more severe droughts are expected to change the intra-annual streamflow variations in the Alps (Saidi et al. 2018), as in many other mountain systems (Beniston et al. 1996; Hock et al. 2019). In the extensive review of past tendencies and future projections, Beniston et al., 2018, have shown that by the end of the century, Europe's mountain cryosphere will have changed to an extent that will impact the landscape, hydrological regimes, water resources, and infrastructures.. According to the projections analysed, the Alps will witness a reduction in Snow Water Equivalent (SWE) of 80– 90 % at an elevation of 1500 m.a.s.l., and a reduction in the snow season equivalent to a shift in elevation of about 700m, by the end of the century. Under these predictions of a much shorter snow season and lower water reserves, focusing on winter tourism seems a mistake. Undoubtedly, tourism serves as an economic engine for these regions, and has often contributed to reversing economic recession and outmigration (Bender and Kanitscheider 2012). However, tourism increases pressures on water resources, especially during summer, and on biodiversity. Diversifying tourism to attract visitors throughout the year would promote greater sector stability within an uncertain future. Nevertheless, this doesn't necessarily imply reduced tourist presence during critical seasons, so implementing measures to reduce water usage is necessary. Some of these measures could include water resource regulations on extraction and usage (Beniston et al. 2011) and improving the supply network to minimize losses (Fan et al. 2021).

Perhaps even more crucial than diversifying the touristic offer would be the revival of an economically and ecologically sustainable agricultural sector. The marginalization of agriculture and livestock sectors has impacted the income of farmers heavily reliant on subsidies (Muñoz-Ulecia et al. 2021) and has altered the landscape of the Alps (Schirpke et al. 2022), leading to a decline in mountain pastures, essential habitats for many species (Fahrig et al. 2011) and a draw for the tourism sector (Wanner et al. 2021). An economic model solely based on one sector, especially one with high external dependence, could be risky and diminish the region's socio-economic stability and resilience (Dissart 2003), as demonstrated by the recent COVID-19 pandemic (Romeo et al. 2021). Improving subsidy systems and agriculture conservation policies would promote a more sustainable agriculture sector (Scown et al. 2020), fostering overall economic diversification and robustness. Irrigation agriculture is water-demanding and will likely be threatened under climate change scenarios (Haro-Monteagudo et al. 2020). Promoting locally adapted crops would increase their survival under this scenario, contributing to food security, water resource control and supporting farmers' income. Additionally, sustainable mountain agriculture encourages landscape heterogenization, curbing forest line expansion and maintaining open spaces that support biodiversity (Ortiz et al. 2021). In the same line of action, controlling urban sprawl is essential to prevent habitat fragmentation and loss, one of the major drivers of biodiversity decline (Dri et al. 2021).

With our approach, we have been able to capture how seemingly distant elements affect each other in a Lombardian SES. It is essential to understand that the observed patterns occur in a specific context, at a specific scale, and may vary among systems and scales. One of the fundamental factors for conducting this type of analysis is the quality and quantity of data. In fact, the main challenge encountered during this study was the lack of data on a suitable temporal scale and scope, as well as missing data. Scale mismatch constitutes one of the obstacles encountered in multidisciplinary approaches to environmental management, like Social Ecological Systems science. To address this issue, it is imperative to establish monitoring standards that can harmonize scales across disciplines and facilitate the acquisition of integrated databases (Virapongse et al. 2016).

Conclusions

We have been able to quantitatively characterize a complex network of interacting social-ecological elements, and to suggest evidence-based sustainable development measures in a Lombardian SES. Good strategies to reduce water consumption and to limit urban sprawl could contribute to alleviate the current pressure on water resources and biodiversity. Efforts to effectively promote employment in agriculture and to stimulate all-year-round tourism should help distribute the economic wealth among sectors and reduce dependence on snow tourism, as well as increasing the system's economic and social resilience. Extrapolated to other mountain systems, our findings highlight the importance of considering social and ecological factors holistically to improve economic and environmental resource management. Future efforts should aim at gathering socio-economic data at appropriate temporal and spatial scales to match environmental data, as well as at developing tools to facilitate the incorporation of feedback loops and computing cascade effects on complex networks such as ours.

References

Agenzia Regionalle per a la Protezione dell'Ambiente. 2023. https://www.arpalombardia.it. Accessed August 3.

Ameztegui, A., A. Morán-Ordóñez, A. Márquez, Á. Blázquez-Casado, M. Pla, D. Villero, M. B. García, M. P. Errea, et al. 2021. Forest expansion in mountain protected areas: Trends and consequences for the landscape. *Landscape and Urban Planning* 216: 104240. doi:10.1016/j.landurbplan.2021.104240.

Bender, O., and S. Kanitscheider. 2012. New Immigration Into the European Alps: Emerging Research Issues. *Mountain Research and Development* 32. International Mountain Society: 235–241. doi:10.1659/MRD-JOURNAL-D-12-00030.1.

Beniston, M., D. G. Fox, S. Adhikary, R. Andressen, A. Guisan, J. I. Holten, J. Innes, J. Maitima, et al. 1996. *Impacts of climate change on mountain regions*. Cambridge, Cambridge University Press.

Beniston, M., M. Stoffel, and M. Hill. 2011. Impacts of climatic change on water and natural hazards in the Alps: Can current water governance cope with future challenges? Examples from the European "ACQWA" project. *Environmental Science & Policy* 14. Adapting to Climate Change: Reducing Water-Related Risks in Europe: 734–743. doi:10.1016/j.envsci.2010.12.009.

Beniston, M., D. Farinotti, M. Stoffel, L. M. Andreassen, E. Coppola, N. Eckert, A. Fantini, F. Giacona, et al. 2018. The European mountain cryosphere: a review of its current state, trends, and future challenges. *The Cryosphere* 12. Copernicus GmbH: 759–794. doi:10.5194/tc-12-759-2018.

Beteta, I. 2021. El mercado del agua en Italia. Oficina Económica y Comercial de la Embajada de España en Roma. (In Spanish)

Cantiani, M. G., C. Geitner, C. Haida, F. Maino, C. Tattoni, D. Vettorato, and M. Ciolli. 2016. Balancing Economic Development and Environmental Conservation for a New Governance of Alpine Areas. *Sustainability* 8. Multidisciplinary Digital Publishing Institute: 802. doi:10.3390/su8080802.

Couch, C., G. Petschel-Held, and L. Leontidou. 2008. *Urban Sprawl in Europe: Landscape, Land-Use Change and Policy*. John Wiley & Sons.

Csardi, G., and T. Nepusz. 2005. The Igraph Software Package for Complex Network Research. *InterJournal* Complex Systems: 1695.

