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Climate response of alpine lakes and impacts on ecosystem services

Abstract

Small alpine lakes are highly sensitive to global warming and human influence, which can affect the ecological integrity of these freshwaters. However, the response of lakes is variable and knowledge about potential impacts on related ecosystem services is insufficient. The project CLAIMES (Climate response of alpine lakes: Resistance variability and management consequences for ecosystem services) therefore aimed at assessing potential impacts on ecosystem services for 15 study lakes located in Niedere Tauern (Austria) and South Tyrol (Italy). In a first step, the lakes' ecological variability was characterized based on limnological data and lake surface temperature modelling. Adopting a participatory approach, the most important ecosystem services were identified, and their importance was evaluated by local stakeholders. The prioritized ecosystem services were quantified using multiple indicators, and potential future impacts were assessed based on different possible worst-case scenarios. Our findings predict that global warming reduces ice cover duration affecting ecosystem functions and consequently the trophic state. Perceptions of local stakeholders were mostly consistent, but key ecosystem services depend on the regional context. Our results also indicate that the provision of ecosystem services by lakes is largely influenced by the local socio-ecological characteristics. The projected decline in ecosystem services in the future calls for better integration of alpine lake ecosystem services into decision- and policymaking across different governance levels.

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1 Introduction

Lakes greatly contribute to human well-being by providing various ecosystem services, for example, water for domestic, agricultural, and industrial use, energy production, flood control, and recreation (Allan et al., 2017; Fu et al., 2018; Reynaud and Lanzanova, 2017; Sterner et al., 2020). Despite the growing number of studies on ecosystem services of freshwater ecosystems, most studies have focused on large lowland lakes (Allan et al., 2015; Sterner et al., 2020), while the ecosystem services of alpine lakes are still poorly understood. However, there is strong evidence that climate change threatens the integrity of alpine lakes more severely and faster than comparable ecosystems in lowland regions (Moser et al., 2019; Schmeller et al., 2018). This is due to a generally more pronounced rise in temperature as well as the high vulnerability of alpine ecosystems (Caldwell et al., 2021; Roberts et al., 2017; Sadro et al., 2019). Higher temperatures reduce the ice-cover duration, affect ecosystem functions such as primary production, and alter hydrological patterns by diminishing the volume of inflowing snow melt (Sadro et al., 2019; Weckström et al., 2016). Moreover, lake surface water temperature and ice cover duration in response to air temperature is greatly influenced by local habitat-specific characteristics such as altitude, topographic shading, and bathymetry, lake depth and residence time (Novikmec et al., 2013; Thompson et al., 2005). This makes it difficult to draw general conclusions about the impacts of global warming on alpine lakes. Therefore, research is needed at the local and regional level to characterize the variability of lakes' responses and the potential impacts of climate change.

In addition, alpine lakes are threatened by agricultural and recreational activities (Senetra et al., 2020; Tiberti et al., 2019). In most cases, higher intensity of use of alpine lakes is associated with higher nutrient inputs and, thus, eutrophication, affecting ecosystem functions and integrity as well as ecosystem services (Culhane et al., 2019; Grizzetti et al., 2019; Weckström et al., 2016). However, cultural ecosystem services, such as aesthetic, recreational, spiritual values, which are particularly important in combination with touristic use, were rarely assessed for alpine lakes. As the importance of alpine lakes for recreational use is expected to increase with global warming in lowlands (Pröbstl-Haider et al., 2021), conflicts of use will become more relevant in the future, e.g., tourists preferring clear lakes, fisheries aiming at higher production through fertilization, and livestock farming requiring water withdrawal during droughts. To deal with conflicts arising from competing uses, it is fundamental to understand how climate change affects the function of alpine lakes, to quantitatively describe the variability of alpine lake responses and to examine the effects on ecosystem services caused by ongoing alpine lake ecosystem deterioration. Such knowledge is of relevance for developing sustainable management strategies and adaptation or mitigation measures to face global change.

Therefore, the inter- and transdisciplinary project CLAIMES (Climate response of alpine lakes: Resistance variability and management consequences for ecosystem services) aimed at (1) examining effects of global warming on the lakes' ecological conditions, (2) quantifying ecosystem service provision under current and future conditions, and (3) evaluating ecosystem services to provide recommendations for decision-making and policymaking. Our capacity to predict future changes in ecosystem services can be increased through the characterization of the variability of the lakes' responses to global change pressures. By applying an integrated ecosystem service approach, the findings can be used to raise awareness on potential (future) conflicts and support an adaptive ecosystem service governance. This paper first presents the methodological approach and then provides a synthesis of the key findings. Finally, the most important conclusions are drawn, and management needs are indicated.

2 Material and methods

2.1 Conceptual background

The project consisted of three work packages (WP), which are related to each other through the provision of data or information (Figure 1). WP1 addressed the characterization of lakes' variability. The ecological status of alpine lakes greatly depends on the specific environmental conditions such as topography, solar radiation, and catchment size as well as on the level of human use. It is expected that global warming increases the variability of the lakes' responses with different effects on the Lake Surface Temperature (LST) and eutrophication (Thompson et al., 2005). The tasks of this WP therefore included the integration of existing limnological data with further sampling to obtain a comprehensive dataset. To assess the impacts of climate change on the lakes' ecological status, LST was predicted under future climate scenarios using multivariate statistical approaches.

WP2 focused on the quantification of ecosystem services. As ecosystem services of small alpine lakes were rarely addressed in previous research, the objective of this WP was first to identify indicators that are suitable to capture small-scale differences between lakes over time. Second, ecosystem services of the study lakes were quantified for current conditions, based on multiple indicators, and applying various assessment approaches. Finally, potential global change pressures were identified and potential changes in ecosystem service provision under future scenarios were assessed at the lake level, hypothesizing that increased variability in lake response also differently affects ecosystem services of individual lakes.

WP3 included the evaluation of ecosystem services and elaboration of policy advice. In addition to quantifying ecosystem services in biophysical terms (WP2), the perceived importance by society is crucial for management and decision-making. Thus, experts, stakeholders and interest groups were involved to identify important ecosystem services, evaluate their importance in the respective study region and compare the stability of ecosystem service provision under future scenarios. It is hypothesized that local factors, leading to an increased variance in ecosystem service provision, would require differentiated management approaches to avoid potential conflicts in the future.

