Climate response of alpine lakes: Resistance variability and management consequences for ecosystem services (CLAIMES)

FINAL REPORT

Funded by Earth System Sciences, Austrian Academy of Sciences

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Twengeralmsee, 1950 m a.s.l., 22.7.2019

Mittl. Landschitzsee, 1940 m a.s.l., 30.7.2019

Photographs by R. Kurmayer

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Suggested citation:

Schirpke, U., Ebner, M., Fontana, V., Ohndorf, M., Enigl, K., Pritsch, H., Pla-Rabes, S., Ilyashuk, B., Kurmayer, R. (2023) Climate response of alpine lakes: Resistance variability and management consequences for ecosystem services. Final Project Report, ÖAW – Austrian Academy of Sciences, Vienna (Austria), 88 pp.

Summary

Due to their pristine nature remote alpine lakes are considered most valuable. At the onset of this project, ecosystem services (ES) of alpine lakes were poorly characterized and have not been recorded in a systematic manner. The central aim of this project was to find out how ongoing climate change affects the function of alpine lakes and in consequence the provision of ES, which requires new management advices accounting for climate and global change. This topic is of relevance since in consequence to global warming those alpine lakes might experience more intense use within the near to distant future. Notably alpine lakes vary in summer epilimnion temperature substantially depending on local factors potentially resulting in a high variability of lake response to climate change and human activities. The study design took advantage **from long-term limnological monitoring of alpine lakes located in two study regions:** Niedere Tauern (22 lakes, 1502-2309 m a.s.l.) and South Tyrol (5 lakes, 1496 – 2922 m a.s.l.).

In WP 1 the variability of the response of alpine lakes to global warming was investigated. Current surface water temperature data were compared with analogous records taken 20 years ago. An influence of warming was visible implying an average increase of 1.2°C during the warmest month (in August) but also **a shortening of the ice cover period** (ICD), which mainly **affects the lakes located below 1900 m a.s.l.** In addition biodiversity from various indicator organisms (e.g. diatoms, was compared implying that planktonic taxa on average increased related to the decreasing ice-cover period. The majority of lakes still showed very good water quality, i.e. an (ultra)oligotrophic status. Overall the long ice cover duration (4 -9 months) and the on average low temperature during the ice-free period were still considered the main limiting factors for primary production in the water column. However, a few lakes indicated more mesotrophic conditions, which was characterized using modern metabarcoding techniques, i.e. a decreasing relative abundance of mixotrophic taxa vs. phototrophic taxa.

In addition, lake surface temperature (LST) has been modeled on a daily basis from various meteorological parameters such as air temperature, pressure and precipitation (including snow) using General Additive Mixed Models. To develop and validate the models for each lake individually the calculated results were compared with measured data of LST. The validated models have been used to calculate the LST for each lake and to **estimate the ICD in the near (2031-60) and distant (2071-100) future** under different global socio-economic developments, i.e. the RCP8.5 (worst-case scenario). From these projections it is expected that **overall, the principal linear (atmospheric) influence of altitude on prolonging the ICD period will persist.** While for individual lakes at lower altitude ice-free years might occur, the ice cover is predicted to remain for most lakes. It is also expected that temperature maxima between 16-18°C will be relatively common at the surface of lakes in the distant future. In particular the average warm lakes of the Niedere Tauern show stronger increases, i.e. react more sensitively than the undercooled lakes, implying that **the existing variation in surface temperature between the lakes will increase in the future.** Due to the increased growth period, an increased primary production and a shift of the trophic state from oligotrophic to mesotrophic for most lakes is likely. This, at first glance moderate shift of the trophic level would, however, already result in a significant reduction of the water transparency and change in ecological conditions.

In WP 2 the ES were quantitatively assessed for lake types defined by WP1 in relation to the UN sustainability developmental goals, such as accessibility (“highly accessible” vs. “remote”). During the stakeholder workshops, the most important ES were selected for each study region, and were overlapping, i.e. **for both study regions the ES for habitat, recreation and aesthetic** were selected. Additionally, stakeholders in South Tyrol selected water and representation, while stakeholders in Niedere Tauern emphasized ES for research, education, and existence. Provisioning and regulating ES (i.e. water provision) were quantified using census data and data from limnological measurements, whereas cultural ES (i.e. aesthetic value, outdoor recreation) were quantified from crowd-sourced information such as geotagged photographs suitable to assess human preferences or by based on questionnaires. Furthermore, socio-economic data in relation to livestock feeding, fisheries, hunting, tourism, nature conservation, etc. have been collected. **For each ES, multiple indicators were identified and used to compare the provision of ES between study lakes**. In general the ES provisions of habitat, aesthetic, and existence depended less while the ES for water, recreation, representation, research, and education depended more on the socio-ecological context. In the future (2081-2100) all lakes will decline in ES for habitat and aesthetic, but easily accessible lakes will decline more than remote lakes. Recreation will increase due to a higher number of warm days at easily accessible lakes while reduced accessibility will lead to an increase in ES for research.

In WP3 the ES provided by the alpine lakes were evaluated using multi criteria decision analysis (MCDA) comparing representative lakes of defined lake types in both study regions. After defining the most important ES through stakeholders (see above), a pair-wise questionnaire for ecosystem services weighing was performed, and subsequent to ES indication the lake types were compared in their ES performance. While larger lakes had highest ES performance it is remarkable that **the influence of aesthetics becomes relatively more important for the overall performance in MCDA the more remote the lakes are.** Overall, the ranking of lake types according to their ES profile showed a stronger gradient in South Tyrol, while the lake performances were more similar within the Niedere Tauern. The comparison of the current and future ES provision performance based on the estimated changes of selected ES under future scenarios (until 2081-2100) revealed subtle differences, both positive and negative, in the overall performance in ES provision, but little changes in the ranking of lakes.

In conclusion, the comparison of lake types (i.e. "highly accessible" vs. "remote") regarding their ES provision can provide a basis for management in the future. From a management point of view, **accessibility to alpine lakes has been and can be regulated** in the future as it has been discussed during the second round of stakeholder workshops, i.e. favored by certain infrastructure development or, in contrast, hampering accessibility. All the data together imply a gradual deterioration of the ecological condition of alpine lakes through eutrophication. Since the estimation of eutrophication due to climate warming, which was made, is to be regarded as rather conservative (assuming that the nutrient situation remains unchanged), it will be essential to minimize nutrient input and water protection in a controlling manner already now. In general, soft measures, such as awareness raising or visitor management are to be preferred over bans or price mechanisms. Nevertheless, current active regulations must be followed if access has been increased to such an extent that ecosystem integrity is endangered.

Acknowledgements

We would like to thank local stakeholders for the permission to sample the alpine lakes. Numerous (high school) students and volunteers helped with the practical sampling of the alpine lakes in summers of 2019 - 2021: Karl Maier, Anneliese Wiedlroither, Nikolaus Kurmayer, Christina Schwaighofer, Ruibao Li, Haiying Huang, Kathrin Geir, Julia Götsch, Marilyn Danner, Yannika Baier, Dominik von Spinn, Moritz Mairl, Xaver Kopf, Jan Holzerbauer, Sebastian Prenneis and the divers group Delfin Sub Bruneck-Brunico.

Roland Schmidt (Res. Dep. Limnology) and Roy Thompson (Univ. of Edinburgh) provided the temperature records during the period 1998-2003. Sincere thanks go to Samuel Vorhauser (Biological Laboratory, Autonomous Region of Bolzano - South Tyrol) for access to the LTER data and assisting with fieldwork. Karin Koinig (Institute of Ecology, Univ. of Innsbruck) provided temperature records from Fischersee and Oberer Saldursee during 2016-2018. Martin Hahn (Res. Dep. Limnology) provided additional temperature records (2015-2016) from Unterer Klaffersee.

We would like to thank Gry Larsen and Elias Dechent (Institute of Ecology) and Johanna Schmidt (Research Dep. Limnology) for the chemical analyses of the water samples and Anneliese Wiedlroither (Res. Dep. Limnology) for laboratory assistance. Christian Jersabek (Univ. of Salzburg) performed the enumeration of zooplankton. Massimo Pindo (Fondazione Edmund Mach) performed the high throughput sequencing of plankton samples. Hans Rund and Josef Wanzenböck (Res. Dep. Limnology) and Stefanie Dobrovolny (Austrian Agency for Health and Food Safety (AGES) performed the analysis of fish biodiversity through eDNA sequencing.

The computational results for the high-throughput sequencing presented here have been processed using the LEO HPC infrastructure of the University of Innsbruck. Orthophotos and digital elevation models were provided by Land Salzburg © SAGIS and Geodaten GIS-Steiermark.

We are grateful to numerous stakeholders for their active participation during workshops on alpine lakes, the resulting ecosystem services, the risks for conservation and future mitigation measures. Sabine Wanzenböck (Res. Dep. Limnology) maintained the project -specific website and assisted in communication with stakeholders.

This project was funded by the Austrian Federal Ministry of Education, Science and Research through the Austrian Academy of Sciences in the Earth System Sciences (ESS 2018) program "Water in Mountains", project CLAIMES (Climate response of alpine lakes: resistance variability and management consequences for ecosystem services): https://www.uibk.ac.at/projects/claimes/

Contents

1 Introduction

1.1 Background

There is evidence that climate change threatens the integrity of alpine lakes more strongly and faster than comparable ecosystems in lowland regions (Moser et al. 2019; Schmeller et al. 2018). This is not only due to a generally more pronounced temperature rise in the alpine region but also due to the high vulnerability of alpine ecosystems (Caldwell et al. 2021; Roberts et al. 2017; Sadro et al. 2019). In addition, anthropogenic influences such as agriculture or touristic and recreational use increasingly threaten these ecosystems (Senetra et al. 2020; Tiberti et al. 2019), which is of concern as soon as ecosystem services (ES) provided by lakes get competitive (Culhane et al. 2019; Grizzetti et al. 2019).

For alpine lakes, it has been shown that lakes respond to climate change rather individually, which, for example, is caused by local habitat-specific influences. From a physico-chemical alpine lake data set from the Niedere Tauern (NT) region in the Austrian Alps but also from long-term monitored lakes in the North of Italy (LTER Italia) a wide scatter in the decrease of summer epilimnion water temperature as a function of altitude has been observed (e.g. Thompson et al. 2005, and other examples in Sadro et al. 2019). It has been shown that altitude, topographic shading, and bathymetry, all influence lake surface water temperature and ice cover duration in response to air temperature (Novikmec et al. 2013). This variable response to a common driver leads to either undercooled or relatively warm lakes located at the same altitude, for example a range in mean summer epilimnion water temperature from 7.5-11.3°C at altitudes from 1929 –1970 m a.s.l. (Thompson et al. 2005).

Local variability also has the potential to interact with climate change effects that influence biodiversity and ecosystem function within relatively short time periods. It has been described how climate related impacts or anthropogenic impacts can change phytoplankton biodiversity and ecosystem function within the relatively short-term (10 years), e.g. through changes in ice cover duration reducing phytoplankton biomass and productivity and drainage of dissolved organic carbon (DOC) favoring mixotrophic algae (e.g. Parker et al. 2008, Szabo et al. 2020). A high biodiversity can influence the resistance of lakes against invasive species (e.g. Schallenberg et al. 2013). On the other hand, rapid changes in biodiversity were observed in response to fish stocking (e.g. Schabetsberger et al. 2009). For example, direct effects cascading down the food web potentially affecting the ecosystem have been described within short time periods both theoretically (Magnea et al. 2013) and in situ (e.g. Brancelji 1999).

In general, the long ice cover duration (> 4 months) and the on average low temperature during the ice-free period are considered the main limiting factors for algal net growth (e.g. Thompson et al. 2005). It seems reasonable to expect that undercooled lakes which are nutrient-rich due to human activities will likely have algal blooms as soon as the ice-free vegetation period increases in consequence to climate change (Weckström et al. 2016). Such (non-linear) regime shifts would have significant consequences on the ecosystem level, e.g. high algal biomass production during summer and oxygen consumption during the ice cover period resulting in a cascade of changes in the whole ecosystem. In summary, since the variables affecting each lake's resistance to changing conditions are different, it is difficult to draw general conclusions on how alpine lakes are affected by global temperature warming. Consequently, when determining the response of alpine lakes, it is necessary to apply strategies that take their individual character into account.

The forecast of alpine lakes response is considered important as due to their pristine nature, alpine lakes are considered of highest value. However, up to date, ES of alpine lakes are poorly characterized. The ES concept has become popular since the United Nations' Millennium Ecosystem Assessment 2005. ES are defined as the benefits to humanity deriving from the functioning of ecosystems (World Resources Institute 2005). These benefits can be divided into market and non-market ecosystem goods or services and classified in multiple ways (Costanza 2001), e.g. provisioning services, regulating services, and cultural services (The Economics of Ecosystems and Biodiversity, further referred to as (TEEB 2010). The ES perspective is conceptual because ES are co-produced by the ecosystems and humans by means of labor, technology or financial resources (Palomo et al. 2016). Thus, it views ecosystems as socio-ecological entities and links ecosystems and their biodiversity with socio-economic systems (Boulton et al. 2016). Up to the onset of this project studies addressing ES of alpine lakes in a systematic manner and in quantitative terms were rare. In particular, cultural (e.g. aesthetic, recreational, spiritual) ES have been rarely considered, although these services are important in combination with touristic use. This lack of knowledge is of relevance, as it is predicted that depending on global warming in the lowlands (e.g. the increasing frequency of heat waves during summer) the importance of ES of alpine lakes (e.g. its use for recreation) will increase (Pröbstl-Haider et al. 2021).

Increasing summer tourism in the Alps due to warmer and drier summers, will increase the intensity of using lakes, especially of those located on higher altitudes, and may cause local problems (EEA 2009). In general, conflicts between different types of water usage can be expected to increase, e.g. related to recreation (e.g. fishing) and nature conservation (e.g. protection of amphibians). It is expected that lakes that already show relatively high traffic due to road accessibility will be at higher risk of suffering from intensive use (e.g. Lago di Braies/Pragser Wildsee, Lago di Anterselva/ Antholzersee). In this context, global warming will rather indirectly than directly increase the environmental pressure on the ecosystem integrity. In summary conflicts may arise in the future from different interests through tourism favoring clear lakes, fisheries favoring higher production through fertilization and livestock feeding favoring water withdrawal during droughts.

When dealing with competing goods and services and when addressing conflicts arising from competing uses, the multi-criteria decision analysis has been shown to be an adequate tool, particularly due to its capacity to account for trade-offs (Langemeyer et al. 2016). In order to assess ES importance and consequently compare ES provision among alternatives, the multi-criteria decision analysis (MCDA) has been promoted (Langemeyer et al. 2016, Saarikoski et al. 2016) bridging from environmental sciences to economics. MCDA comprises a set of flexible methods which result in a transparent framework for integrated valuation of ES, allowing also the involvement of experts and stakeholders (Fontana et al. 2023, Langemeyer et al. 2016). Since, to the authors´ best knowledge, ES from alpine lakes so far have not been collected and evaluated in a systematic manner, this study provides novel and unique outcomes and goes even further modelling future ES provision. Doing so, we aim at identifying changes or losses in ES provision and elaborating policy advices in order to facilitate sustainable interventions.

1.2 Objectives

The major aim of this inter- and transdisciplinary project is to compile limnological information on alpine lakes and to quantify and evaluate ES provision, which has not been studied in a systematic manner before. It is fundamental, to understand how climatic change affects the function of alpine lakes to characterize the variability of the response of alpine lakes on a quantitative scale as well as to explore the cumulative effect on ES under two predicted scenarios of climate change. This is necessary to characterize potential losses of ES presumably caused by ongoing alpine lake ecosystem deterioration. We want to answer the question which lake type is subjected to major changes in ES provision or even endangered to lose ES with ongoing climate change. The comparison of ES provided by alpine lakes differing in their response to climate warming will increase our capacity to predict future ES provision. We use MCDA to bridge the integrated ES approach to the policy and governmental level by raising awareness on potential arising conflicts due to changes in ES provision and plan to elaborate policy advices for an adaptive future ES governance.

The project is structured into three work packages (WP), which are connected to each other (Figure 1).

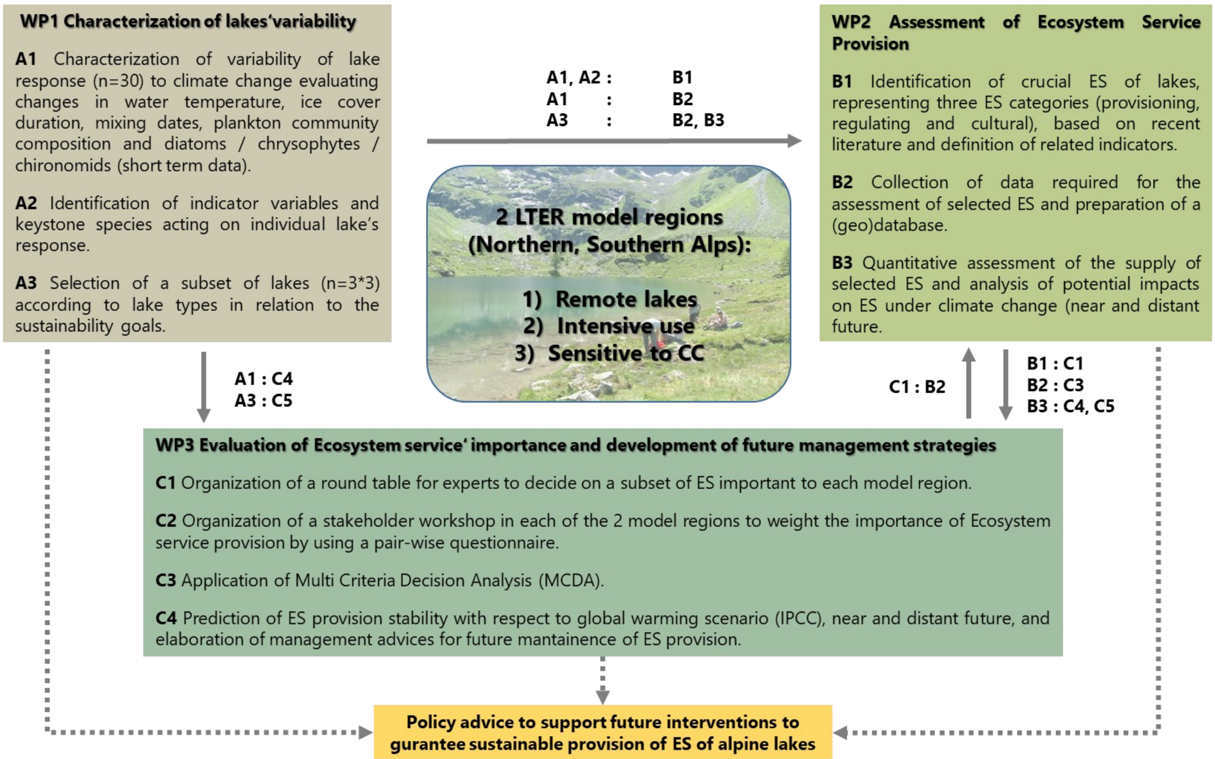

Figure 1: Schematic outline of the workflow from WP 1, 2 to WP3 and respective deliverables (A1, A2, …).