Delgado-Serrano, M. del M., and P. Ramos. 2015. Making Ostrom's framework applicable to characterise social ecological systems at the local level 9. Ubiquity Press: 808. doi:10.18352/ijc.567.

Dissart, J. C. 2003. Regional Economic Diversity and Regional Economic Stability: Research Results and Agenda. *International Regional Science Review* 26. SAGE Publications Inc: 423–446. doi:10.1177/0160017603259083.

Dominiak, J., and J. Weltrowska. 2022. Tertiarisation of the Economy: Restructuring of the Service Sector. In *Three Decades of Polish Socio-Economic Transformations: Geographical Perspectives*, ed. P. Churski and T. Kaczmarek, 197–218. Economic Geography. Cham: Springer International Publishing. doi:10.1007/978-3-031-06108-0_9.

Dornier, R., and C. Mauri. 2018. Overview: tourism sustainability in the Alpine region: the major trends and challenges. *Worldwide Hospitality and Tourism Themes* 10. Emerald Publishing Limited: 136–139. doi:10.1108/WHATT-12-2017-0078.

Dri, G. F., C. S. Fontana, and C. de S. Dambros. 2021. Estimating the impacts of habitat loss induced by urbanization on bird local extinctions. *Biological Conservation* 256: 109064. doi:10.1016/j.biocon.2021.109064.

Dudley, N., and S. Alexander. 2017. Agriculture and biodiversity: a review. *Biodiversity* 18. Taylor & Francis: 45–49. doi:10.1080/14888386.2017.1351892.

Dumont, M., J. Gardelle, P. Sirguey, A. Guillot, D. Six, A. Rabatel, and Y. Arnaud. 2012. Linking glacier annual mass balance and glacier albedo retrieved from MODIS data. *The Cryosphere* 6. Copernicus GmbH: 1527–1539. doi:10.5194/tc-6-1527-2012.

Enti regolatori dei grandi laghi. 2023. https://www.laghi.net/. Accessed August 3.

Fahrig, L., J. Baudry, L. Brotons, F. G. Burel, T. O. Crist, R. J. Fuller, C. Sirami, G. M. Siriwardena, et al. 2011. Functional landscape heterogeneity and animal biodiversity in agricultural landscapes. *Ecology Letters* 14: 101–112. doi:10.1111/j.1461-0248.2010.01559.x.

Fan, X., X. Zhang, and X. (. B. Yu. 2021. Machine learning model and strategy for fast and accurate detection of leaks in water supply network. *Journal of Infrastructure Preservation and Resilience* 2: 10. doi:10.1186/s43065-021-00021-6.

Gobiet, A., S. Kotlarski, M. Beniston, G. Heinrich, J. Rajczak, and M. Stoffel. 2014. 21st century climate change in the European Alps—A review. *Science of The Total Environment* 493: 1138–1151. doi:10.1016/j.scitotenv.2013.07.050.

Haro-Monteagudo, D., L. Palazón, and S. Beguería. 2020. Long-term sustainability of large water resource systems under climate change: A cascade modeling approach. *Journal of Hydrology* 582: 124546. doi:10.1016/j.jhydrol.2020.124546.

Hiltunen, M. J. 2007. Environmental Impacts of Rural Second Home Tourism – Case Lake District in Finland. *Scandinavian Journal of Hospitality and Tourism* 7. Routledge: 243–265. doi:10.1080/15022250701312335.

Hock, R., G. Rasul, C. Adler, B. Cáceres, S. Gruber, Y. Hirabayashi, M. Jackson, A. Kääb, et al. 2019. High mountain areas. In *The Ocean and Cryosphere in a Changing Climate*, ed. H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, et al., 2-1-2–90. Intergovernmental Panel on Climate Change.

Hoegh-Guldberg, O., D. Jacob, M. Taylor, M. Bindi, S. Brown, I. Camilloni, A. Diedhiou, R. Djalante, et al. 2018. Impacts of 1.5ºC global warming on natural and human systems. In *Global Warming of 1.5°C*. IPCC.

Hubacek, K., D. Guan, J. Barrett, and T. Wiedmann. 2009. Environmental implications of urbanization and lifestyle change in China: Ecological and Water Footprints. *Journal of*

Cleaner Production 17. Advances in Life-Cycle Approaches to Business and Resource Management in the Asia-Pacific Region: 1241–1248. doi:10.1016/j.jclepro.2009.03.011.

Huss, M. 2011. Present and future contribution of glacier storage change to runoff from macroscale drainage basins in Europe. *Water Resources Research* 47. doi:10.1029/2010WR010299.

Immerzeel, W. W., A. F. Lutz, M. Andrade, A. Bahl, H. Biemans, T. Bolch, S. Hyde, S. Brumby, et al. 2020. Importance and vulnerability of the world's water towers. *Nature* 577. Nature Publishing Group: 364–369. doi:10.1038/s41586-019-1822-y.

IPBES. 2019. *Summary for policymakers of the global assessment report on biodiversity and ecosystem services*. Zenodo. doi:10.5281/zenodo.3553579.

Jaramillo, F., N. Cory, B. Arheimer, H. Laudon, Y. van der Velde, T. B. Hasper, C. Teutschbein, and J. Uddling. 2018. Dominant effect of increasing forest biomass on evapotranspiration: interpretations of movement in Budyko space. *Hydrology and Earth System Sciences* 22. Copernicus GmbH: 567–580. doi:10.5194/hess-22-567-2018.

Jaureguiberry, P., N. Titeux, M. Wiemers, D. E. Bowler, L. Coscieme, A. S. Golden, C. A. Guerra, U. Jacob, et al. 2022. The direct drivers of recent global anthropogenic biodiversity loss. *Science Advances* 8. American Association for the Advancement of Science: eabm9982. doi:10.1126/sciadv.abm9982.

Kingston, D. G., M. C. Todd, R. G. Taylor, J. R. Thompson, and N. W. Arnell. 2009. Uncertainty in the estimation of potential evapotranspiration under climate change. *Geophysical Research Letters* 36. doi:10.1029/2009GL040267.

Kirwan, B. E., and M. J. Roberts. 2016. Who Really Benefits from Agricultural Subsidies? Evidence from Field-level Data. *American Journal of Agricultural Economics* 98: 1095–1113. doi:10.1093/ajae/aaw022.

Lefcheck, J. S. 2016. piecewiseSEM: Piecewise structural equation modelling in r for ecology, evolution, and systematics. *Methods in Ecology and Evolution* 7: 573–579. doi:10.1111/2041-210X.12512.

McEldowney, J. 2020. EU agricultural policy and climate change - European Parliamentary Research Service.

Mir, R. A., F. A. Dar, and K. M. Gani. 2023. Editorial: Hydrosphere-cryosphere interactions in the Himalayas under climate change. *Frontiers in Water* 5.