2.2 Study area

The project focused on 15 study lakes without direct glacial impact, located in two regions, South Tyrol (Italy) and Niedere Tauern (Austria; Figure 2). The lakes are characterized by partly differing socio-ecological characteristics (Table S1), but all lakes are generally ice-free from May/June to October/November and trophic condition has been assigned within the ultra-oligotrophic to oligo-mesotrophic range. As identified by Schirpke et al. (2021a), the lakes can be grouped into four groups based on their socio-ecological characteristics:

- Group 1 (Antholzer See and Pragser Wildsee) comprises larger lakes at lower elevations, which

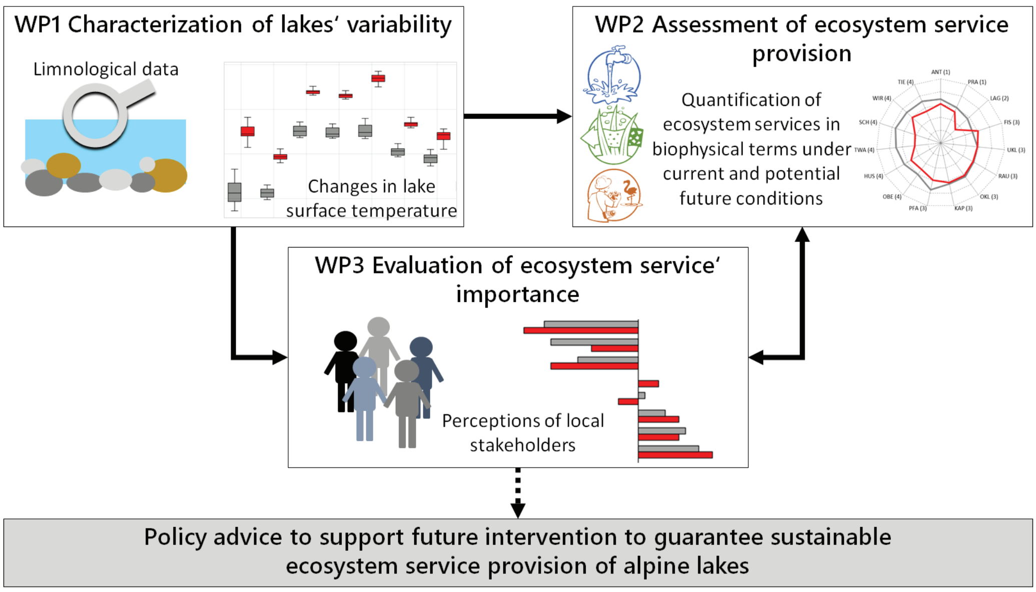

Figure 1. Schematic outline of the three work packages (WP1-3) and their linkages.

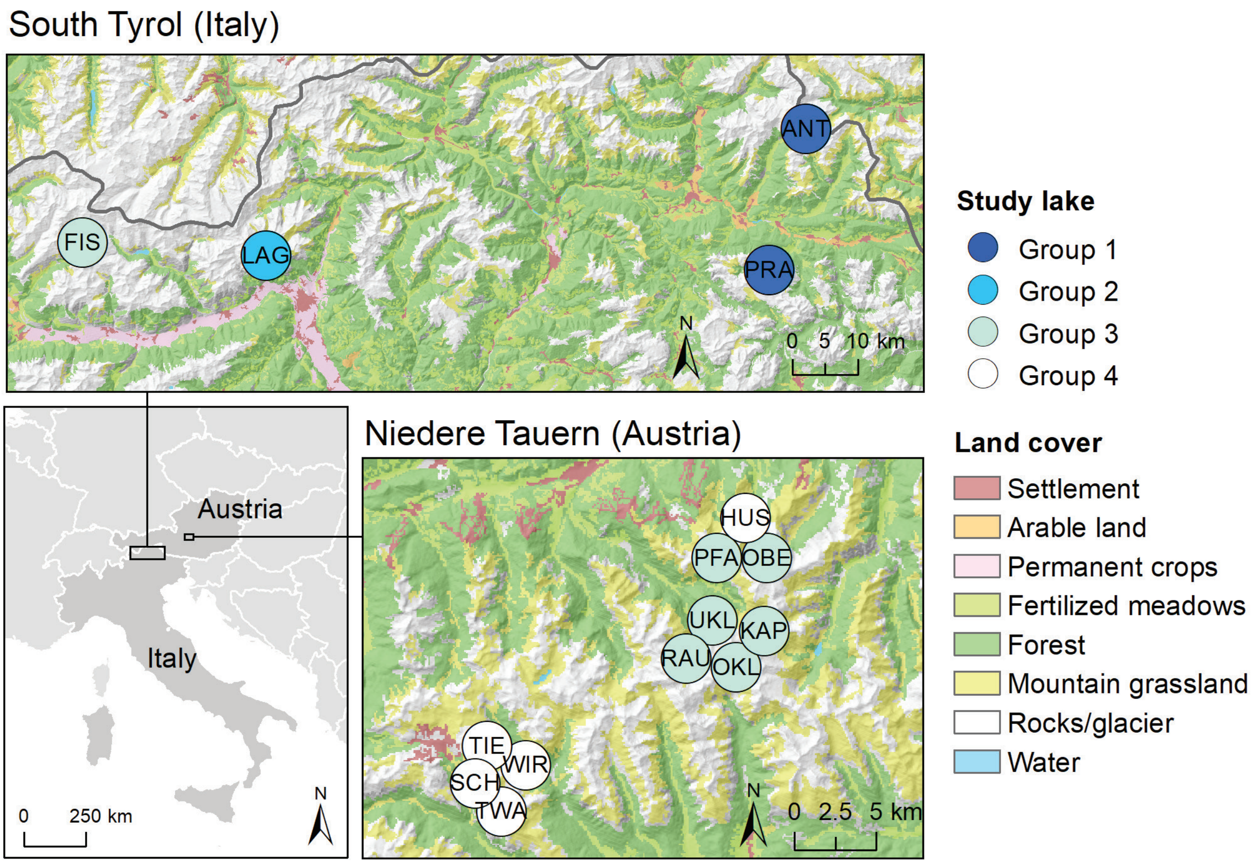

Figure 2. Location of the 15 study lakes in South Tyrol and Niedere Tauern. ANT – Antholzer See/Lago di Anterselva, PRA – Pragser Wildsee/Lago di Braies, LAG – Langsee/Lago Lungo (Spronserseen/Laghi di Sopranes), FIS – Fischersee (Saldurseen/Laghi di Saldura), UKL – Unterer Klaffersee, RAU – Rauhenbergsee, OKL – Oberer Klaffersee, KAP – Kapuzinersee, PFA – Pfannsee, OBE – Obersee, HUS – Hüttensee, TWA – Twenger Almsee, SCH – Oberer Schönalmsee, WIR – Unterer Wirpitschsee, TIE – Tiefenbachsee. Figure modified from Schirpke et al. (2021a).

are easily accessible and have high visitation rates.