Objective of WP 1: Short-term changes (20 years) and their linkage to climate change and human-made effects

It is expected that when considering individual alpine lakes local factors such as topographic shading, extent of solar radiation and catchment size but also its use by humans are substantially influencing and modulating the global warming effect. Consequently, it is hypothesized that the interplay of climate warming and human affairs will lead to an even more increased variability of lake response to increased summer epilimnion temperature (Thompson et al. 2005), (Seekell et al. 2011). In particular cases, non-linear changes caused by both water temperature rise and eutrophication might be predicted. Since short-term data exist for both alpine lake study regions (Niedere Tauern and South Tyrol) these developments could be explored by multivariate statistical approaches a well as established Lake Surface Temperature (LST) reconstruction approaches (Matulla et al. 2019). In particular the LST approaches will allow to construct continuous temperature curves for decades which can be evaluated using the available *in situ* data. For the majority of the lakes, it is expected that exchange processes through the air-water phase interface allow for depicting LSTs via models containing atmospheric covariates. This relationship, however, must be formulated differently for individual lakes and every month of the year since atmospheric forcing trigger processes within waters varying amongst lakes and periods throughout the seasonal cycle.

Objective of WP 2: Ecosystem services from alpine lakes: quantitative assessment

Studies emphasized the vulnerability of ES to land-use and climate change. However, ES of alpine lakes have been rarely addressed and it remains completely unclear how these ES will be affected by climatic and anthropogenic variations. In particular, cultural ES were largely disregarded due to difficulties in their assessment. Therefore, vital ES of alpine lakes need first to be identified and quantified in biophysical terms for current climatic conditions. Potential impacts on the ES due to climate change influenced by anthropogenic activities will then be analyzed at the lake level by estimating present and future ES provision (i.e. under the IPCC “worst-case” scenario) in the near (2031-2060) and more distant (2071-2100) future. It is hypothesized that in consequence to climate change and human affairs the variance in ES provision is generally increasing, which is mainly caused by increased variability in lake response. For example, in the past, sustainable salmonid stocking was possible in all alpine lakes, while nowadays increased eutrophication is leading to increased oxygen consumption during ice cover in winter and approaching critical oxygen levels for salmonid fish survival.

Objective of WP 3: Evaluation and comparison of actual and future ES provision depending on lakes' climate change response variability and elaboration of policy advices

Beside the actual supply of ES (e.g. through tourism and recreation, livestock feeding) the perceived importance of goods and services by society is important. The demand of certain ES, the preference for one service rather than for another one regulates also future handling and sustainable ecosystem management. Hence, the involvement of experts, stakeholders and interest groups is an essential step in ES valuation. Regarding the predictability of the services provided by the individual lakes, the results on ecosystem stability from obj. 1, 2 will be of relevance. It is hypothesized that the more climate change resistant lakes would be increasingly used such as by water withdrawal or local tourism significance in consequence to climate change. Local factors leading to an increased variance and even losses in ES provision would require a revised management plan to solve potential conflicts in the future. In order to test this hypothesis, ensembles of continental-scale Global Climate Model (GCMs) scenarios, driven by two future pathways of mankind, are downscaled (von Storch et al. 1993, Matulla et al. 2002) to climate change corridors at the lakes, which will then be classified into lake types in order to make ES management effective.

1.3 Adopting a transdisciplinary approach

The project was developed in such a way that consultation of persons outside the science system was actively performed to achieve the requested active participation. The **practical legitimacy** of this project resulted from the millennium goals and the availability of ES despite facing global change. For the urgency (in the sense of salience), there are potential conflicts in use as revealed by a survey on cultural ecosystem services that has been carried out within this project, indicating that negative influences from overuse and pollution also affect subjective well-being (Schirpke et al. 2022). The salience was also confirmed by geotagged photo densities posted in social media (Schirpke et al. 2021d). The **scientific legitimacy** arises from the three interdisciplinary work packages, which ultimately translate the scientific results through indication and weighting in such a way that participation of stakeholders became feasible. The **socio-political legitimacy**, in turn, arises from the ranking of interests in the course of the multi-criteria analysis (MCDA) of local stakeholders and experts (Ebner et al. 2022a; Fontana et al. 2023). See also sections 2.3.3 and 2.4.1. In praxis, considerable time and effort were used to include the know-how and perspectives of relevant stakeholders (see section 2.3.3, stakeholder workshops). More detailed information on stakeholder participation is given in the Supplementary (Suppl. Fig. S1-S2, Tables S1-S4). Most importantly, interest groups (stakeholders, social actors) that do not belong to the research landscape or immediate environment of the project participants have contributed to the research process for each study region independently. For example, the ES which were investigated in socio-ecological perspective have been nominated during two independent workshops after discussion and consultation (Schirpke et al. 2021a). Furthermore, active participation was achieved by expert elicitation to identify a potential need for policy measures to adapt to climate risks (see section 2.4.2). Finally, the results were validated by local stakeholders and experts in a final stakeholder feedback round, discussing potential risks, identifying potential measures and evaluating the feasibility of individual measures.

During the entire project phase, information between the projects within the "Transdisciplinary project cluster" was exchanged, which was primarily of an exploratory nature. As a result, two interfaces were derived:

1) There was regular information flow between the CLAIMES and the "Pulling the Plug" project focusing on the restoration effort of the Sulzkarsee in the Kalkalpen National Park ("Restoration of Lake Sulzkarsee (Styria, Austria), an alpine lake degraded by fish introduction", cite Schabetsberger et al 2019?). The interface with the "Pulling the Plug" project laid in an anticipated lake restoration based on the experience from Sulzkarsee, e.g. with regard to the fishing off in alpine lakes that are no longer used for fishing. Unfortunately, for the CLAIMES project a local stakeholder could not yet be found that would agree to such an offensive

measure. The lakes in question are either privately owned or public. During sampling access to privately owned lakes has been partly denied which was justified by bad experiences in the past. Thus, for the future, however, the active inclusion of stakeholders is considered as the only sustainable option for monitoring and restoration, not at least because a basis for communication between science and relevant stakeholders has been (re)established during this project.

2) We also discussed possible synergies with the project "Climate & Cryosphere" (CryoSoil) https://www.uibk.ac.at/geographie/projects/cryosoil_transform/index.html.de. The interface with the "CryoSoil" project laid in the further didactic development of environmental education based on remote ecosystems. Remarkably, the interface of environmental education in the form of the ES habitat/closeness to nature in both regions was also emphasized by the respective stakeholder workshops. In addition to soil formation, interdisciplinary system knowledge could be expanded to include the formation of alpine lakes due to the influence of glaciers. Thus, an integration of natural and artificial lakes has been anticipated for the environmental education program in the future.

2 Methodological approach

2.1 Study area

For limnological analysis 27 mountain lakes located in two regions of the Eastern Alps were selected: 1) Niedere Tauern in Austria with 22 lakes and 2) South Tyrol, Italy with five lakes (Suppl. Table S5) for which LTER data were recorded previously (Suppl. Fig. S3, i.e. during 1998-2003 from Kamenik et al. 2001, Thompson et al. 2005, and between 2009-2012 from Weckström et al. 2016, Jiang et al. 2019). For South Tyrol, data on limnological characteristics were available through the LTER monitoring (Provinz Bozen, Italy). The lakes are located within an elevation range of 1489 to 2922 m a.s.l. and vary in surface area between 0.4 and 43.3 ha and typically have no direct glacial impact (Lakes in South Tyrol, such as Fischersee have a minor direct glacial impact). All lakes are covered by ice between 4-9 months depending on their altitude (typically from November – May/June). So-called undercooled or relatively warm lakes, i.e. showing a mean surface temperature of 7.5 or 11.3°C, respectively within a minor change in altitude from 1929 or 1970 m a.s.l. (Thompson et al. 2005).

For an in-depth analysis of the socio-ecological context fifteen study lakes were selected: (1) four lakes in South Tyrol and (2) eleven lakes in Niedere Tauern, Austria (Figure 2). The two regions differed in environmental and socio-economic characteristics. In South Tyrol, the climate conditions are suitable for cultivating annual and permanent crops as well as managing mountain grassland for producing forage. In Niedere Tauern, more than half of the area is covered by forest. Therefore, agricultural use is less important. The regions also differ in population density (South Tyrol: 72 inhabitants per km^2, ASTAT, 2019); Niedere Tauern: 24 inhabitants per km^2 in the region of Liezen in Styria and 32 inhabitants per km^2 in Upper Styria West (Office of the Styrian provincial Government, 2018). Tourism is more important in South Tyrol (on average 46 overnights per inhabitant in the surrounding municipalities of the study lakes during the summer season) than in Niedere Tauern (15 overnights per inhabitant).

Based on 12 independent socio-ecological variables (Table 1), we divided the lakes into four groups using hierarchical cluster analysis (squared Euclidean distance, Ward's linkage method):

- Group 1 (ANT, PRA) is characterized by large lake size, low elevation, good accessibility, a high number of beneficiaries (in particular, tourists) and high visitation rates.
- Group 2 (LAG) is located at high elevation in a landscape with predominantly bare rocks. Although it has a very high number of beneficiaries (in particular, residents), visitation rates are lower than for Group 1 due to a high access time.
- Group 3 (FIS, UKL, RAU, OKL, KAP, PFA) comprises small, high-elevated, and remote lakes that are difficult to reach. Compared to Groups 1 and 2, this group has less beneficiaries and lower visitation rates.
- Group 4 (OBE, HUS, TWA, SCH, WIR, TIE) includes lakes that are on average lower elevated and easier accessible than Groups 2 and 3, but the number of beneficiaries and visitation rates are similar to Group 3.

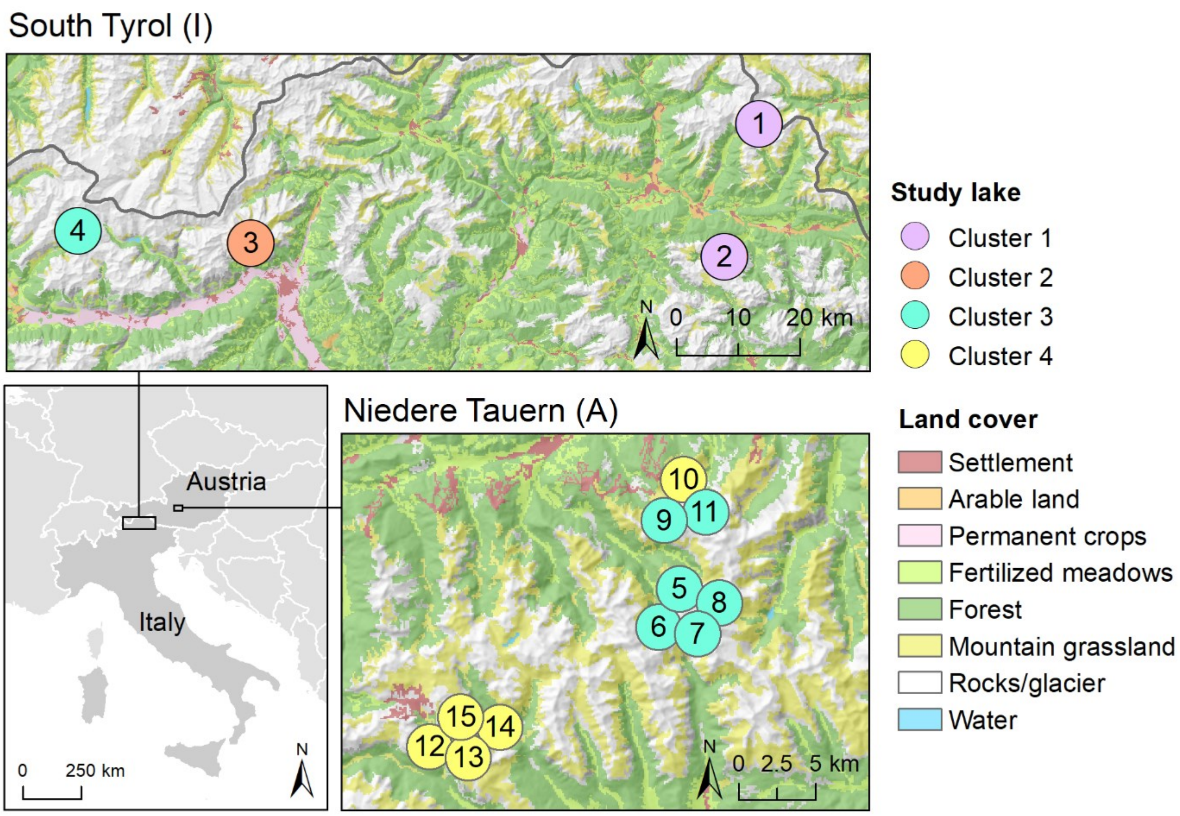

Figure 2: Location of the 15 study lakes (used for both limnological and in-depth analysis of the socio-ecological context) in South Tyrol and Niedere Tauern. 1 – ANT, 2 – PRA, 3 – LAG, 4 – FIS, 5 – UKL, 6 – RAU, 7 – OKL, 8 – KAP, 9 – PFA, 10 – OBE, 11 – HUS, 12 – TWA, 13 – SCH, 14 – WIR, 15 – TIE (from Schirpke et al. 2021a).

Table 1: Socio-ecological characteristics of 15 studied lakes. Table modified from (Schirpke et al. 2021a).

		Group 1		Group 2	Group 3						Group 4					
		ANT	PRA	LAG	FIS	UKL	RAU	OKL	KAP	PFA	OBE	HUS	TWA	SCH	WIR	TIE
Variable	Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Lake area	m^2	432.42	358.23	195.89	5.35	38.36	27.60	53.23	22.73	14.46	72.51	46.69	29.91	52.47	27.41	34.66
Lake perimeter	m	2771	3309	2846	338	831	804	1127	682	800	1360	1055	696	1068	662	918
Watershed area	m^2	18,871	29,306	1994	31	801	444	605	922	1215	3020	5672	132	306	1281	1378
Elevation	m a.s.l.	1642	1493	2381	2758	2103	2264	2310	2146	1968	1673	1502	2118	2112	1701	1844
Terrain ruggedness (500 m around lake)	index	576	598	713	955	734	788	728	827	708	749	743	663	678	60609	624
Precipitation	mm y^{-1}	955	859	1113	1285	1550	1543	1535	1544	1554	1541	1524	1472	1472	1466	1466
Forest/shrub in watershed	%	28.96	32.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.00
Grasslands/heathland in watershed	%	10.34	14.05	0.00	0.00	8.22	0.00	0.00	6.20	11.50	37.79	44.99	85.35	95.61	62.08	37.07
Sparsely vegetated areas in watershed	%	24.25	24.57	73.39	96.97	91.78	100.00	100.00	93.80	66.91	40.31	38.73	14.65	4.39	37.52	62.93
Bare rocks/glaciers/water in watershed	%	36.45	28.50	26.61	3.03	0.00	0.00	0.00	0.00	21.58	21.90	16.28	0.00	0.00	0.00	0.00
Walking time to lake from the nearest access point	min	5	5	210	150	300	300	315	240	210	130	90	135	210	90	110
Distance to nearest hiking trail	m	0	0	4	22	154	511	9	12	298	3	2	2	5	4	0
Distance to nearest asphalted road	m	304	642	4811	4993	8114	7971	8859	9323	7145	7102	6281	1399	1491	2383	2268
Residents within 30 min driving from the nearest access point to the lake	n	48,713	54,533	221,542	20,319	14,880	14,880	14,880	14,880	32,330	32,330	32,330	38,290	18,363	18,363	18,363
Overnights (May–October) within 30 min driving from the nearest access point to the lake	n y^{-1}	2621	3117	6428	932	343	343	343	343	438	438	438	499	109	109	109
Visitation rates (photo-user days derived from Flickr)	n	87	348	7	1	3	1	2	1	1	1	6	2	2	2	2

2.2 Assessing short-term changes and their linkages to climate change

2.2.1 Field sampling and laboratory analysis of limnological parameters

The lakes were sampled during July-October 2019 (n = 25) and September-October 2020 (n = 27) and partly resampled during September 2021 (n = 16). Depth-integrated samples were taken at maximum depth for water chemistry, Chlorophyll a (Chl-a) and plankton community composition. Water samples were transported to the laboratory under cooled and dark conditions and processed on the same day.

In addition, temperature data loggers (HOBO TidbiT MX2203, Onset Computer Corporation, Bourne, MA, USA) were installed to record the water temperature at the lake surface (1-1.5 m depth from surface) and at maximum depth every two hours as proposed by Pierson et al. (2011). From the temperature measurements it was evident that the time of vertical mixing in autumn and spring is indicated by the intersection of the two temperature measurement series (surface and maximum depth) at 4 °C, both in deep and in shallow lakes (Suppl. Fig. S4). The trophic state was estimated using Chl-a and TP concentrations as well as Secchi depth using the OECD trophic classification system (Vollenweider & Kerekes 1982).

In addition, sediment traps were installed (Suppl. Fig. S4) collecting indicator organisms such as diatoms and chrysophytes (golden algae), which sink from the water column over the course of the year and form the natural lake sediment. In addition, a sediment core was taken from each lake, which is cut out of the lake bottom with special equipment. Chironomids were examined in this core for the upper 0-2 cm and compared in proportion with previous records (Kamenik & Schmidt 2005, Schmidt et al. 2004).

Water samples for plankton community composition were low-vacuum filtered into two size fractions: In order to concentrate planktonic algae including bloom-forming cyanobacteria the raw water (2 L) were filtered onto (autoclaved) glass fiber filters (Whatman GF/C, Kent, UK, approx. 1.2 µm pore size). Subsequently the GF/C filtrate (1 L) was filtered onto (autoclaved) nitrocellulose (NC) filters (Sartorius Stedim Systems, Germany, 0.22 µm pore size) to concentrate smallest bacteria including picocyanobacteria.

Both, the 18S rDNA V4 region and the 16S rDNA V3-V4 region, were amplified using the DNA extracts from the large size fraction. In addition, the 16S rDNA V3-V4 region was amplified in the DNA extracts of the small size fraction. Raw reads from sequencing were processed using QIIME2 (Bolyen et al. 2019) (https://qiime2.org). The taxonomic classification was based on the SILVA 132 taxonomic reference database (https://www.arb-silva.de/) (Glöckner et al. 2019). The raw datasets generated for this study have been submitted to the NCBI Raw Sequence Archive (SRA) under BioProject ID PRJNA911210 (for the sampling years 2019, 2020, 2021 separate BioSamples have been submitted, i.e. year 2019, SUB12341986, year 2020, SUB12409818, year 2021, SUB12409985).