Morelli, F., M. Beim, L. Jerzak, D. Jones, and P. Tryjanowski. 2014. Can roads, railways and related structures have positive effects on birds? – A review. *Transportation Research Part D: Transport and Environment* 30: 21–31. doi:10.1016/j.trd.2014.05.006.

Muñoz-Ulecia, E., A. Bernués, I. Casasús, A. M. Olaizola, S. Lobón, and D. Martín-Collado. 2021. Drivers of change in mountain agriculture: A thirty-year analysis of trajectories of evolution of cattle farming systems in the Spanish Pyrenees. *Agricultural Systems* 186: 102983. doi:10.1016/j.agsy.2020.102983.

Ortiz, A. M. D., Charlotte L. Outhwaite, Carole Dalin, and Tim Newbold. 2021. A review of the interactions between biodiversity, agriculture, climate change, and international trade: research and policy priorities. *One earth* 4: 88–101. doi:10.1016/j.oneear.2020.12.008.

Ostrom, E. 2009. A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science* 325. American Association for the Advancement of Science: 419–422. doi:10.1126/science.1172133.

Palmero, M. 2021. Recent Forest Expansion in Europe (1985-2015). Patterns, Drivers, and Implications on Forest Growth. *TDX (Tesis Doctorals en Xarxa)*. Ph.D. Thesis, Universitat Autònoma de Barcelona.

Payne, D., E. M. Spehn, G. W. Prescott, J. Geschke, M. A. Snethlage, and M. Fischer. 2020. Mountain Biodiversity Is Central to Sustainable Development in Mountains and Beyond. *One Earth* 3. Elsevier: 530–533. doi:10.1016/j.oneear.2020.10.013.

Pereira, L. S., A. Perrier, R. G. Allen, and I. Alves. 1999. Evapotranspiration: Concepts and Future Trends. *Journal of Irrigation and Drainage Engineering* 125. American Society of Civil Engineers: 45–51. doi:10.1061/(ASCE)0733-9437(1999)125:2(45).

Pesaro, G. 2003. Waiting for 2005's World Skiing Championship: an Experimental Assessment of Tourism Sustainability in Sondrio Province. In . Louvain-la-Neuve: European Regional Science Association.

Provenzano, D., and S. Volo. 2022. Tourism recovery amid COVID-19: The case of Lombardy, Italy. *Tourism Economics* 28. SAGE Publications Ltd: 110–130. doi:10.1177/13548166211039702.

Ribeiro, I., V. Proença, P. Serra, J. Palma, C. Domingo-Marimon, X. Pons, and T. Domingos. 2019. Remotely sensed indicators and open-access biodiversity data to assess bird diversity patterns in Mediterranean rural landscapes. *Scientific Reports* 9. Nature Publishing Group: 6826. doi:10.1038/s41598-019-43330-3.

Rodríguez-Rodríguez, D., B. Bomhard, S. H. M. Butchart, and M. N. Foster. 2011. Progress towards international targets for protected area coverage in mountains: A multi-scale assessment. *Biological Conservation* 144: 2978–2983. doi:10.1016/j.biocon.2011.08.023.

Romeo, R., L. Russo, F. Parisi, M. Notarianni, S. Manuelli, S. Carvao, and UNWTO. 2021. *Mountain tourism – Towards a more sustainable path*. FAO: Food and Agriculture Organization of the United Nations.

Rye, J. F. 2011. Conflicts and contestations. Rural populations' perspectives on the second homes phenomenon. *Journal of Rural Studies* 27: 263–274. doi:10.1016/j.jrurstud.2011.03.005.

Saidi, H., C. Dresti, D. Manca, and M. Ciampittiello. 2018. Quantifying impacts of climate variability and human activities on the streamflow of an Alpine river. *Environmental Earth Sciences* 77: 690. doi:10.1007/s12665-018-7870-z.

Schirpke, U., E. Tasser, G. Leitinger, and U. Tappeiner. 2022. Using the Ecosystem Services Concept to Assess Transformation of Agricultural Landscapes in the European Alps. *Land* 11. Multidisciplinary Digital Publishing Institute: 49. doi:10.3390/land11010049.

Scown, M. W., M. V. Brady, and K. A. Nicholas. 2020. Billions in Misspent EU Agricultural Subsidies Could Support the Sustainable Development Goals. *One Earth (Cambridge, Mass.)* 3: 237–250. doi:10.1016/j.oneear.2020.07.011.

Sonderegger, R., and W. Bätzing. 2013. Second homes in the Alpine Region. *Journal of Alpine Research | Revue de géographie alpine*. Association pour la diffusion de la recherche alpine et UGA Éditions. doi:10.4000/rga.2511.

Streifeneder, T., U. Tappeiner, F. Ruffini, G. Tappeiner, and C. Hoffmann. 2007. Perspective on the tranformation of agricultural structures in the Alps. Comparison of agro-structural indicators synchronized with a local scale. *Revue de géographie alpine* 95: 27–40.

Terzi, S., J. Sušnik, S. Schneiderbauer, S. Torresan, and A. Critto. 2021. Stochastic system dynamics modelling for climate change water scarcity assessment of a reservoir in the Italian Alps. *Natural Hazards and Earth System Sciences* 21. Copernicus GmbH: 3519–3537. doi:10.5194/nhess-21-3519-2021.

Vanham, D., E. Fleischhacker, and W. Rauch. 2009. Impact of an extreme dry and hot summer on water supply security in an alpine region. *Water Science and Technology: A Journal of the International Association on Water Pollution Research* 59: 469–477. doi:10.2166/wst.2009.887.

Virapongse, A., S. Brooks, E. C. Metcalf, M. Zedalis, J. Gosz, A. Kliskey, and L. Alessa. 2016. A social-ecological systems approach for environmental management. *Journal of Environmental Management* 178: 83–91. doi:10.1016/j.jenvman.2016.02.028.

Wang, J., P. M. Rich, K. P. Price, and W. D. Kettle. 2004. Relations between NDVI and tree productivity in the central Great Plains. *International Journal of Remote Sensing* 25. Taylor & Francis: 3127–3138. doi:10.1080/0143116032000160499.

Wanner, A., U. Pröbstl-Haider, and M. Feilhammer. 2021. The future of Alpine pastures – Agricultural or tourism development? Experiences from the German Alps. *Journal of Outdoor Recreation and Tourism* 35: 100405. doi:10.1016/j.jort.2021.100405.

Yang, Y., S. Wang, X. Bai, Q. Tan, Q. Li, L. Wu, S. Tian, Z. Hu, et al. 2019. Factors Affecting Long-Term Trends in Global NDVI. *Forests* 10. Multidisciplinary Digital Publishing Institute: 372. doi:10.3390/f10050372.