- Group 2 (Langsee) includes lakes located at high elevation with little vegetation. This group is located close to densely populated areas, but as it has long access times, it has lower visitation rates than group 1.
- Group 3 (Fischersee, Obersee, Unterer Klaffersee, Rauhenbergsee, Oberer Klaffersee, Kapuzinersee, Pfannsee) contains small and remote lakes that are located at high elevations. The surrounding municipalities are sparsely populated, and the lakes have low visitation rates.
- Group 4 (Hüttensee, Twenger Almsee, Oberer Schönalmsee, Unterer Wirpitschsee, Tiefenbachsee) comprises lakes that are generally lower elevated and easier accessible than those of groups 2 and 3, but population numbers and visitation rates are similar to group 3.

2.3 Characterization of lakes' variability (WP1)

Temperature data loggers were installed in 2019 to record water temperature every two hours at the lake surface (1-1.5 m depth) and at maximum depth. Water samples were taken in summer 2019, 2020 and partly 2021 at maximum depth for the analyses of the water chemistry, the chlorophyll a concentration and the plankton community composition (Pritsch et al., 2023). Limnological data were used as indicators for quantifying ecosystem services as well as to estimate impacts of climate change on water quality, biotic community, and nutrient composition, influencing ecosystem services (Table S2). A decisive factor is hereby the long ice cover duration (4-9 months), which limits planktonic algal growth and thus influences the trophic condition and the ecological integrity in the lakes (Thompson et al., 2005).

To model LST of individual lakes, we used Generalized Additive (Mixed) Models (GAMs) due to their high flexibility in model setup as well as their high interpretability (Hastie and Tibshirani, 1986). The models were based on (1) LST measurements over the decades and (2) high-quality gridded observational datasets covering different atmospheric parameters (Enigl and Kurmayer, 2023). For LST data, daily means of the 2- and 4-hourly data were computed. For meteorological parameters, nearest grid points to the lakes were identified and the mean of the four neighbouring grid points was calculated accounting for altitude by applying a correction factor, i.e., the moist adiabatic lapse rate of 6.5 °C km-1. We used different meteorological input variables from the SPARTACUS and SNOWGRID dataset for the past (Olefs et al., 2020) and the ÖKS15 and FUSE-AT datasets for future periods. Variables included (i) daily minimum/maximum temperature, (ii) daily precipitation totals and (iii) daily information on snow depth. Furthermore, we derived 14 and 30-day mean values of all variables to consider time lags in the lakes' response to atmospheric parameters. To account for seasonality, we also included the day of year in our model. LST were modelled for different future emission scenarios, including the RCP8.5 (van Vuuren et al., 2011).

To estimate the influence of climate warming on the ecological status of the lakes, i.e., the effects of changes in LST as well as the beginning and end of the (ice-free) growing season were determined for each year in the future by the respective intersection with 4 °C for all lakes individually. If the nutrient situation remains unchanged, the currently observed chlorophyll a concentration (as an indicator of net algal growth) can be adjusted by extrapolating the predicted growing season and the average temperature increase, using the physiological Q10 rule (e.g., Ahlgren, 1987). Ice cover with as little as 10 cm of snow cover acts against eutrophication because it is virtually opaque (i.e., reduction of photosynthetic active radiation to <1% of surface insolation, Wetzel and Likens, 2000, Table 5-4, p. 64). Thus, it can be assumed that during prolonged ice cover formation algal growth in the water column is reduced to an annual minimum close to zero due to darkness and sinking losses (Wetzel and Likens, 2000).

2.4 Quantification of ecosystem services (WP2)

Ecosystem services that are relevant for alpine lakes as well as suitable indicators for their quantification were collected through a literature review using the Scopus database. Based on the results, a set of relevant ecosystem services was identified and aligned with the Common International Classification of Ecosystem Services (CICES, Haines-Young and Potschin, 2018). For the most important ecosystem services as identified by local stakeholders (Table S2, see also section 2.5), multiple indicators describing various aspects of potential ecosystem service provision were identified (Table S3), which were partly derived from literature as well as newly developed to allow assessing and monitoring the variability of ecosystem services at fine spatial scale. To assess different facets of multiple ecosystem services in non-monetary terms, the indicators were calculated using different biophysical quantification approaches, including direct measurements (i.e., limnological data from WP1), modelling based on primary data, and socio-cultural methods (preference survey by Schirpke et al., 2021b). After collecting all necessary data, ecosystem service provision was quantified for all study lakes (see also Schirpke et al., 2021a). Finally, ecosystem service values for each lake were derived by calculating the mean across all rescaled individual indicator values (values between 0 and 1) for each individual ecosystem service.

To estimate future ecosystem service provision, we considered a combination of different possible worst-case developments. These included high emissions under the future emission scenario RCP8.5 (van Vuuren et al., 2011), the construction of a small dam, the intensification of farming activities, tourism increase, and forest regrowth on abandoned grassland. Future indicator values were derived based on data projections or in case of lacking data by applying change rates to current ecosystem service values. For details, see Schirpke and Ebner (2022). Due to socio-ecological differences of the study lakes, only the relevant scenarios for each individual lake were considered to quantify future ecosystem service provision (Schirpke and Ebner, 2022). The selection was based on three variables: These included accessibility, which enables recreational use and was determined based on access time and trail difficulty (Laatikainen et al., 2017; Pröbstl-Haider et al., 2016; Schamel and Job, 2017). The suitability of mountain farming, which depends on climatic conditions (Jäger et al., 2020), was derived from the presence/absence of grassland or agricultural land in proximity to the lake. The third variable regarded the protection status, which is influential for new infrastructure such as dams for hydropower generation or regulating the water flow (Kellner, 2019) with impacts on protected habitats (Porst et al., 2019). For further details, see Schirpke and Ebner (2022). Finally, potential impacts of global change pressures on ecosystem services were assessed by comparing the current and future provision of multiple ecosystem services.