The eukaryotic phytoplankton community was characterized using the V4 region of the 18S rDNA. Cyanobacterial abundance was calculated from 16S rDNA V3-V4 region sequences via dividing reads of free-living cyanobacteria by the total bacterial reads. In addition, the share of putatively mixotrophic vs. phototrophic phytoplankton organisms using read numbers of taxa inferred from

18S rDNA V4 region sequencing was calculated. Generally the mixotrophic nutrition is considered selectively superior under conditions of extremely low primary productivity through both nutrient limitation and reduced growth period (e.g. Parker et al. 2008, Saad et al. 2016).

Zooplankton were collected at the deepest point of each lake by vertical net hauls through the entire water column using a wide plankton net (50 cm in diameter, 100 cm in length, 30 µm mesh size). Specimen were immediately fixed in sugar (4 %, w/v)-formaldehyde (2 %, v/v) solution. Zooplankton species were counted under the inverted microscope or under a dissecting microscope (larger crustaceans) subsequent to staining with Rosé Bengal.

In order to obtain information on fish biodiversity, during the sampling in 2019 and 2020, 2-5 liters of water samples were taken from the shores of each lake and filtered onto (autoclaved) glass fiber filters (GF/C). The resulting eDNA extracts were sequenced (MiSeq) at the Austrian Agency for Health and Food Safety (AGES) using the MiFish-U primer pair (Miya et al. 2015) with a mean amplicon length of 170 bp. Sequencing data analysis was carried out using the qiime2 pipeline, taxonomic classification was based on a curated 12S rDNA reference database (established inhouse of Res. Dep. Limnol. Mondsee and AGES). In total 22 out of 32 samples reached the threshold of 10,000 non-chimeric reads after denoising via DADA2 including the following lakes: HUS, LAN, OBE, OGIG, PFA, RAU, SCH, TWA, TIE, UGIG, WIR (Niedere Tauern) and LAG, PRA, ANT (South Tyrol). High variations of obtained reads were observed for some lakes that were sampled twice (once in 2019 and once in 2020) like ANT, UGIG or OBE.

2.2.2 Simulation of lake surface temperature

For the establishment of Lake Surface Temperature (LST) models, we aim to link LST measurements with atmospheric covariates. When considering a monthly time resolution, it can be assumed that linear relationships exist between the target variable (LST) and predictors (atmospheric parameters) (Matulla et al. 2019). For high alpine lakes, however, long time series over several decades are not available which are a prerequisite to establish robust relationships between target variables and input parameters on a monthly basis. Given the availability of high-resolution LST as well as meteorological data and our interest in detailed limnological assessment of future changes, we increased the temporal resolution of LST models to a daily basis.

However, as far as the relationship between LST and atmospheric parameters such as temperature, precipitation, and snow depth in daily resolution is concerned, nonlinear dependencies appear. Recent literature discusses various approaches and algorithms that can represent nonlinear relationships, most of them being machine learning approaches such as tree models or neural networks. In this project, Generalized Additive (Mixed) Models (Hastie & Tibshirani 1986) were chosen for modeling LSTs because of both their high flexibility in model building and high interpretability (see the subsection "General Additive Models (GAMs)" in the Methods section for more details).

As we want to assess the changes in LST under global warming, we employ climate projections. Thereby we consider different climate scenarios: RCP2.6, RCP4.5 and RCP8.5. RCP2.6 represents the COP21 target (RCP2.6) of the World Climate Conference in Paris (December 2015) to reduce emissions and limit global warming to a maximum of 2°C. RCP4.5 can be described as a still climate friendly scenario that projects an increase in global mean temperatures of about 3°C by the end of the century compared to pre-industrial climate conditions. The RCP8.5 scenario (often referred to as the “worst-case” scenario) assumes that greenhouse gas emissions will not be reduced and that the global average air temperature will rise by almost 5°C.

The lakes’ ambient air temperature changes depend on the scenario. Due to the close linkage between air and water temperature, LST reacts to altering climate conditions. The central question of the CLAIMES project is about the impacts of climate changes on the considered mountain lakes, and, subsequently, how these affect ecosystem services. For this report, we focus on the RCP 8.5 (worst-case) scenario as it provides a representation of the largest predicted climate effect on alpine lakes.

Model input data consisted of the LST time series (1998-2003) sampled by Thompson et al. 2005 and from 2009 to 2011 (Weckström et al. 2016) and during this project (n = 21). For the South Tyrolean lakes we obtained LST time series measured at water level stations at the shore as well as from data loggers installed at maximum depth. The time series differed in length, i.e. In the case of ANT, measurements start at the end of November 2013, for PRA in April 2014, For OSAL and FIS in July and August 2016, respectively.

Meteorological data were taken from SPARTACUS, the Spatiotemporal Reanalysis Dataset for Climate in Austria (Hiebl & Frei 2016; 2018). It provides daily precipitation totals as well as maximum and minimum temperatures on a grid with 1 km spatial resolution. SPARTACUS is kept up to date by ZAMG and is available for Austria, southern parts of Germany and South Tyrol from 1961 to the present. SNOWGRID is an operational snowpack model and its operational version is coupled to the INCA nowcasting system. However, in this project we use the climate version of the model driven by SPARTACUS and the radiation model STRAHLGRID (Olefs & Schöner 2012). The parameters recorded are snow depth and snow water equivalent. SNOWGRID has the same technical specifications as SPARTACUS, i.e., the temporal resolution is one day and the spatial resolution is 1 km. However, only the Austrian national territory is covered (Olefs et al. 2020).

For the Future the ÖKS15 dataset (Chimani et al. 2016) comprises ensembles of regional climate projections for Austria on a 1 km grid and a daily resolution. These ensembles have been generated from CMIP5's (Taylor et al. 2011; IPCC 2014) downscaled `EURO-CORDEX' dataset (Jacob et al. 2014) and provide a plethora of meteorological parameters for three climate projections, i.e. RCP2.6 (8 ensemble members), RCP4.5 (13 ensemble members) and RCP8.5 (13 ensemble members). For this project we use daily maximum and minimum temperatures and precipitation totals. The data set covers the area of Austria.

Finally, the FuSE-AT project extended the climate scenarios of the ÖKS15 dataset including the variables snow depth and snow water equivalent. To perform simulations of these snow-related variables, the adapted climate version of the SNOWGRID snow model is used and applied to the ÖKS15 ensembles. A set of future scenarios of the spatial and temporal evolution of snow cover with a resolution of 1×1 km in daily intervals was generated for the 21st century for the Austrian federal territory (https://fuse-at.ccca.ac.at/).

For South Tyrol the EURO-CORDEX database (Jacob et al. 2014) was used including downscaled regional climate projections for different scenarios on a 12.5 km grid over Europe with a daily time resolution. In this project, we use the RCP2.6, RCP4.5, and RCP8.5 mentioned above for the minimum temperature, maximum temperature, and daily precipitation totals parameters. A summary on input data used for the two study regions is shown in Figure 3.

General Additive Models (GAMs)

The mathematical structure of GAMs features a high similarity to the one of linear regression and is represented by

$$y_i = \beta_0 + \sum_j s_j(x_{ji}) + \epsilon_i$$

with y_i being the target variable, x_{ji} representing the predictors, β_0 describing intercept, s_j depicting smooth functions and ε_i illustrating the random error with $\varepsilon_i \sim N(0, \sigma^2)$. In GAMs, non-linear dependencies are estimated by the usage of splines. These are defined as functions consisting of basis functions b_k weighted with the coefficients β_k:

$$s(x) = \sum_{k=1}^{K} \beta_k b_k(x)$$

Depending on the characteristics of the predictors, multiple types of basis functions, e.g. cubic, cyclic or thin plate can be chosen. Since they are not constrained by the assumption of linearity, these smooth functions allow to follow the shape of the data much more accurately.
The usage of splines with numerous basis functions may, however, easily lead to overfitting. This can be avoided by applying a penalty term representing the wiggliness of the fitted function:

$$\int_R [f'']^2 dx = \beta^T S \beta$$

with f'' exhibiting the curvature of the fitted function, β being the basis functions' weights and S representing the so-called penalty matrix. Therefore, the penalized fit is represented as:

$$\mathcal{L}_p(\beta) = \mathcal{L}(\beta) - \frac{1}{2}\lambda\beta^T S \beta$$

where λ describes the weight of the penalty term.

As GAMs rely on the assumption that investigated data points are independent, they are not valid for time-series modelling. General Additive Mixed Models (GAMMs) feature the same flexibility as GAMs in terms of integrating splines, but they additionally account for the correlation between data points. Unlike autoregressive integrated moving average (ARIMA) processes, there is no necessity to detrend time series when using GAMMs as those elements can correctly be taken into account as part of the model, i.e. including month and date as predictor for the consideration of seasonality. We perform the data pre-processing steps using the Python modules „pandas“ and „xarray“. LST models are built and applied by using R's „mgcv“ package.

Data for modelling LST included (1) LST measurements sampled by various institutions over the last years and decades and (2) high-quality gridded observational datasets covering different atmospheric parameters over the Austrian territory on a daily basis provided by the Austrian weather service. Before using these data, data preparation is necessary. In case of LST data, preparation consists of computing daily means of the 2 and 4-hourly data, respectively. As for meteorological parameters, data preparation procedures are more comprehensive: to estimate the different lakes' ambient meteorological conditions, the nearest grid point to the lakes is identified, and, moreover, the four neighboring grid points, i.e. the one to west, to the east, to the south and to the north, are selected. The mean value of these points is used for the subsequent analysis when using the parameters precipitation and snow depth. Since temperature varies with altitude, the following steps are conducted before computing the mean of considered grid points: (i) identification of the altitude of every grid point in the underlying digital elevation model, (ii) computation of the height difference between the lake and the grid points and (iii) correction of the temperature values with the moist adiabatic lapse rate of 6.5°C/km.

In addition to LST modeling, future atmospheric parameters as available in the ÖKS15, FuSE-AT, and EURO-CORDEX datasets were used to derive four climate indices. These indices include the growing season, summer days, frost days, as well as cold episodes (Table 2).

Table 2: Definition of investigated climate indices *(https://www.climdex.org/learn/indices/).*

Climate Index	Definition
vegetation period	Annual count between the first span of at least 6 days with daily mean temperature TG >5 °C and the first span after July 1st of 6 days with TG <5 °C.
summer days	Days with a maximum temperature >25 °C
frost days	Days with a maximum temperature < 0°C
cold episodes	Number of days with a maximum temperature < 0°C for at least five consecutive days.

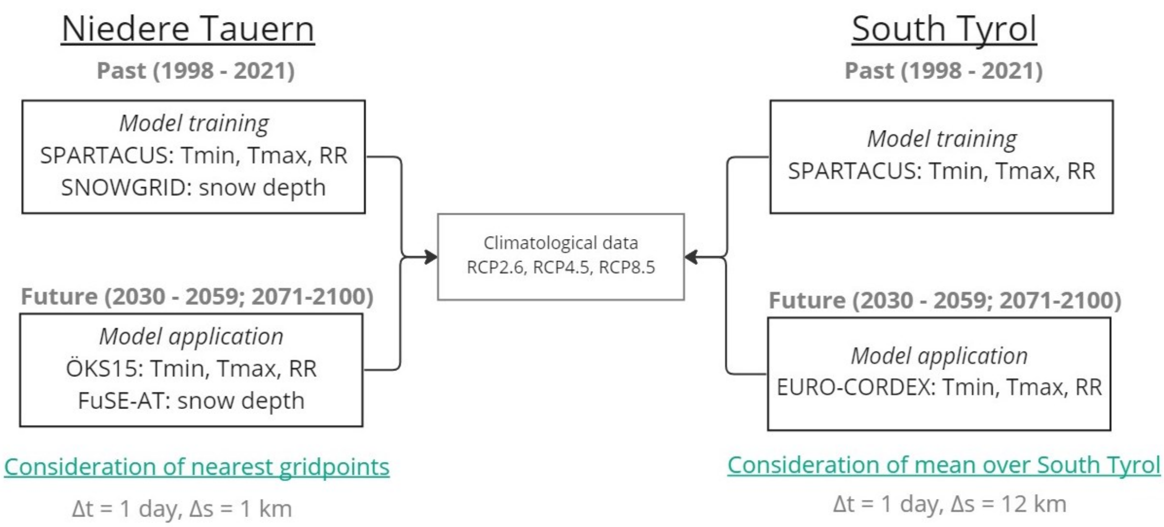

Figure 3. Overview of meteorological and climatological data used for LST simulations in Niedere Tauern and South Tyrol.

LST modelling for the lakes in the Niedere Tauern and South Tyrol (Figure 3)

For the Niedere Tauern region, we use different meteorological input variables available in the SPARTACUS and SNOWGRID datasets for the past and in the ÖKS15 and FUSE-AT datasets for future periods. These are: (i) daily minimum as well as maximum temperature, (ii) daily precipitation totals and (iii) daily information on snow depth. Since the lakes' response to changing atmospheric parameters may be time-lagged, we also incorporate both 14 and 30-day mean values of considered variables. For South Tyrol we used the mean climate conditions based on minimum and maximum temperature as well as precipitation over South Tyrol from the EURO-CORDEX dataset.

In order to account for seasonality, we additionally include the day of year as a feature to our model. Models are trained, tested and validated separately for each lake in the region. The validation procedure encompasses a cross validation suitable for time series modelling, described in Figure 4. Models are trained on past time periods and tested on future time periods.

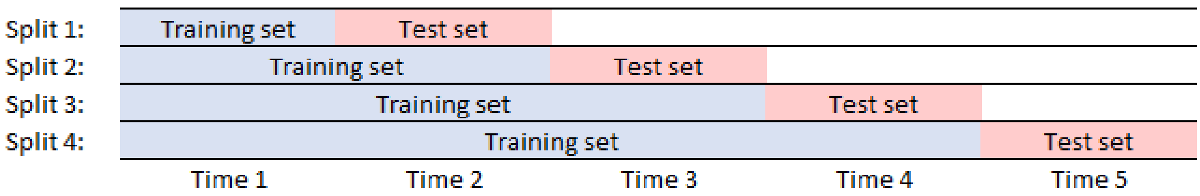

Figure 4: Cross validation for time series modeling.

2.3 Assessing ecosystem services of mountain lakes

2.3.1 Literature review and selection of indicators

To identify relevant ES as well as suitable indicators for their quantification, a systematic literature review was carried out using the Scopus database. The search of 'ecosystem service∗' and 'lake' in abstract, title, and keywords in publications from 1997 resulted in 874 matches (22 August 2019, Figure 5). From this set of publications, articles were selected by searching the terms 'ecosystem service' and 'lake/ pond/ waterbod*' in the title or keywords, assuming that papers containing these terms in their titles or keywords explicitly focus on ecosystem services of lakes. In this way, the total number of publications was reduced to 390. Of these, 89 articles mentioned both ecosystem service and lake in the title. Furthermore, to collect publications focusing on the ES assessment, the search was refined by searching for 'map/ assessment/ quantif*/value / indicator/ model', resulting in 63 papers. Subsequently these papers were screened manually to analyze relevant ES of lakes and to collect indicators for their quantification, resulting in 18 relevant papers.

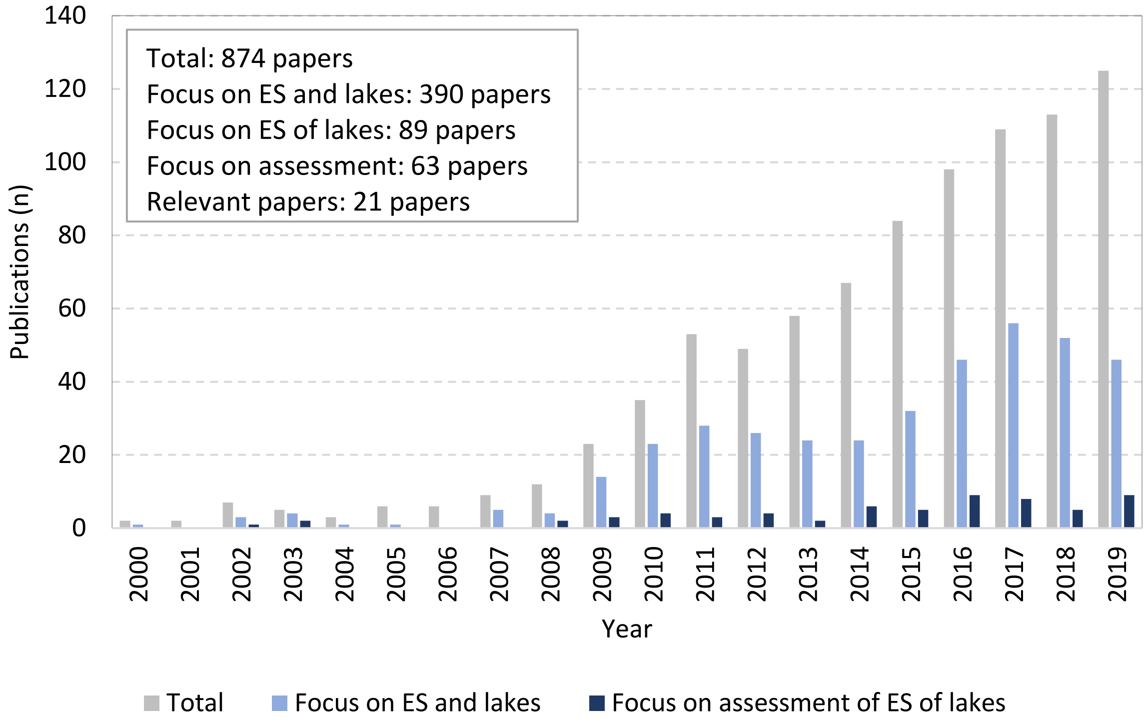

Figure 5: Result of the literature search on ES of lakes from 22 August 2019.

Based on the literature review, a set of relevant ES of mountain lakes was identified and aligned with the Common International Classification of Ecosystem Services (CICES, Haines-Young & Potschin 2018). During the stakeholder workshops, the most important ES were selected for each region (section 2.3.3). For each selected ES, we identified multiple indicators, describing different aspects of potential ES supply, i.e., the capacity of ecosystems to provide ES independently from their actual use (flows of benefits) (Burkhard & Maes 2017, Jones et al. 2016). The indicators include the structure and functions of the lake ecosystems, the lake shore as well as the surrounding landscape and also account for human-derived capital or human preferences (Chen et al. 2017). Indicators were partly selected from literature, but we also developed new indicators at fine spatial scale, which were more suitable to capture variations in ES among different mountain lakes. Moreover, indicators should provide the possibility to monitor changes in ES over time in order to capture potential impacts of global change. To calculate the different indicators in non-monetary terms, we applied different methods, mostly biophysical methods such as direct measurements and modelling based on primary data (e.g., limnological and climate data), but also socio-cultural methods (e.g., preference surveys).