Zhao, X., D. Zhou, and J. Fang. 2012. Satellite-based Studies on Large-Scale Vegetation Changes in China. *Journal Of Integrative Plant Biology* 54. Hoboken: Wiley: 713–728. doi:10.1111/j.1744-7909.2012.01167.x.

Table 1. *Description of the variables used in the path models. For all seasonal variables, summer corresponds to the months April to September, while winter goes from October to March. For details on data sources see Appendix A – Data sources and processing.*

Variable name	Type of variable	Description	Units	Spatial scale
Summer lake height	Hydrological	Averaged lake height of 5 great lakes in the watershed during summer months	cm	Watershed
Winter lake height	Hydrological	Averaged lake height of 5 great lakes in the watershed during winter months	cm	Watershed
Summer flow	Hydrological	Averaged sum of discharge that flows outside 5 main catchments during summer months	10e6 m3	Watershed
Winter flow	Hydrological	Averaged sum of discharge that flows outside 5 main catchments during winter months	10e6 m3	Watershed
Max summer temperature	Climatic	Averaged maximum temperature of summer months	ºC	Brescia and Sondrio
Max winter temperature	Climatic	Averaged maximum temperature of winter months	ºC	Brescia and Sondrio
Regional winter precipitation	Climatic	Accumulated precipitation in the whole region during summer months	mm	Brescia and Sondrio
Regional summer precipitation	Climatic	Accumulated precipitation in the whole region during winter months	mm	Brescia and Sondrio
Local summer precipitation	Climatic	Accumulated precipitation in the watershed of 5 main rivers during summer months	10e6 m^3	Watershed
Local winter precipitation	Climatic	Accumulated precipitation in the watershed of 5 main rivers during winter months	10e6 m^3	Watershed
Summer ET	Environmental	Averaged maximum evapotranspiration during summer months	/	Brescia and Sondrio
Summer NDVI	Environmental	Averaged maximum NDVI during summer months	mm	Brescia and Sondrio
Summer snow	Crysosphere	Mean number of pixels classified as "snow" during summer months	Pixel number	Brescia and Sondrio
Winter snow	Crysosphere	Mean number of pixels classified as "snow" during winter months	Pixel number	Brescia and Sondrio
Winter snow height	Crysosphere	Averaged snow height from 8 mountain weather stations	cm	Brescia and Sondrio
Glacier surface	Crysosphere	Total annual surface classified as “glacier and ice”	km^2	Brescia and Sondrio
Roads	Land-use	Total annual surface classified as “roads”	km^2	Brescia and Sondrio
Urban	Land-use	Total annual surface classified as “urbanized area”	km^2	Brescia and Sondrio
Meadows, bushes, fields	Land-use	Total annual surface classified as “shrubby and/or herbaceous vegetation”	km^2	Brescia and Sondrio

Variable name	Type of variable	Description	Units	Spatial scale
Agricultural land	Land-use	Total annual surface classified as “agriculture area”	km^2	Brescia and Sondrio
Forests	Land-use	Total annual surface classified as “forested area”	km^2	Brescia and Sondrio
Total GDP	Socio-economic	Total Gross Domestic Product per year	Millions of euros	Brescia and Sondrio
Agriculture GDP	Socio-economic	Gross Domestic Product per year devoted to agriculture	Millions of euros	Brescia and Sondrio
Services GDP	Socio-economic	Gross Domestic Product per year devoted to services	Millions of euros	Brescia and Sondrio
Agriculture occupation	Socio-economic	Percentage of workers employed in agriculture (including livestock)	Percentage	Brescia and Sondrio
Services occupation	Socio-economic	Percentage of workers employed in services sector	Percentage	Brescia and Sondrio
Agriculture salary	Socio-economic	Annual salary earned by permanent employees in the agriculture sector	Euros/ year	Italy
Agriculture subsidies	Socio-economic	Total public expenditure on subsidies to agriculture	Millions of euros	Italy
Winter tourism	Socio-economic	Nights spent by tourist during winter months	Count	Brescia and Sondrio
Summer tourism	Socio-economic	Nights spent by tourist during summer months	Count	Brescia and Sondrio
Total population	Socio-economic	Total population registered as resident	Count	Brescia and Sondrio
Tourism establishments	Socio-economic	Number of tourism establishments including rural establishments and hotels	Count	Brescia and Sondrio
Second homes	Socio-economic	Number of non-occupied conventional dwelling and occupied by non-resident.	Count	Brescia and Sondrio
Water consumption	Socio-economic	Total declared water consumption for domestic use	Thousands of m^3	Lombardy
Agriculture production	Socio-economic	Total annual production value from agriculture and forestry	Thousands of euros	Lombardy
Bird diversity	Biodiversity	Shannon Biodiversity Index per ringing station based on 28 sites	/	Brescia and Sondrio
Bird richness	Biodiversity	Number of bird species found per year in the 28 stations	Count	Brescia and Sondrio
Bird Abundance	Biodiversity	Number of bird individuals found per year in the 28 stations	Count	Brescia and Sondrio

Figure 1. *Integrated social-ecological network of an Alpine ecosystem showing the relationships between the 39 socio-ecologic variables inferred through structural equation modelling. Arrows indicate the hypothesized relationships colored by the type of effect found (green: positive effect; red: negative effect; grey: no significant effect). Arrow width is proportional to standardized weight coefficients. Circle colour indicates variable type (Red: socio-economic; blue: hydrological; dark red: remote-sensing environmental variable; purple: climatic; yellow: land use; orange: biodiversity; green: cryosphere).*