2.5 Evaluation of ecosystem services (WP3)

The most important ecosystem services were identified by local stakeholders and experts, representing different sectors, i.e., government & authorities, economy & tourism, research & education, and non-governmental organisations. In two different workshops, which were held in Bozen (Italy) in January 2020 and in Radstadt (Austria) in August 2020, stakeholders collaboratively selected the most relevant ecosystem services provided by the alpine lakes in the respective regional context. Both workshops followed the same structure and included participatory elements such as exercises in small groups, plenary discussions, as well as individual and deliberative feedback rounds. Finally, a concise set of priority ecosystem services was derived using a rating exercise. For further details on the approach, see Ebner et al. (2022a), Fontana et al. (2023), Schirpke et al. (2021a).

The current ecosystem service provision in the two study regions as well as their stability over time was evaluated using a multi-criteria decision analysis (MCDA) approach, comprising four main steps. First, the most important ecosystem services were identified in stakeholder workshops (as described above). Second, perceived relative weights of ecosystem services were analysed using a pairwise comparison questionnaire according to the Analytic Hierarchy Process (Saaty, 1980). Individual priorities were aggregated sector-wise into a single representative evaluation for all stakeholders in each region (Saaty and Peniwati, 2013). Third, attributes to describe ecosystem services were collected and indicators were quantified for the current state and under future scenarios (see section 2.4). Finally, MCDA was applied synthesizing ecosystem services, weights, and indicators for the lakes in each region using PROMETHEE (Brans and Vincke, 1985; Macharis et al., 2004) to visualize and evaluate ecosystem service provision. For details, see Fontana et al. (2023).

To identify a potential need for policy measures for adaptation to climate risks as well as potential management measures, we first carried out an expert elicitation involving representatives of regulatory bodies on the regional and national level focusing on governmental bodies that are primarily in charge of agricultural, environmental, and land use regulations with regard to alpine lakes and surrounding areas. This elicitation round consisted of half-structured interviews following expert elicitation protocols, specific to the area of expertise of the respective governmental body. Before the interview via teleconference, we sent a list of guiding questions to the experts. The questions aimed to elicit the experts' opinion about climate risks for alpine lakes, potential regulatory responses, and current regulations that are suitable to respond to such risks in the near future. The statements on the adequacy of current regulations were analysed in parallel with an analysis of the existing regulatory framework. Furthermore, the expert elicitation extended to potential risks arising from climate change in combination with potential pressures from human activities such as tourism and agriculture.

During two concluding online workshops with local stakeholders (for South Tyrol in May 2022, for Niedere Tauern in April 2022), the resulting insights were validated, following a protocol adjusted from the initial expert elicitation. Two discussion rounds were first carried out in sub-groups and then synthesized in a large plenum group discussion to ensure consensus. In the first round, the risks by global change pressures to the protection of the ecological state of the lakes were collected from different perspectives, notably water quality conservation, tourism, and agriculture (including fishery and hunting). In the second round, stakeholders discussed potential measures, conflicts and solutions regarding the risks arising from human use and climate change.

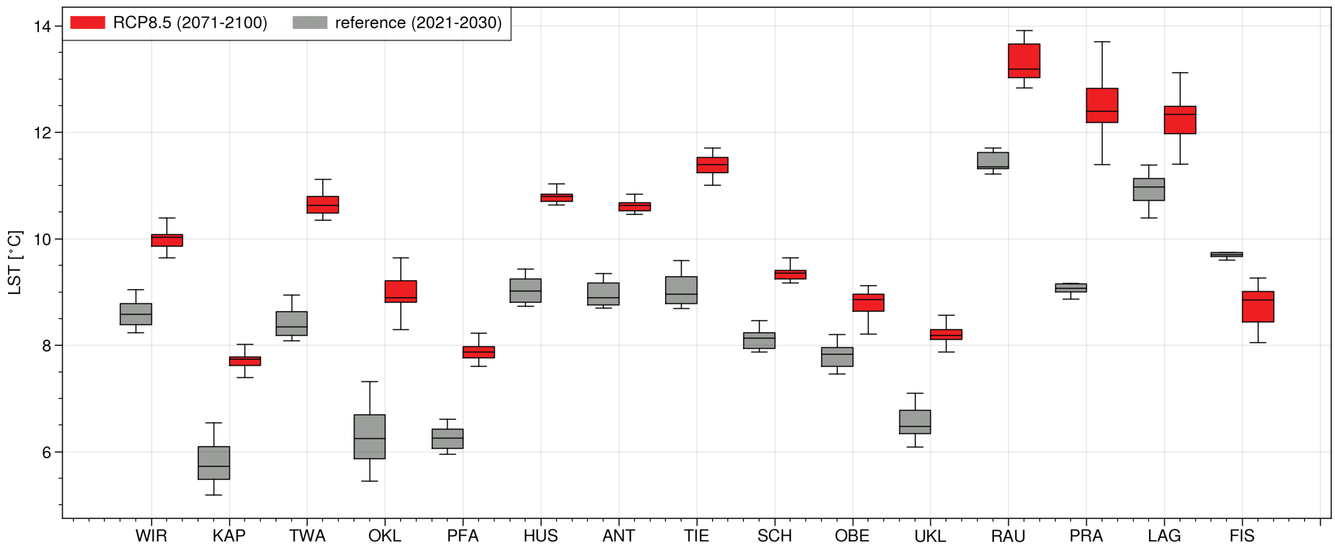

Figure 3. Comparison of mean summer temperatures (ice-free period) of the study lakes (sorted by their trophic status) in the reference period (2021 – 2030, grey) and the distant future (2071-2100, red) accounting for RCP8.5. Interpretation of the boxplots: the middle bar represents the median, and the lower and upper bars represent the 25 and 75% quantiles, while the error bars indicate the 95% confidence interval.