To quantify potential impacts of global change pressures on ES of the study lakes, we compared current ES provision with future ES provision based on multiple indicators (Figure 6). We considered a combination of different developments that are expected to have negative impacts on ES (Ebner et al. 2022b), including (1) high emissions under the future emission scenario RCP8.5 (van Vuuren et al. 2011), (2) the construction of a small dam, which rises the water level by 1 m (Brunner et al. 2019; Huber et al. 2021), (3) intensification of farming activities due to increasing biomass production (Jäger et al. 2020), (4) tourism increase due to higher demand for outdoor recreation (Pröbstl-Haider et al. 2021) and (5) forest regrowth on abandoned grassland (Tasser et al. 2007). Relevant scenarios were selected for each study lakes based on the specific socio-ecological context (Schirpke and Ebner 2022).

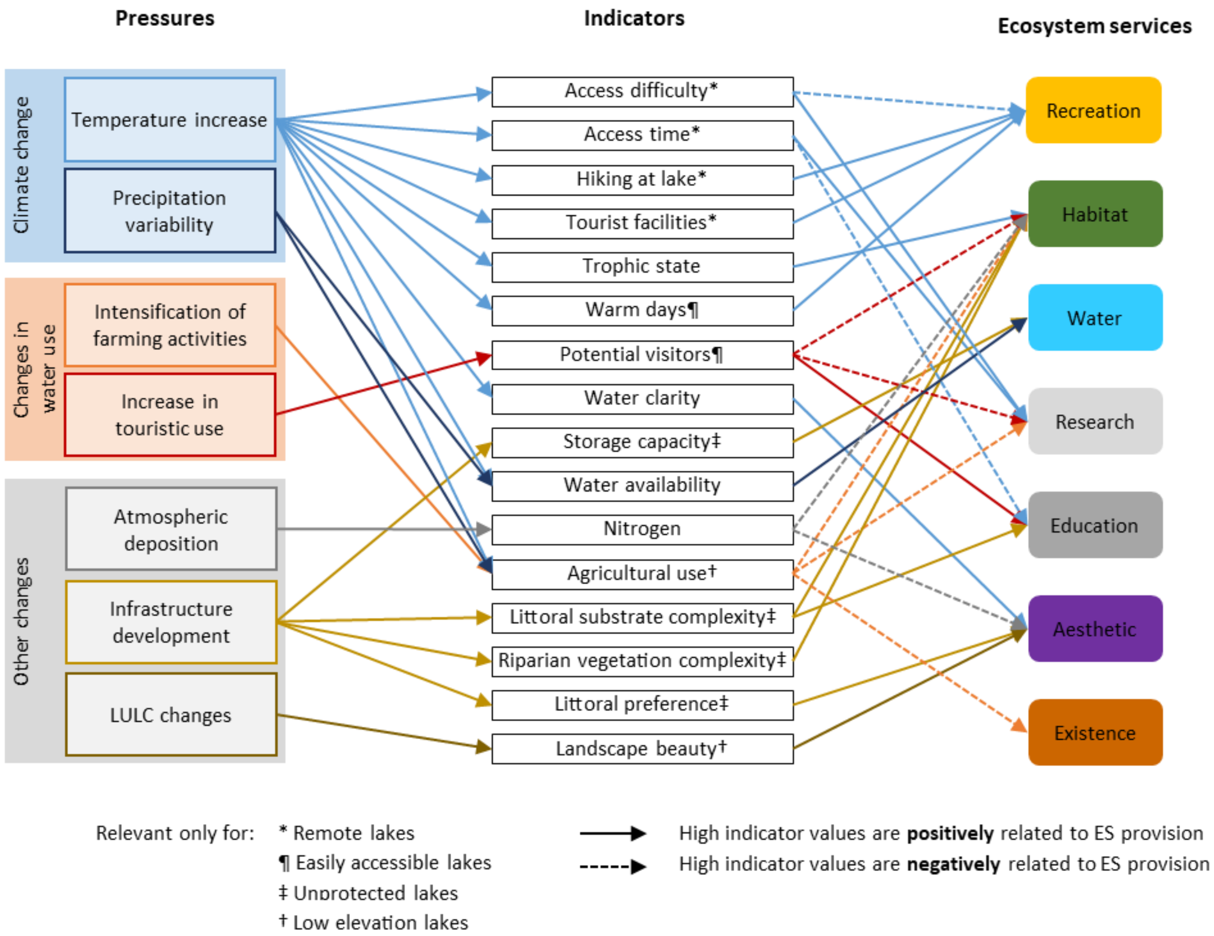

Figure 6: Relationships between potential impacts of global change pressures (left) on multiple indicators (middle) affecting ES of mountain lakes (right), accounting for socio-ecological characteristics of the study lakes (accessibility, elevation and protection status).

2.3.2 Online survey

To collect human perception on cultural ES and to derive indicators for quantifying selected ES, we developed a questionnaire. The questionnaire consisted of closed and open-ended questions, which were thematically organized in separate sections (Table). After a pre-test to check clarity and completeness of the questions and response options, the final questionnaire was translated into the three languages English, German, and Italian.

Table 3: Organization of the online questionnaire on cultural ES of mountain lakes.

Section	Topic
1	Perception of natural assets and cultural ES
2	Aesthetic preferences of the lake water, lake shore and surrounding landscape
3	Relevance of mountain lakes for excursions
4	Accessibility and importance of infrastructure around mountain lakes
5	Benefits and recreational activities associated with mountain lakes
6	Socio-demographic characteristics

Data were collected via an online survey between July and December 2020. We invited people that are likely to visit mountain lakes during hiking excursions, e.g., members of Alpine clubs, as well as people who have a professional interest in mountain lakes, e.g., members of associations of biologists, limnologists etc. The distribution of the invitations via newsletters and social media were supported by Alpine clubs of Austria, Germany, and Italy, associations of biologists and limnologists in Austria and Northern Italy, and the International Commission for the Protection of the Alps (CIPRA). Participation was anonymous and on a voluntary basis. All data were collected via a web survey without collecting identifiers/codes to secure privacy. Responses were registered in a database. For detailed information on the survey, see (Schirpke et al. 2022, 2021b, c). The results of the questionnaire were used to identify and calculate relevant ES indicators (for example, in relation to aesthetic value Figure 7).

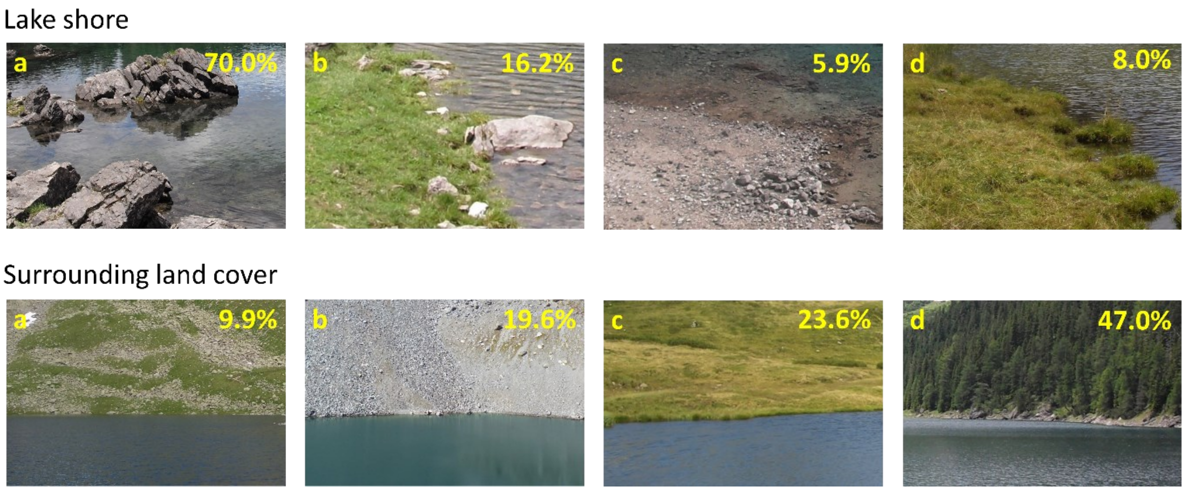

Figure 7: Preferences (%) related to the characteristics of the lake shore and the surrounding land cover, which were used as indicators for quantifying ES. Images by U. Schirpke.

2.3.3 Stakeholder workshops

To define the most important ES for each study region for evaluating mountain lakes' ES provision using MCDA, we conducted two separate regional workshops. First, we purposively identified stakeholders and experts in each region by screening of policy and media documents, interviewing key regional informants and subsequently conducting a snowball sampling, aiming to capture diverse viewpoints and interests related to mountain lakes. Based on this, we selected relevant stakeholders from different sectors (i.e., government & authorities, economy & tourism, research and education, and non-governmental organizations) for which we invited representatives in higher-level positions to participate in the regional workshops. The workshop in South Tyrol (09.01.2020, in Bozen-Bolzano) involved twelve participants representing multiple sectors: governmental nature conservation (n=2), governmental water management (n=2), local authorities (n=2), tourism and economy (n=2), research and education (n=2), and NGO (n=2). The workshop in Niedere Tauern (04.08.2020, in Radstadt) involved 10 participants: governmental water management and conservation (n=2), tourism and economy (n=3), research and education (n=2), NGO (n=2), and private owner (n=1), (Suppl. Fig. S1-2).

The workshops aimed to collaboratively identify and select the most relevant ES provided by mountain lakes in the respective regional context and included participatory elements, i.e., exercises in small groups, plenary discussions, as well as individual and deliberative feedback rounds. Both workshops followed the same multi-level structure: First, an introduction to mountain lakes and the study context was provided by two researchers of CLAIMES. Second, relevant ES were identified and discussed in small groups (3-4 stakeholders, mixed sectors) following the guiding question: "Which services, goods or contributions to human well-being do you associate with natural mountain lakes?". The results of the group discussions were presented to the general plenum afterwards. To derive a concise set of evaluation criteria (i.e., 5-7 priority ES) as deemed optimal for the MCDA approaches used in this project (Buchholz et al. 2007; Saaty & Ozdemir 2003), we moderated a collective selection process on the ES listed in the identification phase using a rating exercise. Initially, each participant was asked to individually reflect on the pool of mentions and assign six points for particularly important ES. Then, in an open plenary discussion, the most important ES were discussed, and group consensus was reached on a set of priority ES in both study regions. For further details on the approach, see (Ebner et al. 2022a; Fontana et al. 2023; Schirpke et al. 2021a). Based on the outcomes of the regional workshops, we used cross-tabulation to determine commonly perceived ES across the study regions.

2.4 Evaluating ES provision and elaborating policy advices

2.4.1 Multi-criteria decision analysis

To evaluate the current ES provision of mountain lakes in the respective study regions and compare the stability of ES provision under future scenarios, we used an MCDA approach comprising four main steps (Figure 8 For further details see also (Fontana et al. 2013, Fontana et al. 2023): **i)** Criteria selection: Most important ES were identified in regional stakeholder workshops (section 2.3.3) and used as criteria to evaluate ES provision of individual mountain lakes. **ii)** Criteria weighting: Perceived relative weights of ES (i.e., importance coefficients, (Cinelli et al. 2020) were inquired in each study region using a pairwise comparison questionnaire according to the Analytic Hierarchy Process (Saaty 1980), consulting a broad range of stakeholders across diverse sectors. ES weights (i.e., priorities) were derived from the comparison matrices, after checking logical validity of individual responses by calculating the consistency ratio (CR) with a threshold of CR ≤ 15%. (De Marinis & Sali 2020; Ishizaka & Siraj 2018). ES weights were then aggregated sector-wise into a single representative judgment for the entire group of consulted stakeholders in each regional context using the geometric mean (Saaty

& Peniwati 2013). **iii)** Collection of attributes to describe the selected ES: Indicators were quantified for the selected ES considering the current state and under future scenarios of climate change (section 2.3.1). **iv)** Application of MCDA (i.e., PROMETHEE; (Brans & Vincke 1985, Macharis et al. 2004): Selected ES, weights, and indicators were synthesized for the case study mountain lakes in each study region to provide a visualization and evaluation of the ES provision (i.e., lakes' ES profile/performance, disaggregated outranking flow *phi*). Phi, or the outranking flow comprises the sum of indicators of each criterion and the corresponding weight of the criterion. It represents the sum of positive (Phi+) and negative (Phi-) flows of all criteria which contribute to the performance of each individual lake. A complete ranking (PROMETHEE II) of the lake alternatives based on the multicriteria net outranking flows was then derived from comparing the weaknesses (i.e., one lake is outranked by other lake alternatives) and strengths (i.e., one lake is outranking other lake alternatives), including a sensitivity analysis of the impacts of differing ES weighting schemes. In order to check the stability of ES weights we calculated stability intervals for each ES (Geldermann & Rentz 2005; Mareschal 1988). A graphical output visualizes the range in which the weighting of an ES can be changed while maintaining the original overall lake ranking (Degener et al. 2013; Geldermann & Rentz 2005). This procedure was repeated for future scenarios (until 2081-2100) of climate change impacts on ES indicators values under the RCP8.5 scenario to compare current and futures conditions and evaluate lakes' variability in ES provision. In addition, potential differences in lake groups (section 2.1) were considered.

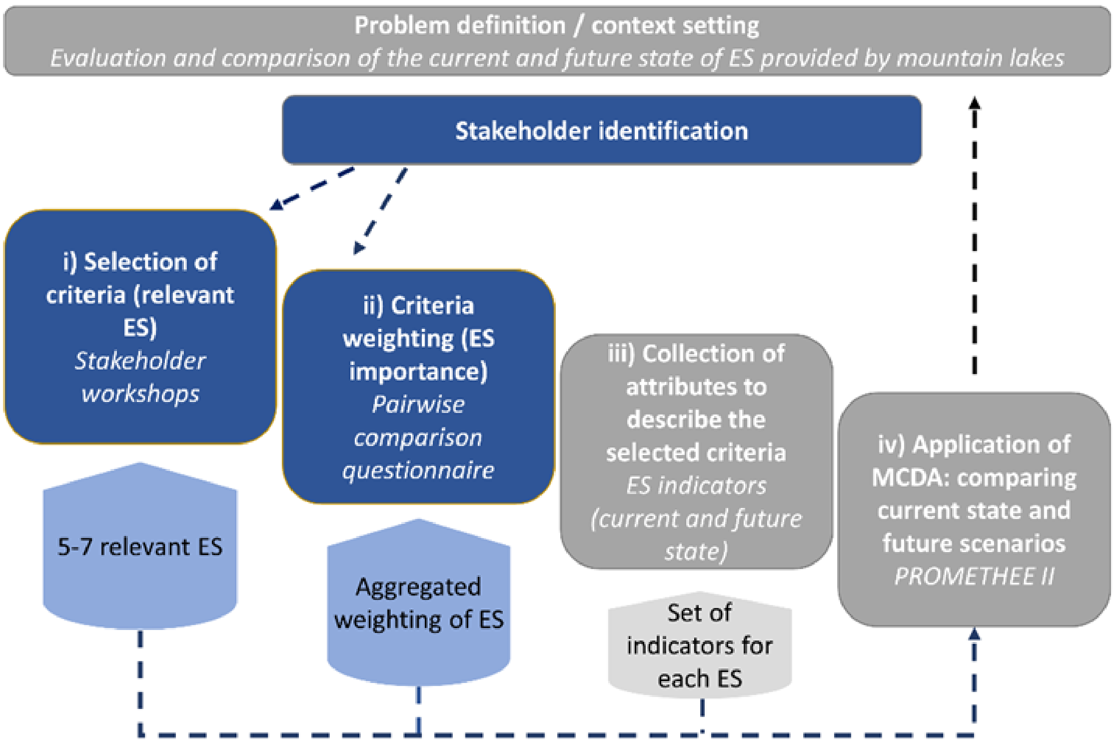

Figure 8: Schematic workflow of the MCDA approach used to evaluate and compare the ES provision of mountain lakes under current and future conditions. Steps involving stakeholder participation are indicated by a blue color.

2.4.2 Expert consultation

To identify a potential need for policy measures to adapt to climate risks in the context of mountain lakes, our approach consisted of multiple stages:

1. An expert elicitation process involving representatives of regulatory bodies on the regional and national level for the study regions in Austria and Italy.
2. An analysis of sources of law on all levels of government on potentially relevant regulatory frameworks, as well as relevant agreements under civil law.
3. The final stakeholder feedback round, which followed a similar expert elicitation protocol as the first step, while taking previous insights into account.

The initial expert elicitation round consisted of half-structured interviews following expert elicitation protocols, specific to the area of expertise of the respective government body. We interviewed experts from regulatory agencies on the regional and national level. Focus was laid on those governmental bodies that are primarily concerned with agricultural, environmental, and land use regulations associated with mountain lakes and adjoining areas. The experts were sent a set of guiding questions before the actual interview was held via teleconference. The questions were structured to elicit expert opinion on climate risks for mountain lakes and potential regulatory responses to those risks. The regulators then were also asked to give an opinion on their toolset (current regulations) to respond to such risks in the near future. Statements on the adequacy of current regulations was then cross-examined with an independent analysis of the existing regulatory framework (Step 2 above). Additionally, the expert elicitation also extended to potential risks that might arise from climate change in combination with potential increases in stress levels due to an increase in human activity (tourism, agriculture) in mountain regions.

The resulting insights were validated within the second stakeholder workshop round held online, which followed a protocol adjusted from the initial expert elicitation: Niedere Tauern (28. 4. 2022), South Tyrol (5.5.2022). Main focus was an assessment of risks by the participants of the stakeholder workshops and a subsequent discussion of potential regulatory remedies to those risks. For this, the stakeholders had to discuss the questions formulated in the protocol in a small group setup. To structure these discussions risks were categorized into areas of concern, notably protection of waters, tourism, agriculture (including fishery and hunting), and issues for neighboring communities. Small group findings were then synthesized in a large group plenum discussion, ensuring consensus over the issues raised, as well as over the potential responses proposed.

3 Results

3.1 Short-term changes and their linkage to climate change

3.1.1 Limnological variability and effects of climate change

Temperature data loggers installed in the mountain lakes for one or two years were read, and mean values for August temperature were calculated from the data (Figure 9A). Values from the warmest month of August in 2019, 2020, and 2021, respectively, were then compared to reference values recorded during August 1998-2002. In general, temperature varied between lakes as well as between years, although the expected decrease due to lake elevation was hardly observed. For example, WIR (1700 m a.s.l.)) showed a mean August temperature of 11.9 °C (2019-2021), while OKL (2311 m a.s.l.) showed 11.2 °C for the same period. Considering that atmospheric temperature decreases on average by 0.65 °C per 100 m sea level, additional local factors (i.e. lake volumes, exposure, topography) must be held responsible for this variation. However, compared to the reference period about 20 years ago, the August temperature increased on average by 1.2 °C (-1.5 to +2.2 °C).