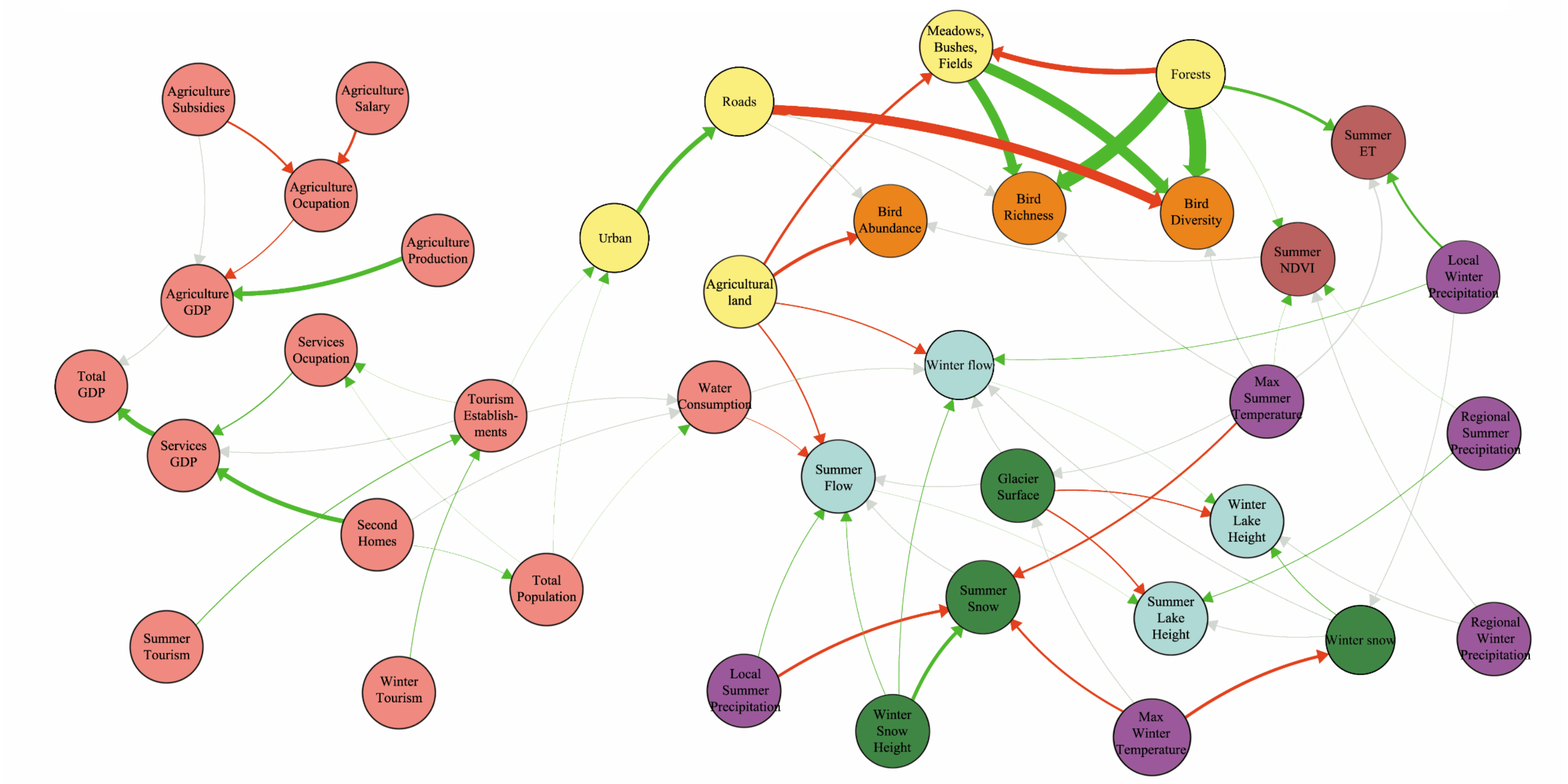

Table 2. *Matrix with the independent and dependent variables of the regressions present in the network, with standardized path coefficients, indicating the strength of the relationship between variables. Coloured cells indicate correspondence with hypothesized relationships: blue, the hypothesized relationship was found; red, the relationship was not found; Bold standardized coefficients indicate marginally significant relationships (p-value<0.1). Columns (dependent variables) receiving no effect and rows (independent variables) causing no effect were removed from the matrix.*

Independent \ Dependent	Bird Abundance	Summer Lake Height	Winter Lake Height	Meadows, Bushes, Fields	Summer flow	Winter flow	Agriculture occupation	Summer ET	Agriculture GDP	Services GDP	Total GDP	Glacier surface	Summer NDVI	Tourism Establishments	Total Population	Bird Richness	Roads	Bird Diversity	Summer snow	Winter snow	Water Consumption
Max Winter Temperature	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.43	-0.63	0
Local Summer Precipitation	0	0	0	0	0.13	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.58	0	0
Max Summer Temperature	0	0	0	0	0	0	0	0	0	0	0	0	0.03	0	0	0	0	0	-0.39	0	0
Roads	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2.09	0	0	0
Agriculture Ocupation	0	0	0	0	0	0	0	0	-0.20	0	0	0	0	0	0	0	0	0	0	0	0
Agriculture Salary	0	0	0	0	0	0	-0.49	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Agicultural Land	-0.68	0	0	-0.53	-0.28	-0.24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Summer NDVI	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Summer flow	0	1.16E-03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Winter flow	0	0	1.25E-03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Summer snow	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Water Consumption	0	0	0	0	-0.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Winter snow	0	0	0.12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Glacier surface	0	-0.28	-0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Agriculture subsidies	0	0	0	0	0	0	-0.37	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Agriculture Production	0	0	0	0	0	0	0	0	0.96	0	0	0	0	0	0	0	0	0	0	0	0
Services Ocupation	0	0	0	0	0	0	0	0	0	0.22	0	0	0	0	0	0	0	0	0	0	0
Agriculture GDP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Dependent Independent	Bird Abundance	Summer Lake Height	Winter Lake Height	Meadows, Bushes, Fields	Summer flow	Winter flow	Agriculture occupation	Summer ET	Agriculture GDP	Services GDP	Total GDP	Glacier surface	Summer NDVI	Tourism Establishments	Total Population	Bird Richness	Roads	Bird Diversity	Summer snow	Winter snow	Water Consumption
Services GDP	0	0	0	0	0	0	0	0	0	0	1.06	0	0	0	0	0	0	0	0	0	0
Summer Precipitation	0	0.12	0	0	0	0	0	0	0	0	0	0	0.02	0	0	0	0	0	0	0	0
Winter Precipitation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Winter Tourism	0	0	0	0	0	0	0	0	0	0	0	0	0	0.11	0	0	0	0	0	0	0
Summer Tourism	0	0	0	0	0	0	0	0	0	0	0	0	0	0.16	0	0	0	0	0	0	0
Urban	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.97	0	0	0	0
Meadows, Bushes, Fields	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.99	0	2.28	0	0	0
Forests	0	0	0	-1.20	0	0	0	0.65	0	0	0	0	0.01	0	0	3.09	0	3.63	0	0	0
Winter Snow height	0	0	0	0	0.09	0.12	0	0	0	0	0	0	0	0	0	0	0	0	0.74	0	0
Local Winter Precipitation	0	0	0	0	0	0.11	0	0.44	0	0	0	0	0	0	0	0	0	0	0	0.00	0
Total Population	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.19E-05
Tourism Establishments	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Second Homes	0	0	0	0	0	0	0	0	0	0.96	0	0	0	0	0.04	0	0	0	0	0	0

Supplementary material

Appendix A - Data sources and processing

All the data presented in this paper was searched for and collected between February and June 2023. Public databases are periodically updated, and new data may become available in the future.

1. Hydrological variables

Hydrological variables were obtained from the (Agenzia Regionalle per a la Protezione dell'Ambiente 2023) (ARPA) website by several formal requests. Digitalized data spanned from January 2011 to December 2021, for all the hydrological variables in a weekly period. Data from January 2006 to December 2010 was extracted from monthly bulletins also available at the website. Data for the years 2003 and 2005 was extracted from the same bulletins by the digitalization of graphs.