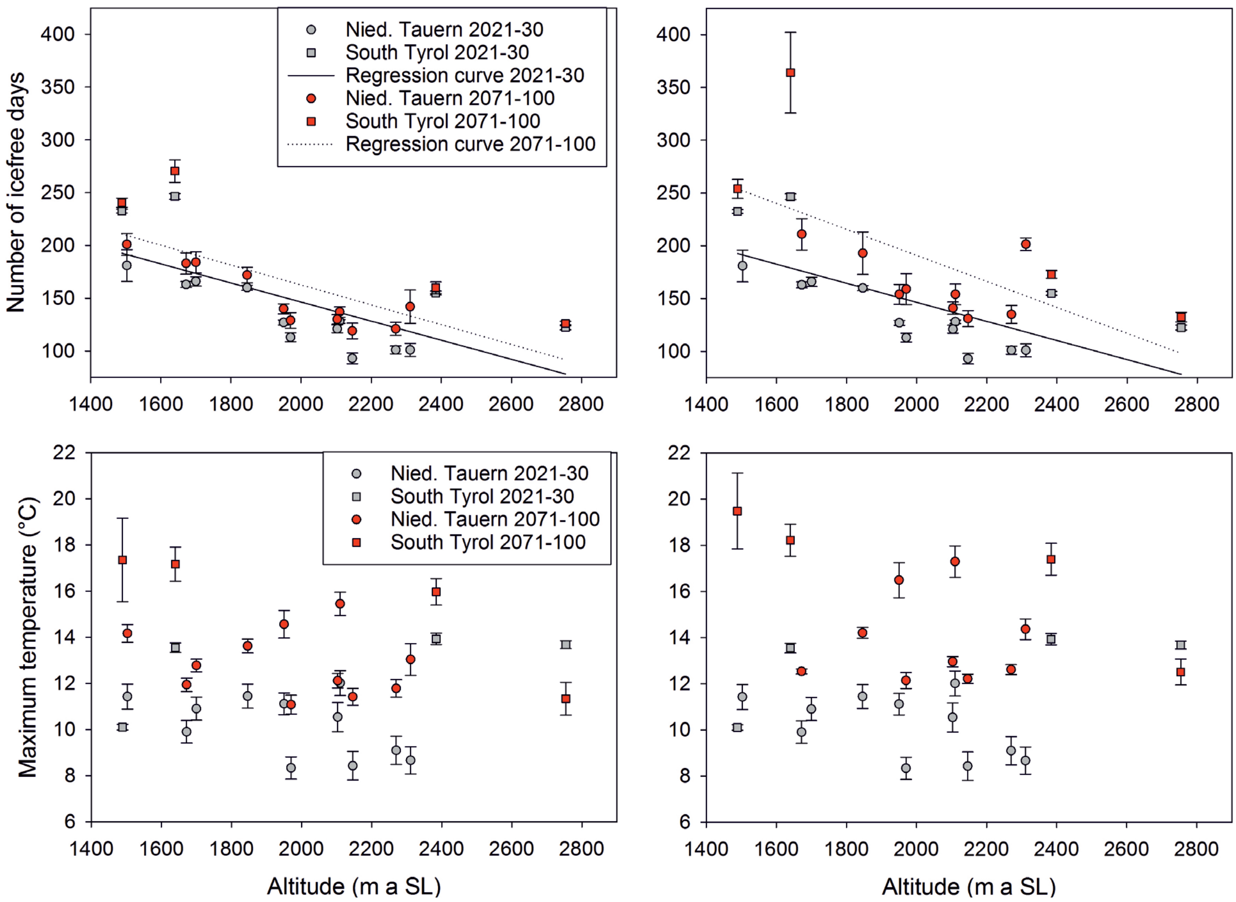

Figure 4. Upper: Growth period (ice-free days) vs. altitude (m a SL) for the distant future (red symbols, 2071-2100) in the median (left) as well as for the 85% quantile (right) compared to the reference period (2021-30), grey symbols. Lower: Maximum surface temperatures vs. altitude compared to the reference period. Left: at the median; right, at the 85% quantile. NT, Niedere Tauern; ST, South Tyrol. Error bars indicate 1 SD. Only statistically significant linear regression curves are shown ($p < 0.01$, $R2 = 0.43 – 0.55$).

3 Key findings

3.1 Lakes' responses to climate change are highly variable

The modelling results indicate that climate change will increase the LST of the study lakes, i.e., by 1.0-2.0-3.3 °C (min-mean-max), (Figure 3; Enigl and Kurmayer, 2023). Compared to the reference period 2021-2030, the largest temperature increase was predicted for the summer months July and August. Consequently, the ice-free period will increase (median 3-40 days, 85% quantile 10-98 days), which corresponds to a maximum increase of 7 to 14 weeks, twice as long as today for some lakes (Figure 4). Although ice cover will remain for most lakes, there could even be completely ice-free years for lower altitude lakes (i.e., Antholzersee). Notably the ice-free time of the lakes in South Tyrol is longer than for the lakes in Niedere Tauern located at the same altitude. In addition, temperature maxima are predicted to increase by 2.2-2.6-6.8 °C (Figure 4). This means that temperature maxima between 16-18 °C will be relatively common at the surface of lakes in the future and LST will become generally more variable. For the 85% quantile, even more extreme temperature maxima can be expected, namely 1.2-4.0-9.2 °C. Because an ice cover is predicted to last over several months for most lakes even during the distant future (2070-2100), planktonic algal net growth is expected to increase moderately only. Accordingly, chlorophyll a is expected to change by -0.1-0.5-0.8 µg/L (for the 85% quantile, 0.1-0.9-1.7 µg/L), inducing a shift from the