The 2019-2021 ice cover duration (ICD) was also compared to the mean ICD from the 1998-2003 reference period (Figure 9B). In general, ice cover time correlated positively with lake elevation for both study periods. The linear regression curves for the reference period were calculated as y = 32 + 0.1 x (R^2 = 0.77), where y is ICD in days and x is m a.s.l. For the study period 2019-2021 y = -15 + 0.12 x (R^2 = 0.74) was calculated. Overall, lakes were covered by ice between 114 and 286 days (approximately 4-9 months). Compared to 1998-2003, a decrease in ice cover time of about 10-20 days for individual lakes below 1900 m a.s.l. was observed. Lakes at higher elevations were less affected by a decrease in ice cover. Overall, the ice cover time varied between -24 and +12 days. The visible reduction of ice cover duration for lakes with an elevation below 1900 m a.s.l. is confirmed by calculations of snow cover duration via the SNOWGRID dataset (Olefs et al. 2020). Since 1961, the duration of snow cover in Austria has decreased by an average of 40 days across all altitudes. However, the lower regions (<1500 m a.s.l.) were particularly affected by a decrease in snow cover.

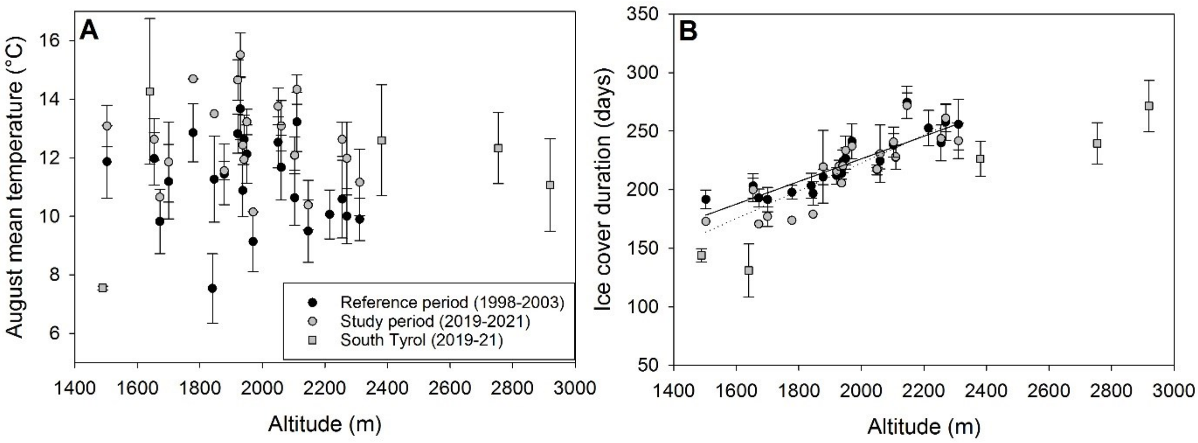

Figure 9: (A) Mean August temperature (°C) measured 2019-2021 and during the reference period 1998-2002 with standard deviation plotted against lake elevation (m a.s.l.) (B) Duration of ice cover (in days) from 2019-2021 and between 1998-2003 plotted against altitude. Error bars indicate 1 SD. Only statistically significant linear regression curves are shown (p < 0.001, reference period: R^2 = 0.77, study period: R^2 = 0.74).

Re-analysis of the diatom and chironomid community composition

Diatom assemblages were collected using sediment traps in 1999 (Kamenik and Schmidt 2005) and compared with samples collected in the same lakes during summer 2020-2021. Diatom assemblages have changed in almost all the studied lakes. A general increase in planktonic diatoms parallels the decrease in tychoplanktonic and benthic ones. The increase in planktonic diatoms was mainly related to an increase in *Asterionella formosa* Hassall, *Fragilaria delicatissima* complex and centric diatoms mainly from *Pantocsekiella comensis* group (Figure 10).

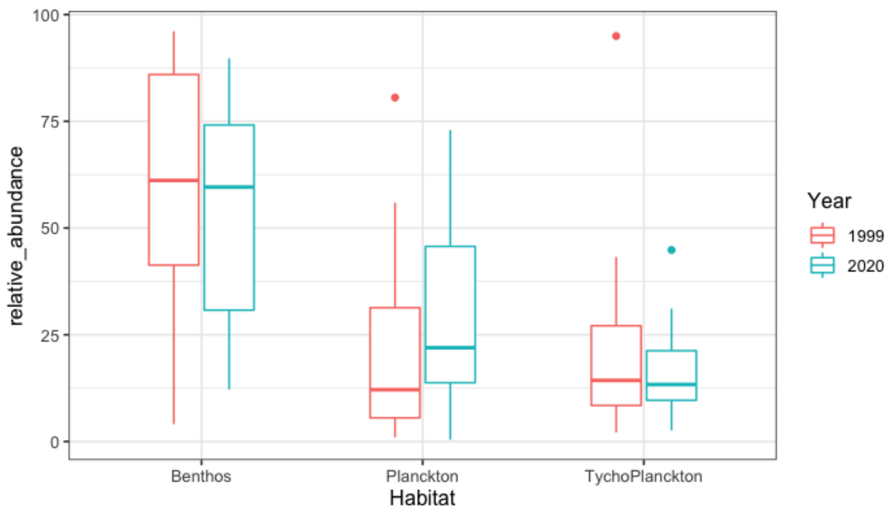

Figure 10: Relative abundance of diatoms assigned to different habitats preferences from alpine lakes (n = 30) collected in sediment traps during 1999 and during 2020.

In addition, surface sediment samples (the topmost 1–2 cm of sediment) from lakes in the Niedere Tauern (n = 20) and South Tyrol (n = 4) were treated for subfossil chironomid analysis following standard procedures. No chironomid subfossils were found in the sample from PRA. Count sums of chironomid head capsules in all other lakes varied from 51 to 96 (mean = 75) per sample. In total, 72 chironomid taxa were identified, 36 thereof have abundances >2% in at least two samples (Suppl. Fig. S5).

The PCA ordination was used to analyze the environmental preferences of the chironomid assemblages in the lakes (Figure 11). Taking into account the species scores and the distribution of the chironomid assemblages, the first PCA axis was interpreted to mainly reflect a temperature gradient. The assemblages dominated by cold-adapted taxa, i.e. *Diamesa*, *Pseudokiefferiella parva*-type, *Pseudodiamesa*, *Micropsectra radialis*-type, *Heterotrissocladius marcidus*-type, *Prodiamesa olivacea*-type, *Zavrelimyia* type A, *Paratanytarsus austriacus*-type, and *Paracladius*, are located in the right part of the ordination, and the ones dominated by more thermophilic taxa are located in the left part. The second PCA axis may integrate environmental driving forces such as changes in substrate type, trophic conditions, oxygen availability.

Changes in the sample scores of the first PCA axis to lower values were interpreted as reflecting the warming over the last 20 years. Thus, the assemblages of the colder lakes PFA and LAN, intermediate lakes TIE, MLA, ELE, RAN, and HIN, and warmer lakes SCH, OGIG, OLA, OKL, TWA, and KNA, were sensitive to the recent warming.

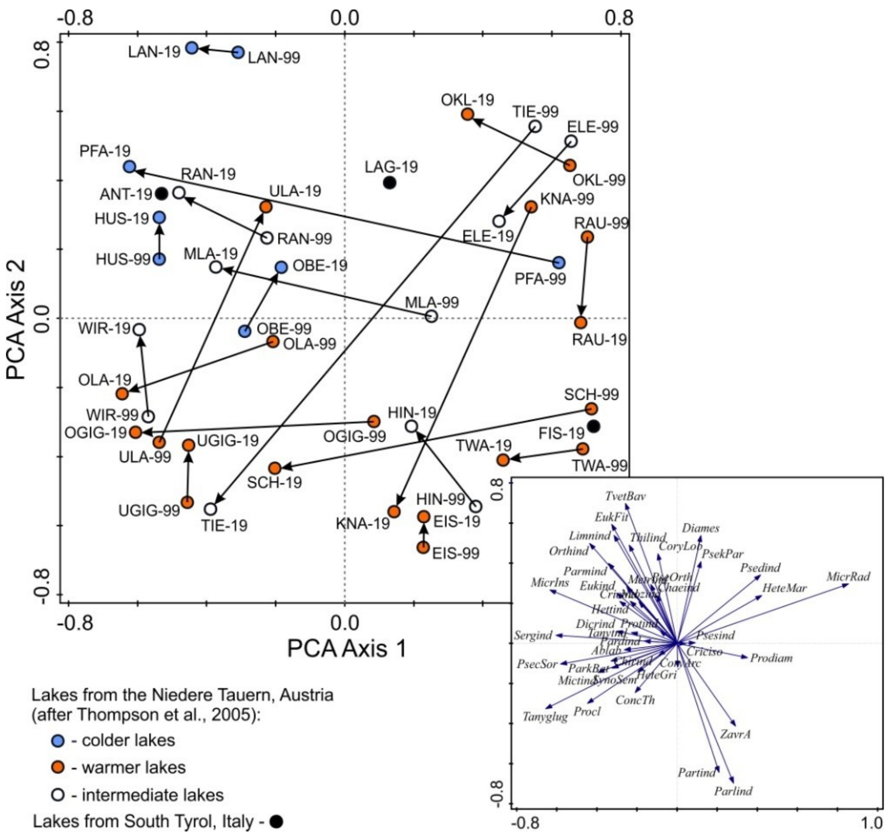

Figure 11: Euclidean distance scatter plot of a Principal Components Analysis (PCA) of the sub-fossil chironomid assemblages sampled in the lakes in 1999 and 2019. The inset shows a scatter plot of the species scores of selected chironomid taxa. The first PCA axis accounts for 22.8% of cumulative variation and the second for 15.9%. According to comparisons with the broken-stick model, both axes account for statistically significant amount of the variations. For PRA no chironomid counting was possible. Because of the high sediment load from tributaries no head capsules in upper layer of sediment core could be found during the years 2019 and 2020.

Species-specific analyses of plankton (algae, zooplankton)

The water chemical quality was evaluated in comparison to the reference period 20 years ago. The electrical conductivity varied between 13-102 µS cm^{-2} during the study period, which means hardly any change with respect to the ion content in the water compared to the reference sampling (13-86 µS cm^{-2}) in October 1998. There was a pronounced variation between the lakes, e.g., the conductivity of OLA (2050 m a.s.l.) varied between 13-16 µS cm^{-2}. Maximum conductivities were measured in the PRA (220 -257 µS cm^{-2}) and ANT (107-143 µS $cm-^{2}$), which can be explained by the relatively large catchment area. More details on physical-chemical parameters from two study periods are shown in the Supplement (Suppl. Fig. S6).

For the trophic characterization of the alpine lakes, a preliminary classification according to the OECD criteria (Vollenweider & Kerekes 1982) was made, namely with respect to the parameters chlorophyll a (Chl-a), transparency and total phosphorus content (TP). The majority of lakes were assigned to the oligotrophic range, with individual lakes even classified as ultraoligotrophic (WIR, MLA, OSAL, KAP, OLA, HIN). These lakes had visual depths of 10-12 m. However, individual lakes were also located on the border of oligomesotrophic or near mesotrophic because the average Chl-a content was relatively high (> 3 µg/L), (UKL, RAU, PRA, FIS), while LAG was found rather extreme (Figure 12).

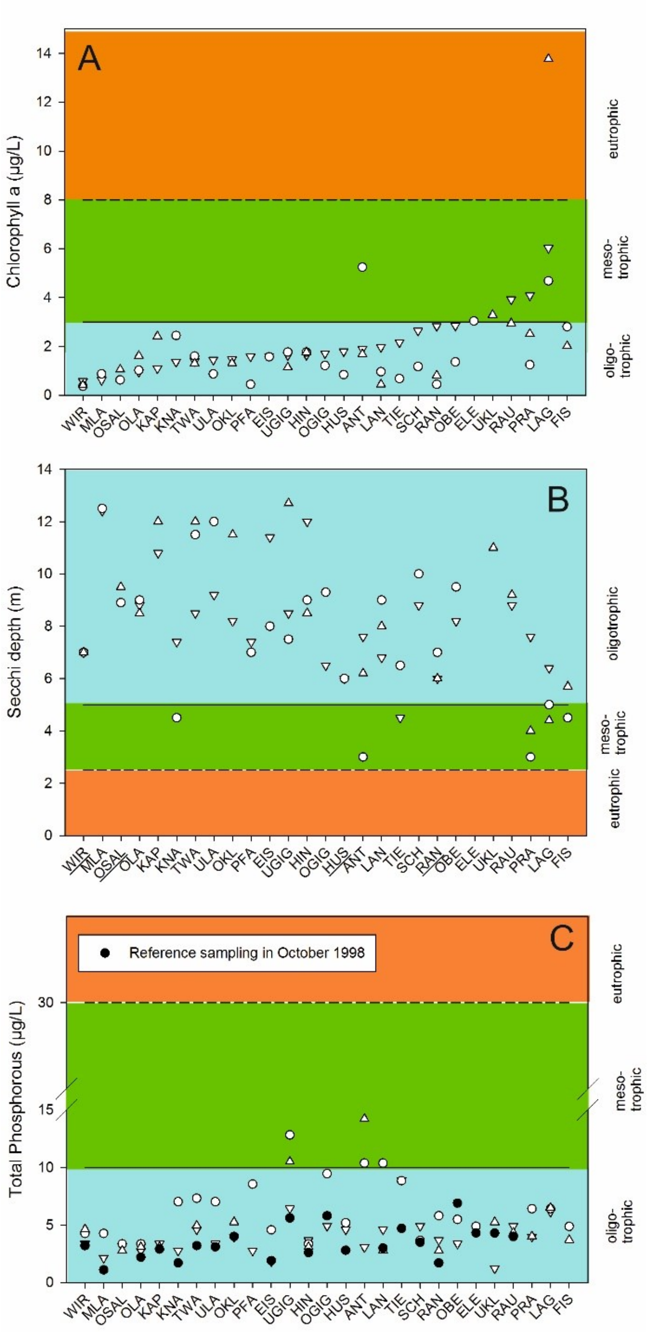

Figure 12: Trophic state of alpine lakes according to OECD criteria, A) average measured values Chl-a (µg/L), B) Secchi depth (m), C) total phosphorus (TP) content (µg/L) from 2019, 2020, 2021 (light symbols). The dark symbols of the TP indicate the average measured values from the reference sampling (1998). No comparative values are available for either Chl-a or Secchi depth. The underline for individual lakes (B) is to indicate the shallow lakes with Secchi depth to bottom. Full names of lakes and corresponding abbreviations are given in Suppl. Table S5. Lakes have been arranged according to increasing trophic state.

Phytoplankton functional groups

Phytoplankton communities differed depending on the trophic state of the lakes. In lakes classified as ultra-oligotrophic (Figure 13A), Chrysophyceae, Dinoflagellata and Cryptophyceae dominated, while green algae as well as other photoautotrophs occurred only to a lower extent. Similarly, for oligotrophic lakes the phytoplankton community was dominated by Chrysophyceae, Dinoflagellata and Cryptophyceae. In addition, increased proportions of Bacillariophyceae were detected (Figure 13B). In contrast, for lakes with oligo-mesotrophic conditions, green algae dominated while Chrysophyceae, Cryptophyceae and Dinoflagellata still occurred with high frequency (Figure 13C). The cyanobacteria generally occurred with low relative abundance.

Analyzing the chloroplast composition from 16S rDNA, we detected *Asterionella formosa* in 2019 in low relative abundance in OBE (7.8%), RAU (0.6 %) and ANT (0.2 %). In addition, 24 taxa of coccal green algae were found across all lakes. The proportion of coccal green algae taxa and desmids were highest in oligo-mesotrophic lakes FIS and LAG, i.e. where 15 and 48% of green algae, respectively, belonged to coccal taxa (mainly desmids). In contrast, we found overall a lower relative abundance of green algae in (ultra-)oligotrophic lakes (avg. 8 ± 2% and 8 ± 1%, respectively; Suppl. Table S6) and within the group of green algae, we detected a low proportion of coccal taxa, i.e. 4 ± 2% and 2 ± 1%, respectively.

In most of the lakes we detected a high share of putatively mixotrophic taxa. Lakes assigned to an ultra-oligotrophic state were dominated by putatively mixotrophs with an average relative abundance of 93.5 ± 2.5% (Suppl. Table S6). We detected the highest relative abundance in HIN, which was mainly dominated by Dinoflagellata of the genus *Biecheleria* (Woloszynskia). In summary with increasing trophic state, a decreasing relative abundance of mixotrophic taxa vs phototrophic taxa was observed.

Zooplankton community composition

A total of 39 taxa were identified, i.e., 25 taxa of rotifers, six taxa of cladocerans, and eight taxa of copepods. The most frequent taxa included *Keratella hiemalis*, which is considered as a cold-stenotherm species, and *Kellicottia longispina*, occurring in 18 and 15 of the 27 lakes, respectively. In addition, early life stages such as copepodids and nauplia (larval stages of of Cyclopidae) occurred in 19 and 23 lakes, respectively, whereas adult Copepoda were found in 11 lakes. The zooplankton of ELE and HIN solely consisted of Rotifera.

Altogether larger sized cladocerans or copepods were rare. *Cyclops abyssorum* including the subspecies *C. abyssorum praealpinus* and *C. abyssorum tatricus* were found in nine lakes. In addition, *Eucyclops* sp. and Daphnia rosea were found in two and five lakes, respectively. *Daphnia galeata* was found only once. No calanoid copepods (e.g. *Diaptomus*) were found. Small cladocerans of the genus *Bosmina* occurred more frequently: *B. longispina* was detected in 11 lakes and *B. longirostris* in five lakes.

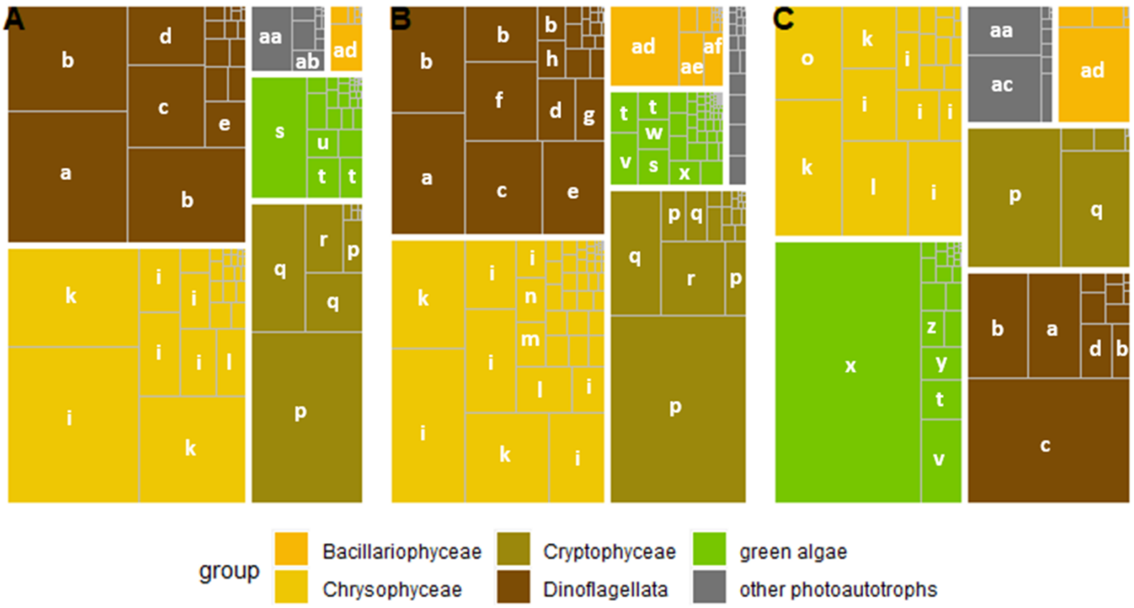

Figure 13: Mean relative abundance of the abundant phytoplankton groups as indicated by different colours: Dinoflagellata, Chrysophyceae, Cryptophyceae, green algae, Bacillariophyceae and other photoautotrophs recorded from (A) ultra-oligotrophic, (B) oligotrophic, (C) oligo-mesotrophic conditions. Each rectangle in the treemap corresponds to the proportion of a specific algal genotype (calculated from rarified read numbers). For clarity, rectangles with a proportion less than one percent are not labeled.