Snow height was also collected from APRA website. The data was available for different mountain stations at both Sondrio and Brescia regions in a daily period from January 2000 to December 2021.

2. Climatic data

Historical monthly maximum temperature and monthly accumulated precipitation data from CRU-TS-4.0 (Harris et al. 2014), downscaled with WorldClim 2.1 (Fick and Hijmans 2017) were obtained for 1999-2018. To later extract the data, we conducted a mask extraction of the study area using QGis Desktop 3.24 version. Monthly climatic data from this area were then extracted from the WorldClim .tif files using the *raster* package (Hijmans 2015) in R software.

3. Remote sensing-derived environmental data

Remote sensing normalized difference vegetation index (NDVI) at 250 m spatial resolution, maximum summer evapotranspiration (ET) at 500 m spatial resolution and maximum snow cover extent data at 500 m spatial resolution in Sondrio and Brescia were extracted from NASA's Application for Extracting Analysis Ready Samples (AppEEARS Team, 2021). NDVI data was available at a temporal resolution of 16 days, between February 2000 and December 2020, ET data at eight-day temporal resolution between February 2000 and December 2019, and maximum snow cover extent data at an eight-day temporal resolution between February 2000 and December 2016. In the data provided, the pixel values for the NDVI data are the values produced at 16-day intervals, and for ET they are the sum of all eight days. In the case of maximum snow extent data, pixels are classified as "snow" if snow cover is found any day of the 8-day period. If another pixel type is found more than once, the pixel is classified as belonging to that type.

3.1 Data quality assessment

NDVI data

Pixels for each date were provided with a classification according to the reliability and usefulness of the data. Only the pixels classified as "Good quality", "Marginal data/Useful" and "Snow/Ice Target" were considered as suitable, and data for a date was only used when the percentage of suitable pixels was higher than 90% of the total number of pixels. Otherwise, the data for that date was ruled out.

ET data

Pixels for each date were provided with a classification according to the quality of the data and presence of clouds. We considered suitable the pixels classified as "Good quality" with no clouds and "Good quality" with mixed clouds, and only used data for a date when the percentage of pixels under these categories was higher than 70%.

Maximum snow cover extent data

The pixels for each date were classified as "snow", "no snow", "cloud" and "no decision". Pixels classified as "cloud" we considered as uncertain. Therefore, data for a date was only used when the percentage of pixels classified as "cloud" or "no decision" remained under 10% of the total number of pixels.

4. Land use data

We gathered data on land use types for the study region using $30cm^2$ spatial resolution land use maps from Infrastruttura per l'Informazione Territoriale (IIT) from the project DUSAF (Destinazione d'Uso del Suolo Agricolo e Forestale) (Nova et al. 2019). It was available for the years 1999,2007,2009,2012,2015 and 2018. Total surface (km2) was calculated for each land use type using QGis Desktop 3.24 version, following the categories specified at the Corine Land Cover (CORINE Land Cover — Copernicus Land Monitoring Service 2023).

5. Biodiversity data

Bird census data was downloaded from the (Instituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) 2023) website which hosts the Italian bird ringing database (Banca dati inanellamento degli uccelli BIO-AVM ISPRA - NNB 2023). This data was filtered, selecting only the ringing stations that had more than 10 years of continuity and a sampling effort of more than 2.200 total birds per year. Finally, we used the data from the remaining 29 bird ringing stations and calculated the mean annual bird abundance, richness, and Shannon Biodiversity Index from 2000 to 2018.

At the moment, additional bird census data has been requested to the (Pan-European Common Bird Monitoring Scheme 2023) coordinators in Italy and is still being processed and will be used to improve the data quality and extent.

6. Social and economic data

Social and economic data for the Brescia and Sondrio region was provided by I.Stat (Statistical Database of Italy)(Statistiche Istat 2023), for a period between 2000 and 2020.

6.1 Gross domestic product (GDP) variables

GDP data was provided for Brescia and Sondrio regions divided into sectors (services and primary sectors) and in total, from year 2000 to year 2020. Given that GDP was heavily impacted by the COVID-19 pandemic in 2020 (Gühnemann et al. 2021),this year was forecasted as it is explained bellow.

6.2 Employment-related data and subsidies

Employment by sector was provided for Brescia and Sondrio regions divided into sectors (services and primary sectors) and in total, from year 2000 to year 2020.

Annual gross salary of the workers employed in the agriculture sector was provided for the whole Lombardy region annually from the year 2005 to 2021.

6.3 Population data

Total population registered as resident was available from years 2000 to 2020 for Brescia and Sondrio regions.

6.4 Second homes and tourism establishments data

The total number of second homes was available only for the years 2001,2011 and 2019 for the Brescia and Sondrio regions, but as it had a clear linear tendency, we decided to use it with the corresponding interpolation. The number of tourism establishments was available from year 2000 to year 2020 for the Brescia and Sondrio regions.

6.5 Tourism presence

Tourism presence data was available in a monthly period from January 2016 to December 2021, and in an annual period from 2008 to 2015. Due to the constancy of the percentage of each seasonal tourism in the annual tourism, seasonal data for the years 2008 to 2015 was calculated using this percentage. The years 2020 and 2021 were considered outliers due to the circumstances derived from the COVID-19 pandemic and were therefore imputed fitting a linear regression accordingly to the clear linear tendency.

6.6 Water consumption

Total declared water consumption for domestic uses was available for the years 1999,2005,2008,2012 for Sondrio and Brescia regions and for years 2015, 2018 and 2020 for the Lombardy region. As the province water consumption and the region water consumption had a constant relationship over the years, we computed the values for the years 2015, 2018 and 2020 for the provinces of Brescia and Sondrio using the Lombardy value as a reference.

7. Seasonal data calculations

For all variables available on an intra-annual scale for which we wanted a seasonal resolution, annual values for 6-months periods classified as “summer” or “winter” periods were computed as follows:

- The winter value for a given year was calculated over the months of October, November and December of the previous year and the months of January, February, and March of the current year. These annual winter values correspond to the temporal time scope of climatic seasons, and thus this seasonal separation enable us to match the semesters of all seasonal variables with each other (seasonal population and hydrological, climatic, and environmental variables)
- Summer values were calculated for the months of April to September of every given year.

When available data did not include all the months for a given season, these values were discarded, so that annual winter and summer values were always calculated with no missing months. The original data was taken from several different spatial data points (gauging stations for hydrological data, geographic points for climatic data, the two counties for data from NASA). The final mean winter and summer values thus correspond to the mean annual values for winter and summer across all spatial data points available.