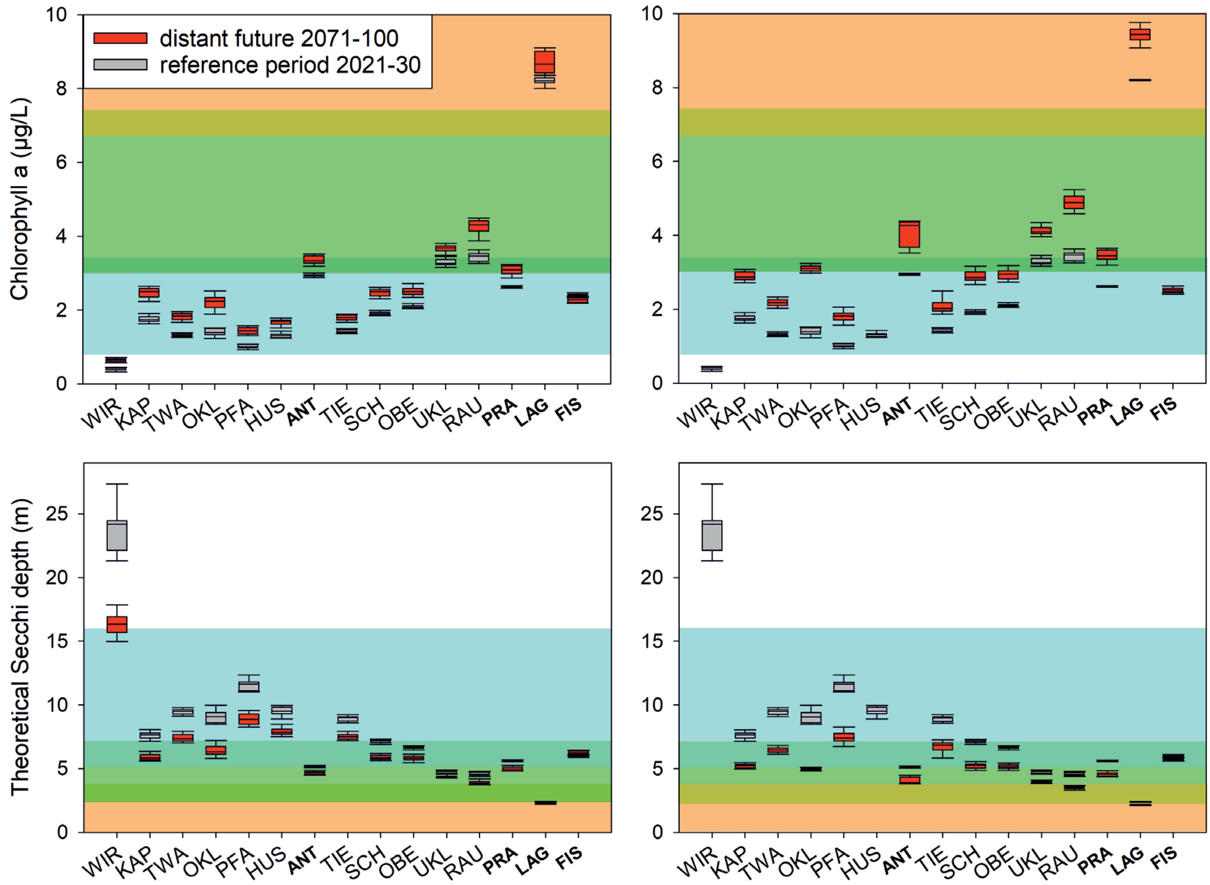

Figure 5. Prediction of chlorophyll a concentration (upper) and transparency (lower) for the distant future (2071-2100) compared to the reference period (2021-30). Left: at the median; right, at the 85% quantile. Interpretation of the boxplots: the middle bar represents the median from the 30 y of observation, and the lower and upper bars represent the 25 and 75% quantiles from 30 y of observation, respectively, while the error bars indicate the 95% confidence interval. The colours indicate the trophic classification: oligotrophic (blue), mesotrophic (green), eutrophic (orange). The study lakes were arranged according to increasing trophic status. The full name of study lakes is given in Figure 2 (Lakes located in South Tyrol are indicated by bold letters).

(ultra-)oligotrophic to (oligo-)mesotrophic trophic level of the study lakes (Figure 5). Consequently, a decrease in Secchi depth between 0.3-1.8-7.5m will result from higher irradiance absorption due to algal growth (for the 85% quantile, 0.2-2.4-5 m). Thus, transparency would decline towards the mesotrophic range.

3.2 Stakeholders` perceptions of ecosystem services are largely consistent

Across the two regions, stakeholders selected seven different ecosystem services (Figure 6, Table S2). In both study regions, stakeholders prioritised habitat, recreation, and aesthetic, while the other ecosystem services differed (Schirpke et al., 2021a). In South Tyrol, the stakeholders attributed highest weighting to habitat, followed by aesthetics, water, recreation, and representation (Ebner et al., 2022a). In the Niedere Tauern, stakeholders weighted habitat highest, followed by existence, aesthetics, research/education, and recreation. In both regions, the priorities of each stakeholder group were largely consistent with the weightings of the individual stakeholders, although some dispersion occurred for water and recreation in South Tyrol and aesthetic and research/education in Niedere Tauern.

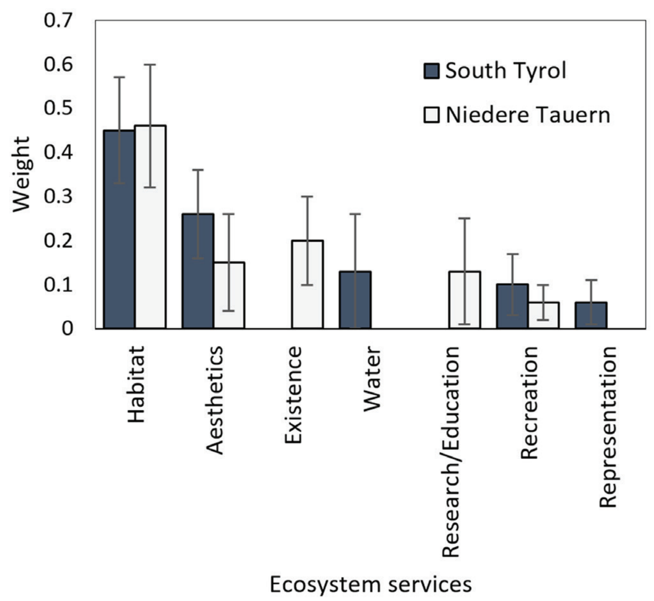

Figure 6. Weighting (aggregated) of ecosystem services selected by stakeholders (South Tyrol, n=39; Niedere Tauern, n=16) in the two study regions.

3.3 Lakes' socio-ecological characteristics influence ecosystem service provision

To capture the multifaceted characteristics of each ecosystem service, multiple indicators are required including biophysical variables as well as socio-cultural valuations. Moreover, the indicators need to enable the detection of differences in ecosystem services among small lakes and to allow the monitoring of changes over time, resulting in a comprehensive set of indicators (Schirpke et al., 2021a). Mean ecosystem service values differed across the groups of lakes (Figure 7). Larger and lower elevated lakes (group 1) had higher ecosystem service values (particularly for water, recreation, and representation) than smaller and higher elevated lakes (groups 2-4). The socio-ecological context led to significant differences for water, recreation, representation, research, and education) across the four groups, while it had less influence on habitat, aesthetics, and existence. Such differences were also confirmed by the results of the MCDA (see also Fontana et al., 2023) providing a disaggregated view on the ecosystem service profiles, which were based on the relative contribution of an individual ecosystem service to overall performance of a lake, i.e., positive or negative outranking flow of a respective ecosystem service (Figures S1 and 2).