Legend to letters: a=Pelagodinium, b=Biecheleria, c=Dinoflagellata, d=Thoracosphaeraceae, e=Gyrodinium, f=Woloszynskia pascheri, g=Gymnodinium clade, h=Ceratium hirundinella, i=Chrysophyceae, k= Chrysophyceae P34-48, l=Chromulinales, m=Uroglena, n=Dinobryon sertularia, o=Ochromonas, p=Cryptomonas, q=Kathablepharidae, r=Plagioselmis, s=Chlorella sp. YACCYB54, t=Chlorophyceae, u=Mychonastes, v=Trebouxiophyceae, w=Chlamydomonas sp. NIES-3906, x=Desmidiales, y=Tetranephris, z=Monoraphidium, aa=Mallomonas elongata, ab=Pseudopedinella, ac=Mallomonas torquata, ad=Mediophyceae, ae=Fragilarium, af=Thalassiosira.

Fish biodiversity

After filtering of the sequencing data, six different fish species were detected: *Phoxinus phoxinus*, *Cottus gobio*, *Salvelinus fontinalis*, *Salvelinus alpinus*, *Salmo trutta* and *Coregonus lavaretus*. The taxonomic analysis has been carried out for 22 samples. For most samples, only minor variation was observed (identical or almost identical species composition), when we looked at both sampling years. However, in some cases, like OGIG the number of species doubled from 2019 to 2020.

The combined biodiversity for all samples, shows that the majority of all reads belonged to *Phoxinus phoxinus* (81,6%). The second most abundant reads were assigned to *Cottus gobio* (8,6%), followed by *Salvelinus fontinalis* (7,8%), *Salvelinus alpinus* (1,3%), *Salmo trutta* (0,4%) and *Coregonus lavaretus* (0,2%), (Suppl. Fig. S7).

In summary, an influence of warming was generally visible, which corresponds to an average increase of 1.2°C in August, but also means a shortening of the ice cover, which mainly affects the lakes located below 1900 m a.s.l. The majority of lakes still showed very good water quality, i.e. an oligotrophic status. However, individual lakes indicated rather mesotrophic conditions, which is not only caused by the size of the catchment (e.g. PRA, ANT). Four lakes showed signs of eutrophication despite a relatively small catchment area (UKL, RAU, LAG, FIS), and would also become more eutrophic by the increase in average temperature in the water column or the extended growing season in the future.

3.1.2. Future of relevant climate indices

Before focusing on the climate indices defined in Section 2.2.2, we briefly review the raw data of the climate projections. The focus here is on the maximum temperature and the snow depth around the lakes studied, since these have a special significance - especially in summer. We focus on the „worst-case“ scenario RCP8.5. Note that for the lakes in South Tyrol ÖKS15 data are not available.

According to future climate projections, the median of both maximum temperature and snow depth for the near future changes only slightly in the vicinity of the lakes examined (Figure 14). Projections reveal an increase of maximum temperatures of 0.31-0.43-0.54°C (min-med-max) and a decrease in snow depth by 0.01-0.05-0.07 m. Thus, snowpack will persist even in the watersheds of lakes located at lower altitude (HUS, WIR, LAN) until the middle of the 21st century. However, we expect a significant increase in maximum temperatures (2.9 - 3.1 - 3.1°C) in the second half of the century. This has the effect that snow depth will decrease between 0.03- 0.18 - 0.29 m (Figure 14). Therefore, stable snowpack is unlikely in the watershed of lakes at relative lower altitude (e.g., HUS, LAN, OBE, WIR, RAN). As snow cover is likely a key parameter for runoff, water balance, and cooling of the lakes into the summer months, we expect a significant increase in temperature or decrease in water level during the summer with the loss of snow cover.

Based on the ÖKS data, we calculated further indicators (for definitions see chapter 2.2.2) for the climate conditions in the near and distant future at the lakes in the Niedere Tauern. The length of the growing season (Figure 15) shows only a moderate prolongation in the near future (9 - 12 - 16 days). However, the extension of growth period is more pronounced in the second half of the century, i.e. 42 - 47 -53 days (6-7.5 weeks).

The differences in summer days (Figure 15) show an even stronger signal, especially in the distant future. In the near future, summer days increase only slightly (0.07-1.8-4.9 days) for the lower lakes in the Niedere Tauern (HUS, LAN, WIR) and the lakes in South Tyrol (OSAL, ANT, PRA, FIS, LAG). However, in the distant future, this rise is 4.7-12.7-16.3 days, which represents a significant increase in bathing days at mountain lakes compared to the current reference (2021-2030) of 1 -5 summer days. Summer days will increase particularly pronouncedly at the lakes in South Tyrol (>20 summer days), while the other lakes in the Niedere Tauern will have about 15 summer days.

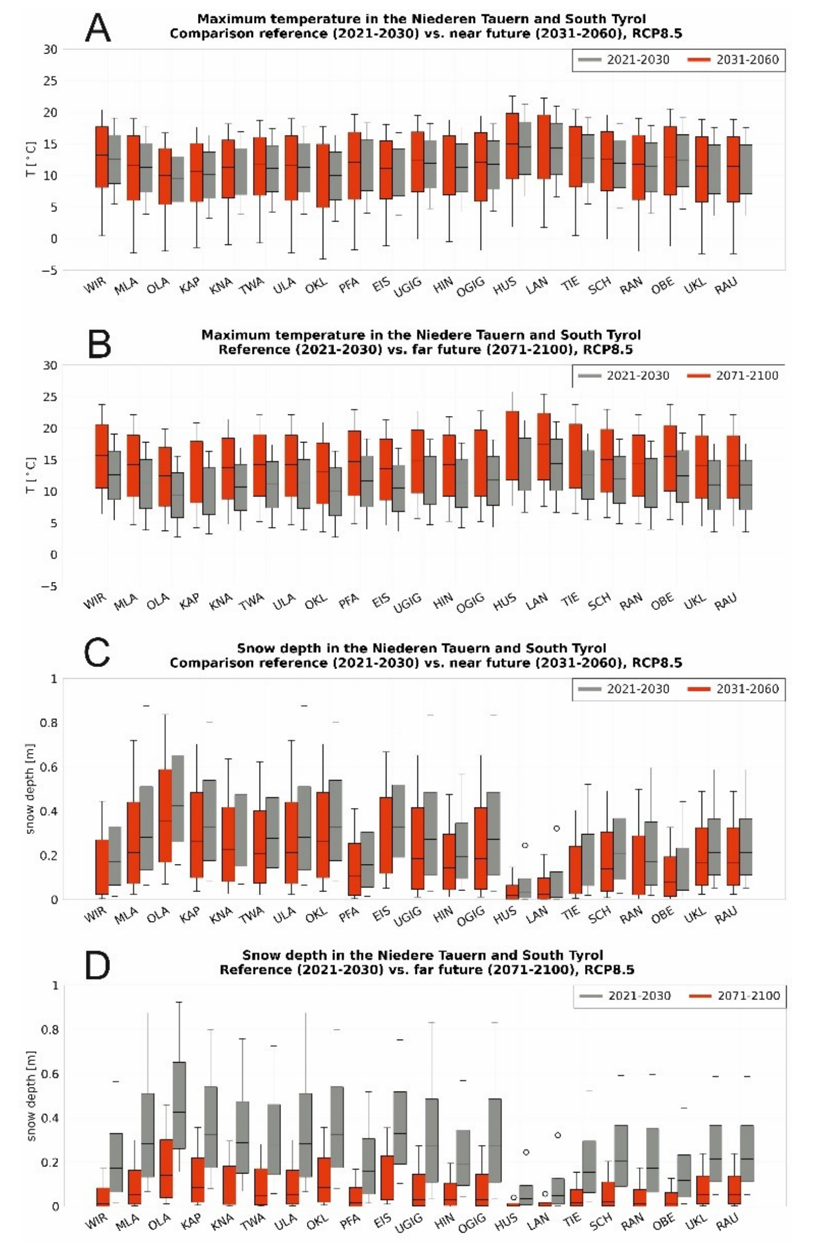

Figure 14: ÖKS15 raw data: Maximum temperature (A, B) and snow depth (C, D) for the near (2031-2060) and distant (2071-2100) future (red boxplots). Boxplots represent the median from the 30 years of observation, and the 25-75% quantiles. The error bars indicate the 95% confidence interval. For the reference period we use the model values from the current decade (2021-2030; grey boxplots). Full names of lakes and corresponding abbreviations are given in Suppl. Table S5. Lakes have been arranged according to increasing trophic state (see Figure 12). Note that for the lakes in South Tyrol ÖKS15 and FUSE-AT data are not available.

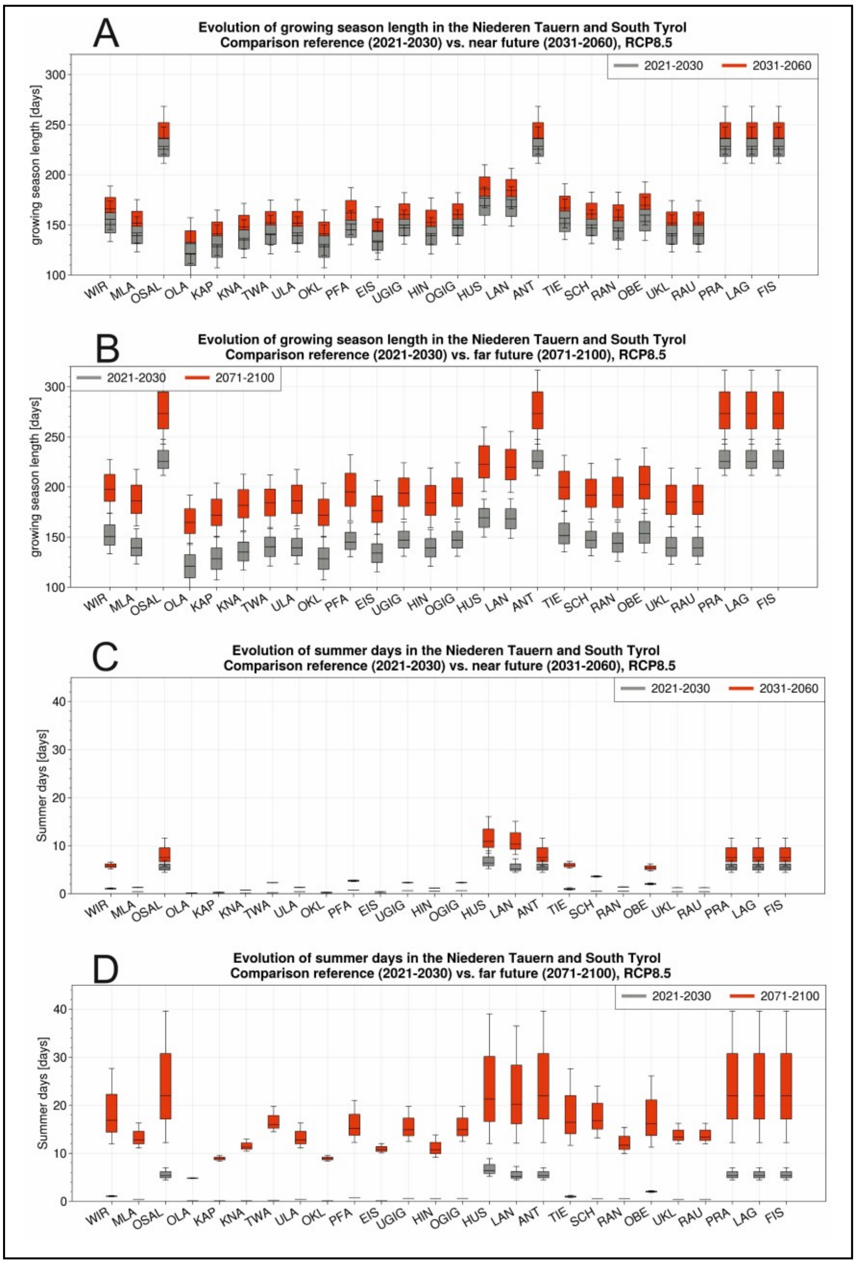

Figure 15: Length of growing season (A, B) and summer days (C, D) for the near (2031-2060) and distant (2071-2100) future (red boxplots). Boxplots descriptions as in Figure 14. For the lakes in Nied. Tauern ÖKS15 data and for South Tyrol the EURO-CORDEX data were used.

Conversely, frost days (Figure 16) decrease significantly, but remain relevant even in the second half of the 21st century. They decrease by 10-11.8-13.7 days, and by 34-43-49 days in the near and distant future, respectively. Hence, number of frost days in the present period (2021-2030) varies between 140 and 60 days, but especially the lakes at lower altitude in Niedere Tauern (HUS, LAN) and the lakes in South Tyrol (OSAL, FIS, LAG, PRA, ANT) will experience a significant decrease down to about 30 frost days per year.

Finally, according to the evolution of frost days, cold episodes (Figure 16) decrease by 5-8-10 days in the near future and by 14-28-37 days in the distant future. In particular, lakes at lower altitude in the Niedere Tauern (WIR, HUS, LAN) and lakes in South Tyrol (OSAL, FIS, LGA, PRA, ANT) will show only relatively short cold episodes of 10-15 days during the 2nd half of the century.

Overall, it can be concluded that even while frost days and cold episodes are decreasing significantly, they still occur and most lakes therefore will form ice cover even under the RCP8.5 climate scenario.

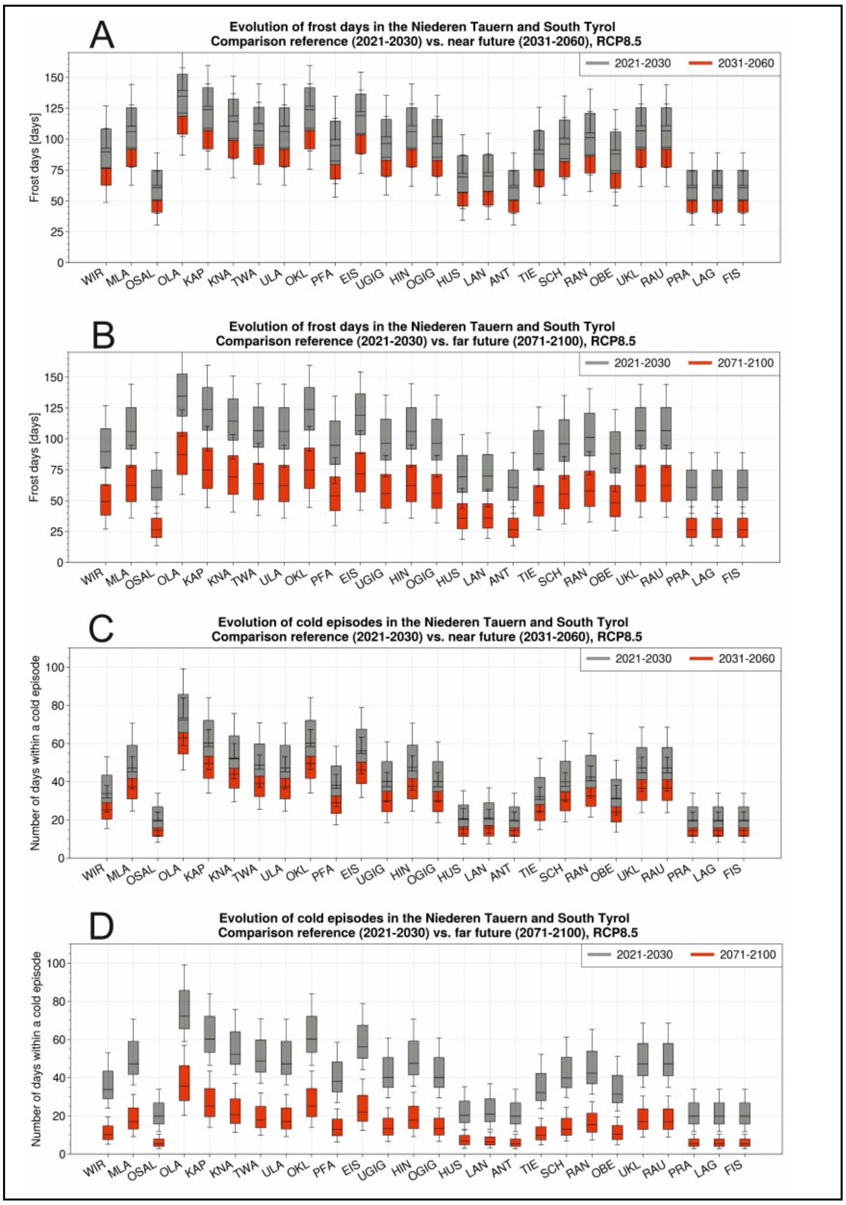

Figure 16: Frost days (A, B) and cold episodes (C, D) for the near (2031-2060) and distant (2071-2100) future (red boxplots). Boxplots descriptions as in Figure 14. For the lakes in Nied. Tauern ÖKS15 data and for South Tyrol the EURO-CORDEX data were used.

3.1.3. LST models and predictions

The LST models were trained, tested, and validated specifically for each lake using the methodology described in Section 2.2.2. In this process, we could identify the most important atmospheric parameters for lake temperature. For almost all lakes (except for UKL) the daily minimum temperature plays a decisive role for the daily LST. In contrast, the daily maximum temperature is an important parameter only at LAN, OLA and UKL. Likewise, the daily precipitation plays a subordinate role: it is considered significant only at UKL and MLA. Notably daily snow depth was not found to be important for daily LST at any of the lakes studied. The 14-day means of maximum temperature, precipitation and snow depth, however, turned out to be highly significant for the vast majority of lakes. SCH is particularly striking, being the only lake where the 14-day mean of both precipitation and snow depth are not significant in modeling its LST.