Appendix B – Missing data imputation

In the case of variables for which winter and summer values were calculated (environmental, climatic and hydrological variables), we arranged the data into chronological time series with two values per year (winter followed by summer) to impute missing values on a semester scale. Missing values at the end of this time series were imputed using Holt-Winters filtering with a seasonal component using the package *forescast* (Hyndman and Khandakar 2008). For missing values at the beginning of the time series, the same procedure was used on the reversed time series. Once the imputations were done, the final chronological time series was split again into two distinct winter and summer annual variables to obtain the desired seasonal scale.

Hydrological variables (lake height and river flow) where available continuously by a monthly period from 2006 to 2021. For the flow variable, the remaining years where imputed as described above. For the lake height, it was available also data for the years 2003 and 2005. The value of 2004 was imputed using the package *imputeTS* (Moritz and Bartz-Beielstein 2017), fitting a linear regression using the existing data and the remaining years with the forecast method.

Averaged maximum temperatures and accumulated precipitation variables were available only from winter 2000 to summer 2018. Winter and summer values for 2019 and 2020 were forecasted as described above. Local accumulated precipitation was available from 2006 to 2021 so the previous years were forecasted as described.

For the remote-sensing variables (NDVI, ET and snow extent) and snow height the data was available for all the years of the study, so no imputation was needed.

In the case of land use data, the data was available for the years 1999, 2007, 2009, 2012, 2015 and 2018. As we assumed a gradual variation in all land use variables, linear interpolation was carried out to impute annual values of each land use type from 2000 to 2018 and forecasting by Holt's method with no seasonal component was carried out to impute the years 2019-2021.

For bird biodiversity data, the data was available from 2000 to 2020 but the years 2019 and 2020 where outliers probably due to, on one hand, the no inclusion of all data for recent years and, on the other hand, the circumstances linked to the COVID-19 pandemic. Thus, the values for these years where forecasted.

For the socio-economic data, all GDP (total GDP, agriculture GDP and services GDP), occupation (occupation in agriculture and occupation in services) and subsidies were available from 2000 to 2020 so the value for 2021 was forecasted using the Holt's method with no seasonal component.

The salary on agriculture was missing the years 2000-2004, tourism occupancy was missing 2000-2007 and agriculture production was missing 2019-2021. All this values were forescasted using the Holt's method with no seasonal component.

Second homes values were only available for the years 2001, 2011 and 2019, but were considered consistent over time and for that reason the missing years where imputed using a linear regression and the years 2000 and 2020-2021 were forecasted with the above-mentioned method. Something similar happened with the water consumption data, that was available for the years 1999,2005,2008,2012, 2015 and 2018 and was therefore imputed and forecasted in the same way.

Appendix C – Model evaluation

We specified and test individual models for each response variable (Table C2). Continuous response variables were fit using linear regressions. Count data were fitted using generalized linear models (GLMs) with Poisson distribution. Under and overdispersion in GLMs were tested using the function *testOverdispersion* from R package *DHARMa* (Hartig 2017) and when encountered quasipoisson or negative binomial responses were used to account for it. Due to the use of time series data, there could be temporal autocorrelation in some of the response variables. In such cases, autocorrelation was accounted for by running a generalized least squares (GLS) model, with first-order autocorrelation (1 year lag). When the assumptions of the GLS were not met, 1-year-lagged residuals were included as an additional predictor in the original model. Assumptions of the linear models were validated using the *gvlma* package (Slate 2019). When encountered, heteroscedasticity was accounted for in the GLS model.

The goodness of fit of the linear models was based on the model's R^2 and the global model's significance, as well as the significance of each individual relationship tested. For the GLMs, it was assessed based on the pseudo-R^2 (1-(Residual Deviance / Null Deviance)) and the significance of each individual relationship tested. Finally, for the GLS models, the goodness of fit was evaluated by measuring the correlation between the observed values and the fitted values of the response variable, as well as the significance of each individual relationship specified in the model.

Table C1.: *Stats for all hypothesized relationships. Significant (p-value<0.05) and marginally significant (p-value<0.1) relationships are shown in the last column. Relationships with the same response variable belong to the same model. Model details can be found in Table C2.*

Response	Predictor	Estimate	Std.error	p.value	
Bird abundance	Agriculture land	-0.678	0.284	0.028	*
Bird abundance	Roads	-0.393	0.356	0.284	
Bird abundance	Summer NDVI	13.398	15.136	0.388	
Summer Lake Height	Glacier	-0.281	0.062	0.000	***
Summer Lake Height	Summer flow	0.001	0.000	0.001	***
Summer Lake Height	Summer precipitation	0.122	0.054	0.038	*
Summer Lake Height	Winter snow	0.082	0.052	0.135	
Winter lake height	Winter flow	0.001	0.000	0.000	***
Winter lake height	Glacier	-0.245	0.065	0.002	**
Winter lake height	Winter snow	0.120	0.053	0.038	*
Winter lake height	Winter precipitation	0.062	0.053	0.256	
Meadows, bushes fields	Forests	-1.204	0.008	0.000	***
Meadows, bushes fields	Agriculture land	-0.528	0.008	0.000	***
Summer flow	Agriculture land	-0.258	0.064	0.001	**
Summer flow	Local summer precipitation	0.132	0.043	0.009	**
Summer flow	Winter snow height	0.074	0.026	0.015	*
Summer flow	Water consumption	-0.083	0.000	0.084	
Summer flow	Glacier	0.051	0.064	0.453	
Winter flow	Agriculture land	-0.238	0.085	0.015	*
Winter flow	Winter snow height	0.122	0.045	0.018	*
Winter flow	Local winter precipitation	0.107	0.058	0.094	
Winter flow	Glacier surface	-0.071	0.092	0.464	
Winter flow	Water consumption	-0.004	0.000	0.948	
Agriculture occupation	Agriculture salary	-0.488	0.204	0.027	*
Agriculture occupation	Agriculture subsidies	-0.372	0.204	0.083	
Services occupation	Total population	0.000	0.000	0.008	**
Services occupation	Tourism establishments	0.001	0.001	0.027	*
Summer ET	Forests	0.599	0.223	0.014	*
Summer ET	Local winter precipitation	0.476	0.223	0.046	*
Agriculture GDP	Agriculture production	0.958	0.042	0.000	***
Agriculture GDP	Agriculture occupation	-0.203	0.058	0.003	**