3.4 Ecosystem service provision will mostly decline in the future

Under the future scenarios, habitat and aesthetics will decline for all lakes (Schirpke and Ebner, 2022, Figure 7). Ecosystem services of easily accessible and non-protected lakes (groups 1 and 4) may be more affected than remote lakes due to potential increase in farming activities (group 3). In contrast, a higher number of warm days will lead to increased recreation potential at easily accessible lakes (groups 1 and 4), while reduced accessibility may increase the ecosystem service potential for research due to lower levels of human use. Despite the difference in the provision of individual ecosystem services under current and future conditions, there were no changes in the ranking of the lakes in South Tyrol according to the overall performance (Figure 8, Figure S1). In contrast, changes in ecosystem service values resulted in changes in the overall ranking in Niedere Tau-

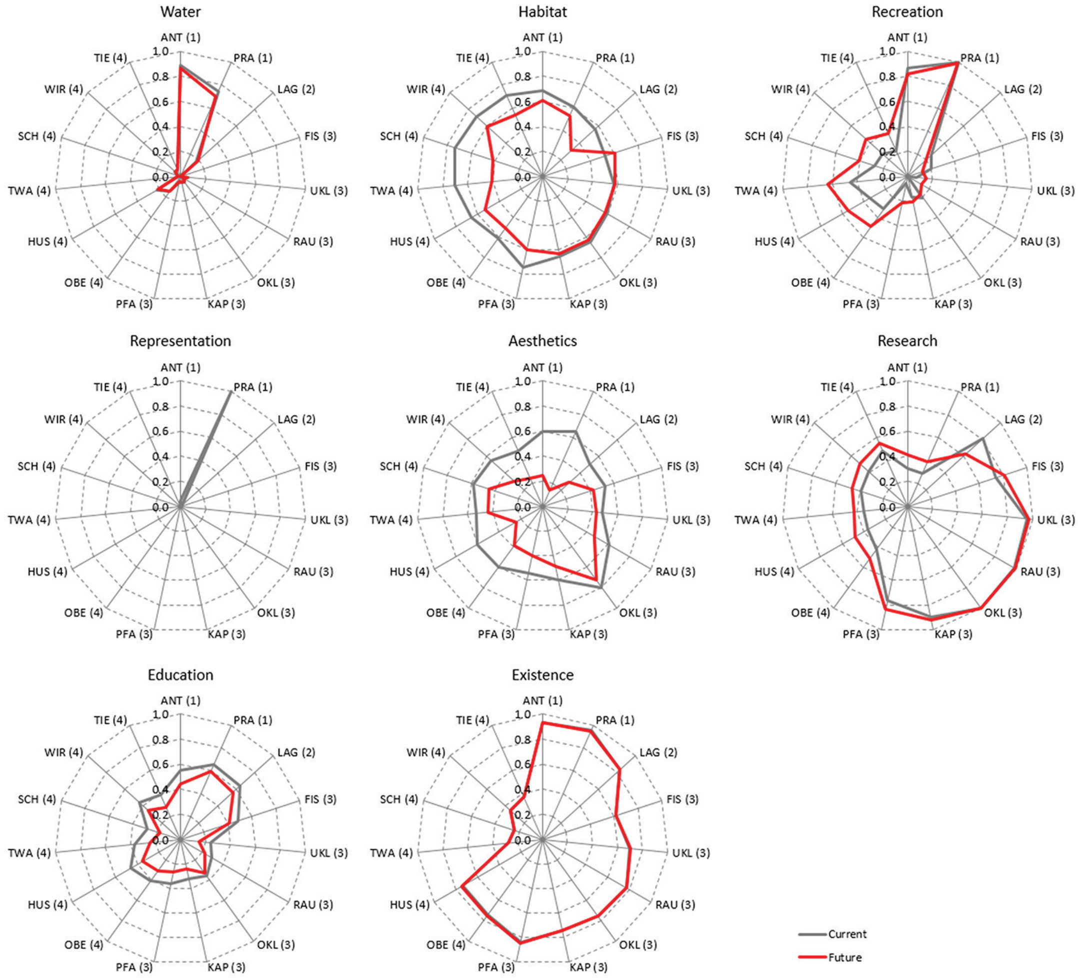

Figure 7. Standardized ecosystem service values under current (grey) and potential future (red) developments (2071-2100) of the 15 study lakes. The number after the lake acronym indicates the socio-ecological group (see Figure 2). For representation, future values could not be calculated with the indicators.

ern, particularly for lakes in the middle ranks (Figure 8, Figure S2). In general, the results indicate negative changes in the performance of the lakes for groups 1, 2 and 4, but positive changes for group 3.

3.5 Management is needed to face global change pressures

Experts from regulatory agencies mostly indicated that climate change per se does not require immediate regulatory intervention. The current institutional framework seems appropriate to respond to potential regulatory concerns that might arise from climate change alone in the next 20 to 30 years. However, in combination with an increasing use for recreational, agricultural, or other human purposes, additional instruments for resource management will be necessary due to local specificities.

In both study regions, local stakeholders recognized risks from global change pressures from different uses, including tourism, agriculture, fishery, and climate change. The stakeholders emphasized that management options need to be carefully evaluated, as conflicts between different types of use may increase and be more critical due to higher pressure on natural resources. In general, they favoured "soft" measures such as visitor guidance and information to face pressures from recreational use. Further examples are provided in Table 1. In South Tyrol, stakeholders would also support strict regulations, if necessary, for example, in the management of water reservoirs for artificial snow and hydroelectric use. As such structural interventions have massive impacts on the ecosystems, they can cause a decline in biodiversity as well as other associated ecosystem services such as aesthetic and recreation. A solution