As already outlined above, we set up a specific LST model for each lake separately. These models can subsequently be used to derive future LSTs based on climate projections of three different climate scenarios: RCP2.6, RCP4.6 and RCP8.5. All analyses were performed for all lakes. Due to the large volume of results, the outcomes are presented below for one lake as an exemplary case (UGIG, Figure 17). Depending on the scenario, the temperature develops in different directions. Up to the middle of the century, the three considered scenarios show very similar results of around 9°C to 9.5°C for the near future period (2031-2060). Only from 2050 onwards scenarios begin to diverge, profound differences are revealed in the distant future period (2071-2100). While RCP2.6 assumes conditions remain as they are in the near future, RCP4.5 shows a warming of the median summer temperature to 10°C. RCP8.5 indicates an even greater warming to just around 11.5°C for the median, with the uncertainty ranges being largest for RCP8.5.

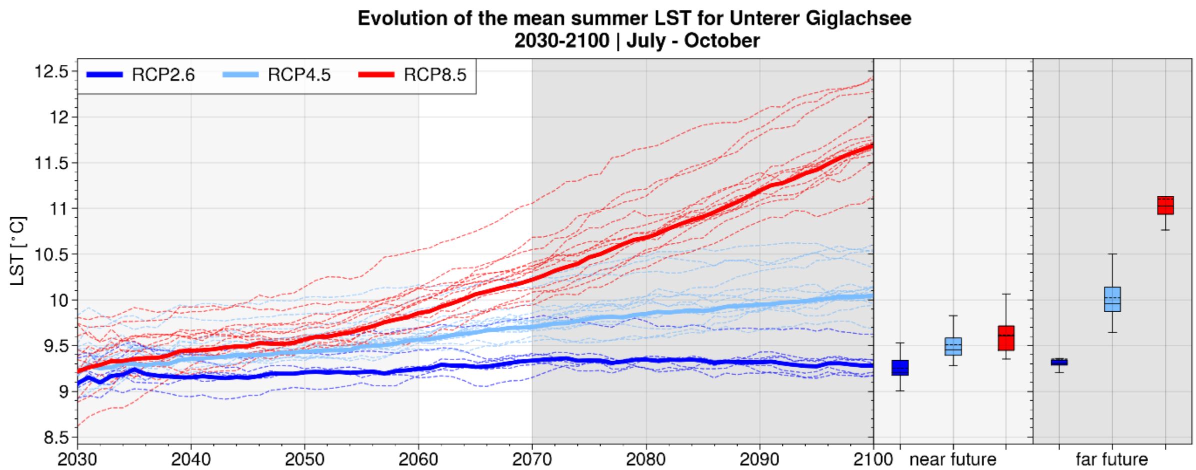

Figure 17: LST evolution from 2030 to 2100, investigating the scenarios RCP2.6 (dark blue), RCP4.5 (light blue) and RCP8.5 (red). The near future period corresponds to the time period 2031-2060, the distant future represents the period from 2071 to 2100. Dashed lines represent single ensemble members, i.e. 8 for RCP2.6, 13 for RCP4.5 and 13 for RCP8.5. Solid lines refer to the associated ensemble mean. Boxplots on the right side represent the ensemble distribution of mean values over the near and distant future, respectively.

Figure 18 displays the project mean summer LSTs in the distant future considering RCP8.5 compared to the reference period. It can be seen that climate change impacts the investigated lakes differently. Whereas high-altitude lakes like OSAL will show only a slight warming of about 1°C, lakes at lower elevation like HUS or PRA exhibit pronounced warming at the end of the century of more than 2°C and 3°C, respectively (median values). This higher resistance can be explained by the fact that at these altitudes of over 2500 m the temperature changes, but not the presence of snow, which has a significant effect on the temperature regime of the lakes. The strongest changes in the alpine terrain are to be expected at an altitude of about 1500 m, since the 0°C as well as the snow line will shift further upwards in the future and precipitation will fall in liquid form for most of the year.

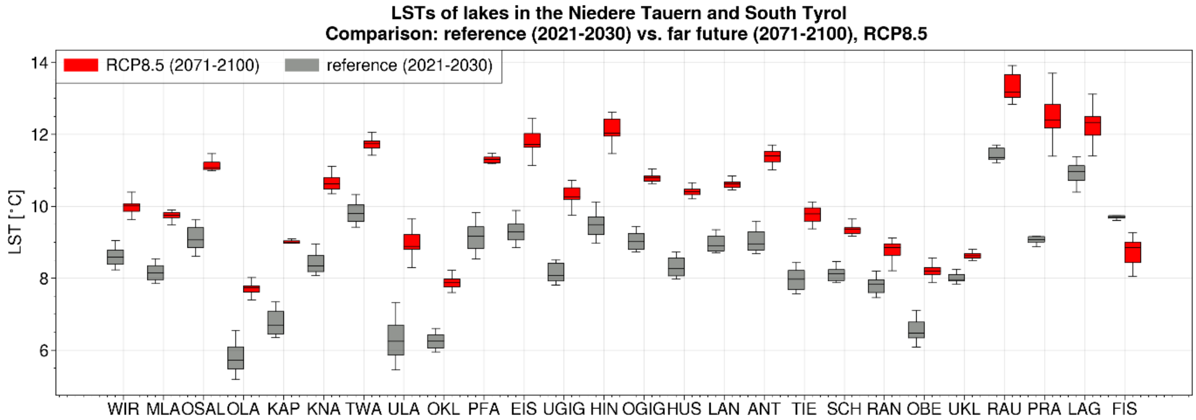

Figure 18: Mean summer temperatures (ice-free period) of all investigated lakes (sorted by their trophic status) in the reference period (2020 – 2030, grey) and the distant future (2071-2100, red) accounting for RCP8.5. Boxplots descriptions as in Figure 14.

Seasonal development of LST simulations

For the following analyses, the focus will again be laid on the distant future period considering the ‚worst-case' scenario RCP8.5. Using the example of UGIG in the Niedere Tauern region, we can identify differences between reference and future periods in the projected course of LST throughout the year. These detailed analyses have been made possible by modeling at high (daily) temporal resolution. Differences between projections and reference period are, however, highest during the summer months featuring around 3°C difference between the respective median values (

Figure 19). The investigation of LST courses over the year serves as basis for the determination of future changes in the length of the ice-free period.

The modeling of the surface temperature mostly showed a very steep rise in temperature in May or June, which reaches a plateau in July-August and drops again similarly steeply in September-October (Figure 19). Analogous to the measured data, 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. For individual lakes at lower altitude with little snow cover in the catchment area, the growing season will probably be significantly longer, as could be inferred from a less steep temperature increase at the beginning of the year to the temperature maximum in July-August and a gradual decrease by the end of the year.

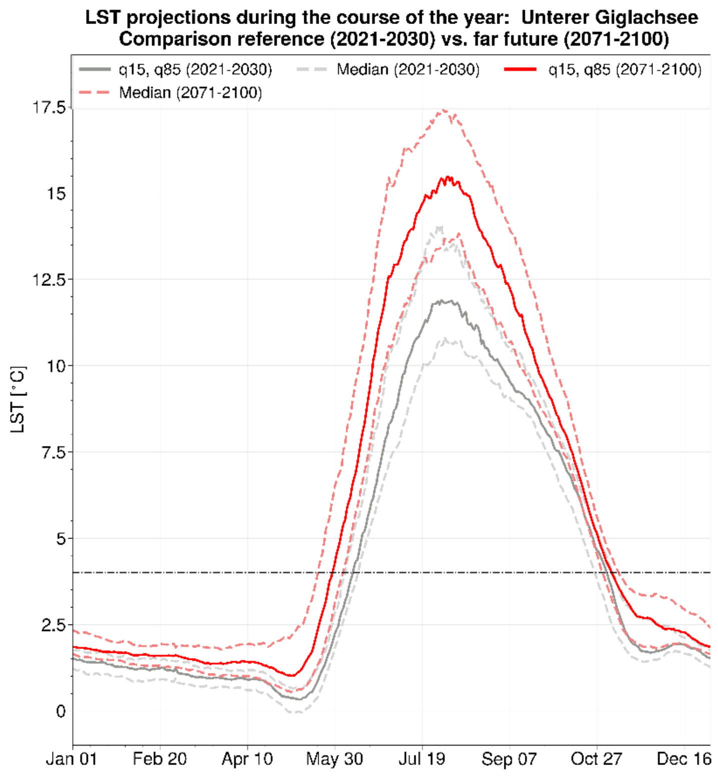

Figure 19: Course of LSTs throughout the year for the reference period (2020-2030) in grey and distant future (red). The dark grey line corresponds to the median in the reference period; the light grey lines represent the 15 and 85 quantile of the underlying distribution (ÖKS15 ensemble of 16 members). Analogously the red lines indicate RCP8.5. The straight dotted line indicates 4°C intersection used to estimate the onset and end of the icefree period.

3.1.4. Predicted response of lakes to climate warming

In the near future the increase in the growing season is still relatively small (median 1-12 days), but in the distant future it is significant (median 3-40 days), corresponding to a maximum of 7 weeks (Figure 20A, B). While the median is equal to the 50% quantile (representing the middle value of the modeled distribution), it was also of interest to inspect less probable but more extreme values, such from the 85% quantile (still occurring with a probability of 15%). For the 85% quantile, the increases are 12-60 days for the near future and 10-98 days for the distant future, respectively, corresponding to a maximum of 14 weeks. Thus, the ice-free period for OKL in the 85% quantile is projected to be twice as much in the second half of the 21st century (200 vs. 100 days). For individual lakes at lower altitude, there could then be completely ice-free years (ANT, PRA). It follows that the growing season will be extended by a maximum of 100 days, but the ice cover will remain for most lakes.

Furthermore, it can be said that the principal linear (atmospheric) influence of the altitude on the duration of the ice-free vegetation period persists for the near as well as for the distant future. The regression lines for the present time (2021-2030) show that the ice-free time per 100 m a.s.l. decreases by 10.3 days (Figure 20A, B). Even at the 85% quantile, the influence of altitude remains significant, i.e., the regression line shifts practically in parallel. Notably the ice-free time of the lakes in South Tyrol is above the distribution of ice-free days in the Niedere Tauern at the same altitude.

Finally, the modeled maximum temperature forecasts were examined on a daily basis, since temperature maxima can have a disruptive effect and lead to the extinction of entire populations in the absence of refugia (e.g., in a shallow water body). For the near future, temperature maxima are still increasing relatively moderately between 0.4-0.8-1.5°C. For the distant future, however, temperature maxima increase by 2.2-2.6-6.8°C. This means that temperature maxima between 16-18°C will be relatively common at the surface of lakes in the future. For the 85% quantile, even more extreme temperature maxima above this can be expected with 15% statistical probability, namely 0.1-2.3-3.5°C for the near future and 1.2-4.0-9.2°C for the distant future (Figure 20C, D). Notably, the average warm lakes of the Niedere Tauern show stronger increases, i.e. react more sensitively than the undercooled lakes, i.e. the variation in surface temperature between the lakes (Suppl. Fig. S8) at the same altitude will increase even more due to climate warming. During the near future the average, undercooled and warmer lakes will increase in maximum temperature by 0.8 ± 0.2 (1 SD), 0.8 ± 0.1, 1.1 ± 0.2°C, respectively (ANOVA on ranks, $p < 0.01$). During the distant future the average, undercooled and warmer lakes will increase in maximum temperature by 2.1 ± 0.4, 2.4 ± 0.4, 3.4 ± 0.4°C, respectively (ANOVA on ranks, $p < 0.001$). Thus the variation in median temperature during the vegetation period between lakes will increase.

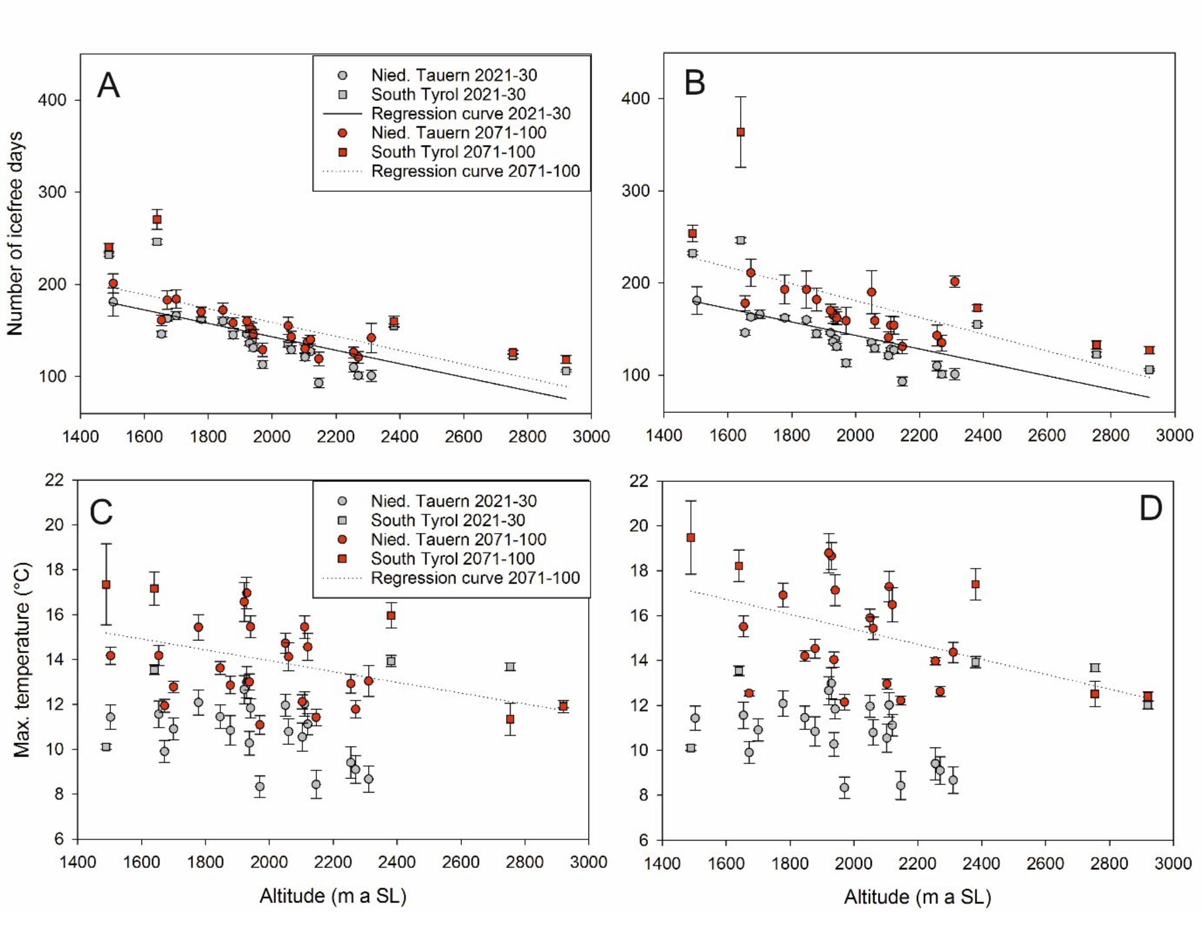

Figure 20: (A, B) Growth period (ice-free days) vs. altitude (m a.s.l.) for the distant future (red symbols, 2071-2100) in the median (A) as well as for the 85% quantile (B) compared to the reference period (2021-30), grey symbols. (C, D) Maximum surface temperatures vs. altitude compared to the reference period. (C) median; (D) 85% quantile. Error bars indicate 1 SD. Only statistically significant linear regression curves are shown (A, B: $p < 0.001$, $R^2 = 0.47 – 0.55$; C, D $p < 0.001$, $R^2 = 0.18-0.22$).

If the nutrient situation in the pelagic zone of the lakes remains unchanged, the currently observed chl-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 2001, 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 2001).

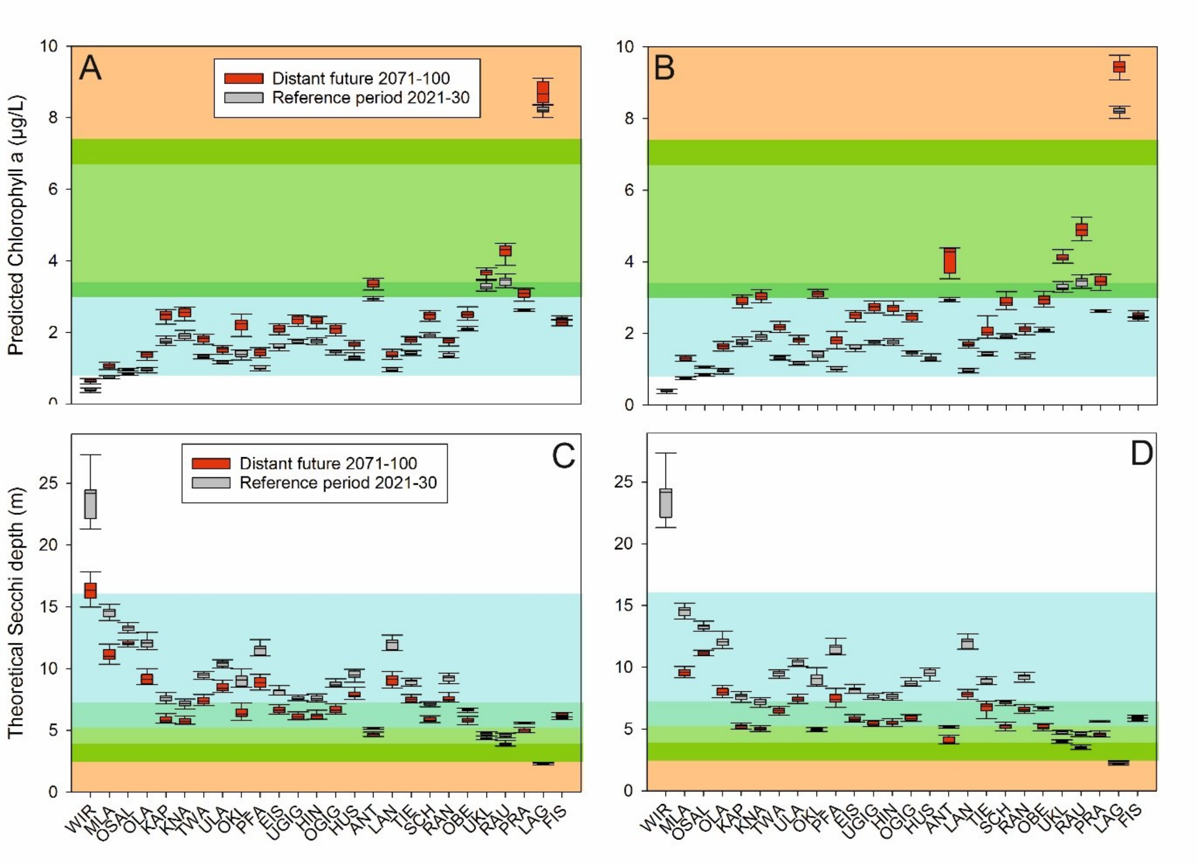

Figure 21: Prediction of chlorophyll a concentration and transparency for the distant future (2071-2100) compared to the reference period (2021-30). A, C: at the median; B, D at the 85% quantile. Interpretation of the boxplots: the middle bar represents the median from the 30 y of observation, and the 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 Suppl. Table S5.