Agriculture GDP	Agriculture subsidies	0.028	0.061	0.656	
Services GDP	Services occupation	0.217	0.087	0.023	*
Services GDP	Second homes	0.956	0.397	0.027	*
Services GDP	Tourism establishments	0.000	0.001	0.970	
Total GDP	Services GDP	1.059	0.089	0.000	***
Total GDP	Agriculture GDP	0.014	0.035	0.691	
Glacier	Max winter Temperature	-0.010	0.040	0.808	
Glacier	Max summer Temperature	-0.005	0.037	0.898	
Summer NDVI	Max summer Temperature	0.028	0.009	0.010	**
Summer NDVI	Summer precipitation	0.021	0.007	0.017	*
Summer NDVI	Forests	0.014	0.006	0.074	
Summer NDVI	Winter precipitation	-0.007	0.005	0.252	
Tourism establishments	Summer Tourism	0.161	0.019	0.000	***
Tourism establishments	Winter Tourism	0.112	0.019	0.000	***
Total population	Second homes	0.041	0.003	0.000	***
Bird richness	Meadows bushes fields	1.987	0.692	0.011	*
Bird richness	Forests	3.092	1.643	0.077	
Bird richness	Roads	-1.867	1.102	0.109	
Bird richness	Max summer temperature	-0.118	0.199	0.559	
Roads	Urban	0.972	0.020	0.000	***
Bird diversity	Meadows bushes fields	2.281	0.697	0.005	**
Bird diversity	Forests	3.629	1.654	0.042	*
Bird diversity	Roads	-2.091	1.110	0.077	
Bird diversity	Max summer temperature	-0.073	0.200	0.721	
Summer snow	Winter snow height	0.738	0.155	0.000	***
Summer snow	Local summer precipitation	-0.579	0.208	0.013	*
Summer snow	Max winter temperature	-0.426	0.181	0.031	*
Summer snow	Max summer Temperature	-0.391	0.178	0.042	*
Winter snow	Max winter Temperature	-0.627	0.189	0.004	**
Winter snow	Local winter precipitation	0.147	0.189	0.445	
Urban	Total population	0.000	0.000	0.000	***
Urban	Tourism establishments	0.001	0.000	0.000	***
Water consumption	Second homes	-0.124	0.019	0.000	***
Water consumption	Total population	0.099	0.000	0.000	***
Water consumption	Agriculture production	-0.017	0.007	0.020	*

Table C2. *Details of each linear, generalized linear (GLM), and generalised least squares (GLS) model used to build the network of interactions in piecewiseSEM. Significance of each pair relationships from the models can be found in Table C1.*

Nº	Model formula	Model type
1	*total GDP ~ agriculture GDP + services GDP*	GLS with AR1 correlation
2	*services GDP ~ occupation services + tourism establishments + second homes*	GLS with AR1 correlation
3	*agriculture GDP ~ agriculture subsidies + agriculture occupation + agriculture production*	Linear model
4	*services occupation ~ tourism establishments + total population*	Linear model
5	*agriculture occupation ~ agriculture salary + agriculture subsidies*	Linear model
6	*total population ~ second homes*	GLM quasipoisson family
7	*tourism establishments ~ winter tourism + summer tourism*	GLM quasipoisson family
8	*summer lake height ~ winter snow + summer flow + regional summer precipitation + glacier*	GLM Gamma family
9	*winter lake height ~ winter snow + winter flow + regional winter precipitation + glacier*	GLM Gamma family
10	*summer flow ~ local summer precipitation + snow height + glacier + agriculture land + water consumption + summer snow*	GLM Gamma family
11	*winter flow ~ local winter precipitation + snow height + glacier + agriculture land + water consumption + winter snow*	GLM Gamma family
12	*water consumption ~ total population + second homes + tourism establishments*	GLS with AR1 correlation
13	*summer et ~ local winter precipitation + forest + max summer temp*	Linear model
14	*summer ndvi ~ forest + regional summer precipitation + regional winter precipitation + max summer temp*	GLM Gamma family
15	*summer snow ~ winter snow height + max summer temp + local summer precipitation + max winter temp*	Linear model
16	*winter snow ~ max winter temp + local winter precipitation*	Linear model
17	*glacier ~ max summer temp + max winter temp*	GLS with AR1 correlation
18	*bird abundance ~ roads + agriculture land + summer ndvi*	Linear model
19	*bird richness ~ roads + forest + bushes + max summer temp*	Linear model
20	*bird diversity ~ roads + forest + bushes + max summer temp*	Linear model
21	*roads ~ urban + roads model residuals*	Linear model
22	*urban ~ total population + tourism establishments + urban model residuals*	Linear model
23	*bushes ~ forest + agriculture land + bushes model residuals*	Linear model

References Supplementary material

Agenzia Regionalle per a la Protezione dell'Ambiente. 2023. https://www.arpalombardia.it. Accessed August 3.

Banca dati inanellamento degli uccelli BIO-AVM ISPRA - NNB. 2023. https://www.geonode.nnb.isprambiente.it/catalogue/#/dataset/169. Accessed August 4.

CORINE Land Cover — Copernicus Land Monitoring Service. 2023. Land Section. https://land.copernicus.eu/pan-european/corine-land-cover. Accessed August 8.

Fick, S. E., and R. J. Hijmans. 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology* 37: 4302–4315. doi:10.1002/joc.5086.

Gühnemann, A., A. Kurzweil, and M. Mailer. 2021. Tourism mobility and climate change - A review of the situation in Austria. *Journal of Outdoor Recreation and Tourism* 34. Editorial: Tourism and Climate Change – an Integrated Look at the Austrian Case: 100382. doi:10.1016/j.jort.2021.100382.

Harris, I., P. d. Jones, T. j. Osborn, and D. h. Lister. 2014. Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset. *International Journal of Climatology* 34: 623–642. doi:10.1002/joc.3711.

Hartig, F. 2017. DHARMa: residual diagnostics for hierarchical (multi-level/mixed) regression models.

Hijmans, R. J. 2015. Raster: Geographic Data Analysis and Modeling. R Package Version 2.4-15. *http://CRAN.R-project.org/package=raster*.

Hyndman, R. J., and Y. Khandakar. 2008. Automatic Time Series Forecasting: The forecast Package for R. *Journal of Statistical Software* 27: 1–22. doi:10.18637/jss.v027.i03.

Instituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA). 2023. *ISPRA Istituto Superiore per la Protezione e la Ricerca Ambientale*. https://www.isprambiente.gov.it/it. Accessed August 4.

Moritz, S., and T. Bartz-Beielstein. 2017. imputeTS: Time Series Missing Value Imputation in R. *The R Journal* 9. doi:10.32614/RJ-2017-009.

Nova, M., A. De Luigi, and L. Pedrazzini. 2019. DUSAF 6.0 - Uso del suolo.

Pan-European Common Bird Monitoring Scheme. 2023. *PECBMS*. https://pecbms.info/. Accessed August 4.

Slate, E. A. P. and E. H. 2019. gvlma: Global Validation of Linear Models Assumptions (version 1.0.0.3).

Statistiche Istat. 2023. http://dati.istat.it/. Accessed August 4.