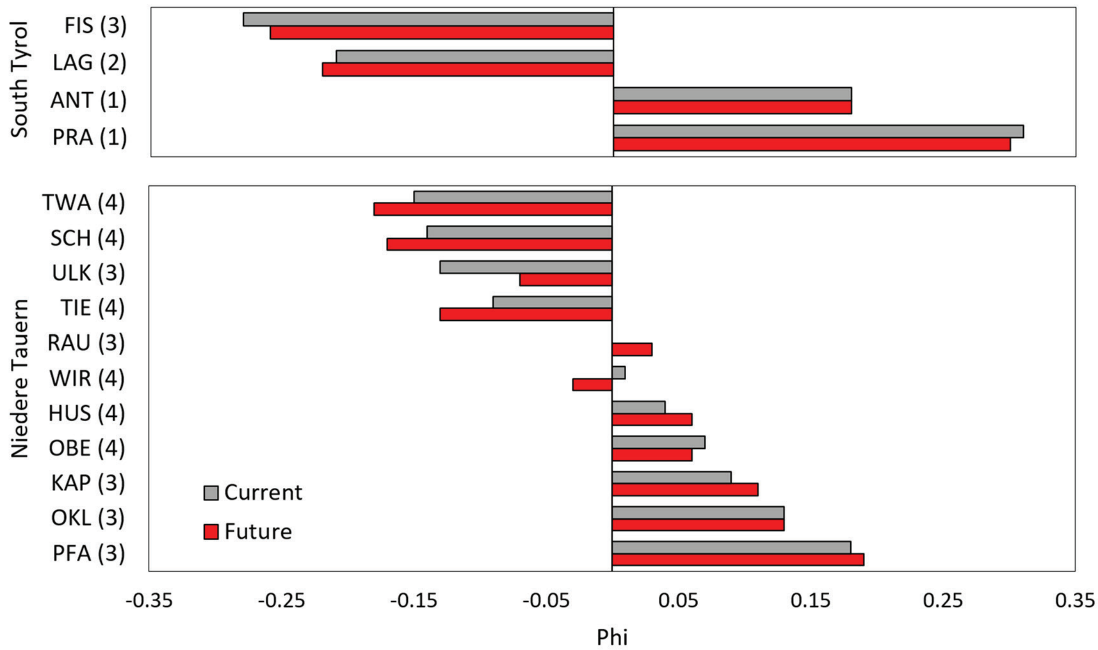

Figure 8. Comparison of ecosystem service provision under current conditions and future scenarios (2071-2100). Phi-values represent the net outranking flows (multicriteria, PROMETHEE II, scaled from -1 to 1) and provide a complete ranking of the performance of the lakes in each region, reflecting the ecosystem service prioritization and integrating indicator values and weights. The number after the lake acronym indicates the socio-ecological group (see Figure 2)

may be the construction of new artificial basins instead of altering natural lakes, even though aesthetic values of mountain landscapes may be negatively affected by artificial infrastructures.

Regarding potential conflicts of interest between user groups, neither regulators nor other stakeholders indicated an urgent need for more restrictive national regulation. However, a regionalized touristic overuse of lakes, e.g., during peak times in the summer as well as temporal expansion into shoulder seasons, may require an active visitor management at the local and regional level. Similarly, stakeholders indicated that potential issues of illegal over-abstraction of water resources or fish introduction for recreational fishing might become more frequent in the future and are best identified and prevented at the local level.

4 Conclusion and outlook

This project contributes to the knowledge on small alpine lakes' responses to climate change and related impacts on ecosystem services in several ways

Table 1. Examples of measures discussed by local stakeholders to counteract the impacts of tourism and agriculture on the ecological integrity of alpine lakes.

Pressure	Measures
Tourism increase	• Awareness raising through information boards at lakes that are already highly frequented, rangers, social media, tourism associations • Sensitization of stakeholders and visitors (e.g., through the tourist information) • Targeted and adapted infrastructure (paths, benches) for visitor guidance • Reducing accessibility (no maintenance of hiking trails, remove trails from maps, move trails further away from the lakes, prohibition of E-bikes) • Reducing visitation rates through price control (parking fees, bus tickets) • Hut concessions depending on the number of visitors • Regulation of bathing
Agricultural use	• Control of grazing in the immediate vicinity of the lakes (fencing) • Providing drinking troughs for cattle • Regulation of the number of livestock and duration of grazing • Stricter regulations for agriculture in the region (i.e., use of pesticides, fertilization) to reduce potential atmospheric input

by applying an integrative approach. First, although predictions of LST indicated a variable temperature increase across the lakes, the results suggest that the growing season for all lakes will be longer but still depend mostly on the influence from altitude, i.e., through the environmental lapse rate of temperature. Most lakes will continue to be ice-covered, but there could be years when lakes at lower elevations are completely ice-free. This reduction in the duration of ice cover will lead to a shift towards higher trophic levels and a significant reduction in transparency. Since in the climatic projections of this study nutrient inputs were assumed to remain unchanged, this estimate of eutrophication due to climate warming as a single factor is rather conservative but may be more extreme if nutrient loading increases.

Second, key ecosystem services of alpine lakes were identified in a participatory process with local stakeholders (Ebner et al., 2022a; Fontana et al., 2023; Schirpke et al., 2021a). Although stakeholders partly prioritized the same ecosystem services in the two different regions, it also became clear that the selection of the most important ecosystem services depends on the regional context. Further, we propose multiple indicators for quantifying the ecosystem services in non-monetary terms (Schirpke et al., 2021a). These indicators account for different ecological and socio-economic aspects that are relevant for measuring fine-scale differences in ecosystem service provision among different lakes and allow monitoring of ecosystem services over time.

Third, by accounting for the lakes' local socio-ecological context, we gained deeper insights into underlying mechanisms that influence ecosystem service provision and potential future changes. Our findings suggest that some ecosystem services such as habitat, aesthetic and existence are rather independent from the socio-ecological context, while water, representation, research, and education mostly varied across groups of lakes (Schirpke et al., 2021a). Consequently, also the application of future scenarios to ecosystem services indicates potential impacts that are mostly negative, especially on habitat and aesthetic, while for the other ecosystem services, level and direction of changes are more variable, depending on the individual lakes' ecological conditions and the local socio-ecological context (Schirpke and Ebner, 2022).

Our findings about potential future impacts on ecosystem services underline the need for better integration of alpine lakes into the broader governance and across different levels of management (Fontana et al., 2023), for example, through stronger integration of risk management approaches into water management plans. While cross-national policies may enable research activities and support decision-making in general, measures need to be tailored to the specific environmental conditions, the local demands, and values, as emphasized by stakeholders. However, to enable the management of future impacts of global change on alpine lakes and associated ecosystem services, further research activities need to be intensified adopting inter- and transdisciplinary approaches. These will help to deepen the understanding of lakes' responses to environmental changes and to strengthen the awareness of potential impacts of human uses.

About this work

This work synthesizes the key findings of the project CLAIMES (CLimate response of AlpIne lakes: resistance variability and Management consequences for Ecosystem Services, https://www.uibk.ac.at/projects/claimes/), partly based on published findings by Ebner et al. (2022a, 2022b), Enigl and Kurmayer (2023), Fontana et al. (2023), Pritsch et al. (2023), Schirpke et al. (2021a), and Schirpke and Ebner (2022).

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Declaration of Competing Interest

The authors report no potential conflict of interest.

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