The chl-a concentration will change moderately by 0-0.13-0.26 µg/L for the near future and increases by -0.13-0.45-0.82 µg/L for the distant future. For the 85% quantile, the increase varies from -1.3-0.38-1.0 µg/L for the near future and 0.12-0.88-1.7 µg/L for the distant future, respectively. Looking at the plot of Chl-a concentration at the present time (2021-2030) and in the near vs. distant future, the shift in Chl-a concentration from the (ultra)oligotrophic to (oligo)mesotrophic trophic level is apparent. Individual lakes, which are oligomesotrophic now, could then be mesotrophic. An exception is the LAG which was classified as mesotrophic in this study and will probably become eutrophic due to climate warming (Figure 21A, B).

Since the presented changes in chl-a concentration seem to be rather moderate, it was of interest to find out what influence the chl-a increase might have on the transparency in the lakes. Water clarity is generally emphasized as an important ecological feature in mountain lakes, so the magnitude of the reduction in viewing depth may be considered an important gauge of anticipated change due to climate warming. Conversely, the resulting Secchi depths can be inferred from the predicted chl-a concentration. Since light availability is exponentially reduced by algal biomass according to Lambert-Beer's law, the Chl-a dependence of light attenuation can be described as a logarithmic function, (e.g., for oligotrophic Lake Constance, e.g. Tilzer 1983; Sommer 1994).

Accordingly, a decrease in Secchi depth of 0-0.6-2.6 m is found for the near future and 0.26-1.75-7.49 m for the distant future. For the 85% quantile, the decreased Secchi depth would range from 0.14-1.52-3.2 m for the near future and 0.21-2.35-4.96 m for the distant future. In general, Secchi depths would shift toward the oligomesotrophic and mesotrophic ranges, respectively. For comparison, long-term data for mesotrophic Lake Mondsee (481 m a.s.l.) show that annual mean visibility depths have declined from 7 m to 5 m since the mid-1990s (Kurmayer et al. 2022). It follows that, due to climate warming, the Secchi depths in the alpine lakes and the larger lakes at lower altitude of the Alps will increasingly converge.

3.2 Ecosystem services of mountain lakes

3.2.1 Selection of ES and indicators for quantifying ES

During the stakeholder workshops, the most important ES were selected for each region (Table), including one provisioning ES, one regulating ES and six cultural ES. For both study regions (Niedere Tauern and South Tyrol), the ES for habitat, recreation and aesthetic were selected. Additionally, stakeholders in South Tyrol selected water and representation, while stakeholders in Niedere Tauern indicated ES for research, education, and existence. For each ES, we identified multiple indicators (Table), describing different aspects of potential ES supply (see also section 2.3.1).

Table 4: Definition and selection of ES used in CLAIMES based on the Common International Classification of Ecosystem Services (CICES, Haines-Young & Potschin 2018). ES were selected in the two study regions (ST = South Tyrol, NT = Niedere Tauern) by local stakeholders.

Section	Division	Group	Class	Code	Type	ES in CLAIMES	Description	ST	NT
Provisioning	Water	Surface water used for nutrition, materials or energy	Surface water used as a material (non-drinking purposes)	4.2.1.2	Abiotic	Surface water for non-drinking purposes (water)	Surface water that can be used for non-drinking purposes such as industry, agriculture or energy production	x	
			Freshwater surface water used as an energy source	4.2.1.3	Abiotic				
Regulating	Transformation of biochemical or physical inputs to ecosystems	Lifecycle maintenance, habitat and gene pool protection	Maintaining nursery populations and habitats (Including gene pool protection)	2.2.2.3	Biotic	Maintaining populations and habitats (habitat)	Maintenance of nursery populations and provision of suitable habitats (food, protection) for plant and animal species	x	x
Cultural	Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting	Physical and experiential interactions with natural environment	Characteristics of living systems that that enable activities promoting health, recuperation or enjoyment through active or immersive interactions	3.1.1.1	Biotic	Outdoor recreation (recreation)	Recreational activities that can be carried out at lakes such as swimming, bathing, recreational fishing, boating, and birdwatching	x	x
			Natural, abiotic characteristics of nature that enable active or passive physical and experiential interactions	6.1.1.1	Abiotic				
			Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions	3.1.1.2	Biotic				
		Intellectual and representative interactions with natural environment	Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge	3.1.2.1	Biotic	Scientific research (research)	Characteristics of the natural environment (abiotic and biotic) that enable scientific research		x
			Characteristics of living systems that enable education and training	3.1.2.2	Biotic	Educational value	Characteristics of the natural environment (abiotic and biotic) that enable education and traditional ecological knowledge		x
			Characteristics of living systems that enable aesthetic experiences	3.1.2.4	Biotic	Aesthetic value (aesthetic)	Characteristics of the natural environment (abiotic and biotic) that enable aesthetic experiences in direct interaction with nature, focusing on visual enjoyment of the landscape	x	x
			Natural, abiotic characteristics of nature that enable intellectual interactions	6.1.2.1	Abiotic				
	Indirect, remote, often indoor interactions with living systems that do not require presence in the environmental setting	Spiritual, symbolic and other interactions with natural environment	Natural, abiotic characteristics of nature that enable spiritual, symbolic and other interactions	6.2.1.1	Abiotic	Entertainment and representation (representation)	Natural characteristics used for entertainment or representation, e.g. films, tourism brochures	x	
			Elements of living systems used for entertainment or representation	3.2.1.3	Biotic				
		Other biotic characteristics that have a non-use value	Characteristics or features of living systems that have an existence value	3.2.2.1	Biotic	Existence, option or bequest value (existence)	Natural characteristics that have an existence, option or bequest value		x
			Characteristics or features of living systems that have an option or bequest value	3.2.2.2	Biotic				
			Natural, abiotic characteristics or features of nature that have either an existence, option or bequest value	6.2.2.1	Abiotic				

Table 5: Indicators for quantifying selected ES. '+' or '–' indicate if a high indicator value positively or negatively influences the ES. Assessment methods include biophysical methods (D—direct measurement/mapping, M—model) and socio-cultural methods (S—preference survey). Table modified from (Schirpke et al. 2021a).

ES	Indicator	Description	Method	Unit	Data Sources
Water	Storage capacity (+)	Amount of water stored by the lake	D	10^6 m^3	(Thompson et al. 2005)
	Water availability (+)	Amount of water that can be used for non-drinking purposes, derived from the water balance of the lake watershed during the summer (May–August) considering seepage, surface runoff and interception (Schirpke et al. 2012)	M	10^6 m^3 y^{-1}	(Fürst et al. 2005; Schirpke et al. 2012)
Habitat	Littoral substrate complexity (+)	Mean index of major substrate classes ranked by size, with higher complexity providing habitat and shelter for different species, e.g., as nursery and spawning areas or suitable structures for aquatic invertebrates (Kostylev et al. 2005; Kovalenko et al. 2012; Porst et al. 2019; Strayer & Findlay 2010)	D	index	Orthophotos [1]
	Shoreline development (+)	Ratio of the length of the shoreline to the length of the circumference of a circle of area equal to that of the lake (Hutchinson 1957), with higher values providing more habitat and shelter for different species	D	index	Orthophotos [1]
	Riparian vegetation complexity (+)	Index based on vegetation coverage of shore habitat types as well as land cover types along the lake (~up to 20 m) (Kaufmann et al. 2014), providing habitat and shelter for different species	D	index	Orthophotos [1]
	Trophic state (+)	Trophic state of the lake water indicating water quality, calculated based on chlorophyll-a, the concentration of total phosphorus and Secchi depth (Vollenweider 1968; Vollenweider & Kerekes 1982)	D	index	(Kamenik et al. 2001), Autonomous Province of South Tyrol (1990–2019), own measurements (2019/2020)
	Nitrate (−)	Concentration of reactive nitrogen indicating water quality (Grizzetti et al. 2019)	D	NO_3-N mg L^{-1}	(Kamenik et al. 2001), Autonomous Province of South Tyrol (1990–2019), own measurements (2019–2020)
	Plant species (+)	Number of vascular plant species, algae and mosses depending on water and including red list species (double weight)	D	n	(Wilhalm et al. 2014)
Recreation	Access difficulty (−)	Difficulty of the main hiking trail to the lake; SAC hiking scale: T1 (easy) -T6 (very difficult)	D	index	Hiking websites [8]
	Access level (−)	Type of recreational activities (Doherty et al. 2014): visual (3), secondary (2) or primary contact (1)	D	index	Own mapping
	Warm days (+)	Number of warm days (≥20°C) per year, supporting water-related activities (Vesterinen et al. 2010)	D	days y^{-1}	Climate stations [2]
	Hiking at lake (+)	Length of hiking trails around the lake (distance from lakeshore ≤50 m) in relation to the lake perimeter	D	m	OSM [3]
	Tourist facilities (+)	Density of tourist facilities (picnic area, benches, playground, etc.) around the lake (distance from lakeshore ≤50 m), providing recreational opportunities (Ghermandi & Fichtman 2015; Kandziora et al. 2013)	D	n km^{-1}	OSM [3]
Aesthetic	Water clarity (+)	Secchi depth indicating water clarity, supporting aesthetic appreciation (Angradi et al. 2018; Lee 2017; Schirpke et al. 2021c; Tallar & Suen 2017)	D, S	m	Own measurements (2019/2020)
	Littoral preference (+)	Mean preference score for different littoral habitat types (Schirpke et al. 2021c) weighted by the length of each habitat type	D, S	index	Orthophotos [1], (Schirpke et al. 2021c)
	Land cover preference (+)	Mean preference score for different land cover types near the lake (<50 m) (Schirpke et al. 2021c) weighted by the length of each habitat type	D, S	index	Orthophotos [1], (Schirpke et al. 2021c)
	Landscape beauty (+)	Landscape beauty index of randomly distributed viewpoints in 500 m buffer around the lake (Schirpke et al. 2021e)	M, S	index	DEM [1], CLC [4]

ES	Indicator	Description	Method	Unit	Data Sources
Representation	Videos (+)	Number of videos resulting from google search based on lake names	D	n	Google Videos [5]
	Google Trends (+)	Search interest (relative search volume worldwide) of lake names derived from Google Trends	D	n	Google Trends [6]
	Instagram (+)	Number of posts using the lake names at Instagram	D	n	Instagram [7]
Research	Access time (+)	Walking time of the ascent to the lake from the nearest access point (parking, cable car, etc.), with higher access time limiting the number of people that can reach the lake	D	min	Hiking websites [8]
	Access difficulty (+)	Difficulty of the main hiking trail for reaching the lake, reducing the number of visitors and related impacts (Senetra et al. 2020)	D	index	Hiking websites [8]
	Livestock farming (−)	Percentage coverage of grassland in the lake watershed for grazing as proxy for potential presence of livestock farming, potentially altering water quality through increased nutrient inputs (Bottarin et al. 2011; Van Colen et al. 2018)	D	%	CLC [4]
Education	Littoral substrate complexity (+)	Mean index of major substrate classes ranked by size, with higher complexity supporting the potential presence of observable species (Mocior & Kruse 2016)	D	index	Orthophotos [1]
	Access time (−)	Walking time of the ascent to the lake from the nearest access point (parking, cable car, etc.), with lower access time supporting visits by school classes or people not used to long hikes	D	min	Hiking websites [8]
	Beneficiaries (+)	Number of residents and tourists who can reach the nearest access point to the lake (parking, cable car, etc.) within 30 min driving by car, representing the potential level of interest in environmental education	D	n	OSM [3], residents and overnights [9]
Existence	Protected area (+)	IUCN category indicating the level of protection, recognizing the conservation value of ecosystems (Asaad et al. 2017)	D	category	CDDA [10]
	Lake abundance (−)	Number of lakes with an area greater than 0.1 ha and up to a distance of 5 km, measuring uniqueness and rareness as important criteria for conservation (Asaad et al. 2017)	D	n	OSM [3]
	Agricultural intensity (−)	Percentage coverage of grassland in the lake watershed for grazing as proxy for potential presence of livestock farming indicating the level of anthropogenic influence and potentially altering ecosystem integrity (Roche & Campagne 2017)	D	%	CLC [4]

[1] Orthophotos and DEM (digital elevation model) provided by Autonomous Province of South Tyrol (2011), Land Salzburg (2018), Land Steiermark (2018).
[2] Precipitation and temperatures measured at climate stations: Autonomous Province of South Tyrol (1999–2018), Niedere Tauern (1989–2009) (Nemec et al. 2013).
[3] OSM: OpenStreetMap (https://www.openstreetmap.org/, accessed on 9 November, 2016).
[4] CLC: Corine Land Cover 2018 (https://land.copernicus.eu/pan-european/corine-land-cover/clc2018, accessed on 2 March 2021).
[5] Google Videos (https://www.google.com/videohp; accessed on 17 August, 2020).
[6] Google Trends (reference period January 2004–August 2020; https://trends.google.com/trends/; accessed on 24 August, 2020).
[7] Instagram (https://www.instagram.com/; accessed on 15 October, 2020).
[8] Hiking websites (https://www.outdooractive.com/, https://www.sentres.com/, https://www.gps-tour.info/, http://www.preintaler.at/, https://www.bergwelten.com/, https://www.lungau.at/, https://www.alpenvereinaktiv.com/, https://www.eggerwirt.at/, https://www.bergfex.at/; accessed on 25 August 2020).
[9] Demographic data and overnights (2019): http://www.statistik.at, http://www.astat.it, accessed on 26 August 2020.
[10] CDDA v18 (2020): Common Database on Designated Areas (https://www.eea.europa.eu/data-and-maps/data/nationally-designated-areas-national-cdda-15, accessed on 3 September 2020).

3.2.2 Current and future ES provision

A total mean ES index for each study lake was derived by rescaling all individual indicator values to values between 0 and 1 (min–max normalization) and then calculating the mean value across all indicators associated with each ES (Figure). Mean ES indices varied across the 15 study lakes (Table). The two larger and lower elevated lakes in South Tyrol (Group 1) had generally higher ES indices (especially for water, recreation, and representation) than the smaller and higher elevated lakes (Groups 2-4). For the ES habitat, aesthetic, and existence, there were no significant differences between groups, i.e., ES were more independent from the socio-ecological context (Table). In contrast, the ES for water, recreation, representation, research, and education differed significantly across the four groups, indicating a stronger dependence on the socio-ecological context.

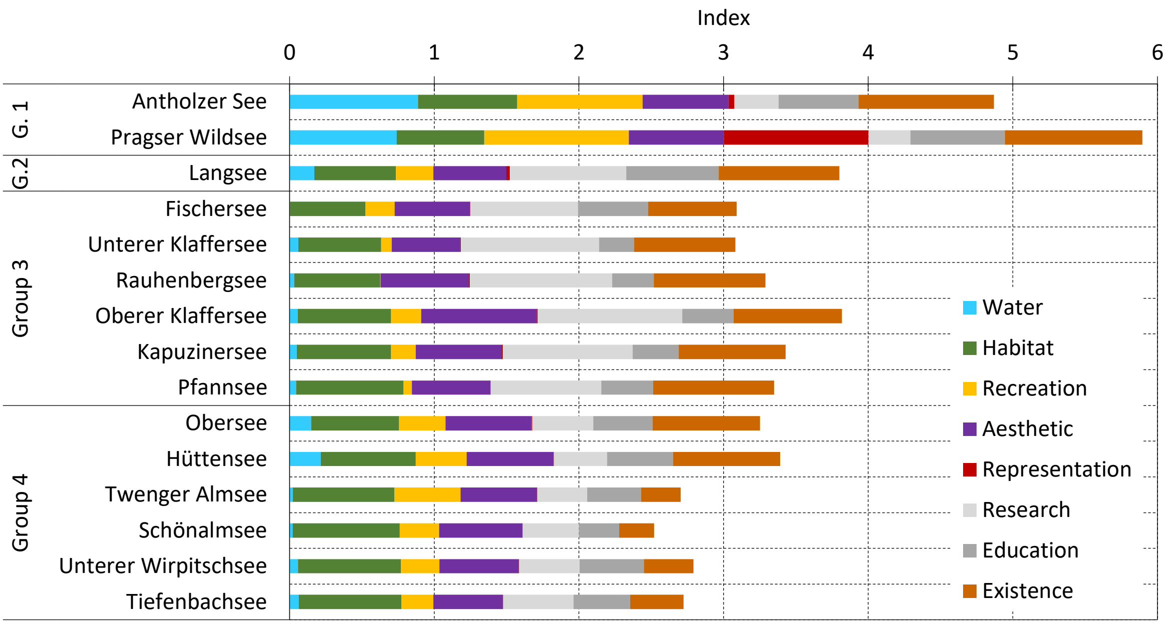

Figure 22: ES of the 15 study lakes.

Table 6: Mean ES indices and results of one-way ANOVA to indicate statistically significant differences of ES among the four groups. From (Schirpke et al. 2021a).

ES	Group 1		Group 2		Group 3		Group 4		ANOVA				
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	SS	df	MS	F	Sig.
Water	0.814	0.105	0.171	-	0.041	0.021	0.088	0.078	0.970	3	0.323	82.174	<0.000
Habitat	0.645	0.056	0.563	-	0.622	0.076	0.688	0.047	0.021	3	0.007	1.753	0.214
Recreation	0.933	0.094	0.260	-	0.118	0.087	0.315	0.083	1.000	3	0.333	45.335	<0.000
Aesthetic	0.625	0.045	0.504	-	0.591	0.114	0.556	0.046	0.014	3	0.005	0.657	0.595
Representation	0.521	0.677	0.025	-	0.004	0.002	0.001	0.001	0.463	3	0.154	3.701	0.046
Research	0.298	0.011	0.806	-	0.891	0.112	0.405	0.050	0.960	3	0.320	46.691	<0.000
Education	0.603	0.071	0.640	-	0.341	0.083	0.392	0.064	0.157	3	0.052	9.685	0.002
Existence	0.943	0.011	0.833	-	0.735	0.074	0.452	0.229	0.483	3	0.161	6.103	0.011

Future projections indicate partly different developments for the different socio-ecological groups (Figure). All lakes will be affected by a decline in ES for habitat and aesthetic, but easily accessible lakes (Groups 1 and 4) will be significantly more affected than remote lakes without farming activities or protected lakes (Group 3). Water availability is likely to decline for most lakes, but the construction of a dam can slightly increase the storage capacity of some lakes. Recreation will increase due to a higher number of warm days at easily accessible lakes (Groups 1 and 4). In contrast, reduced accessibility will lead to an increase in ES for research (Groups 2 and 3), but a slight decrease in ES for education.

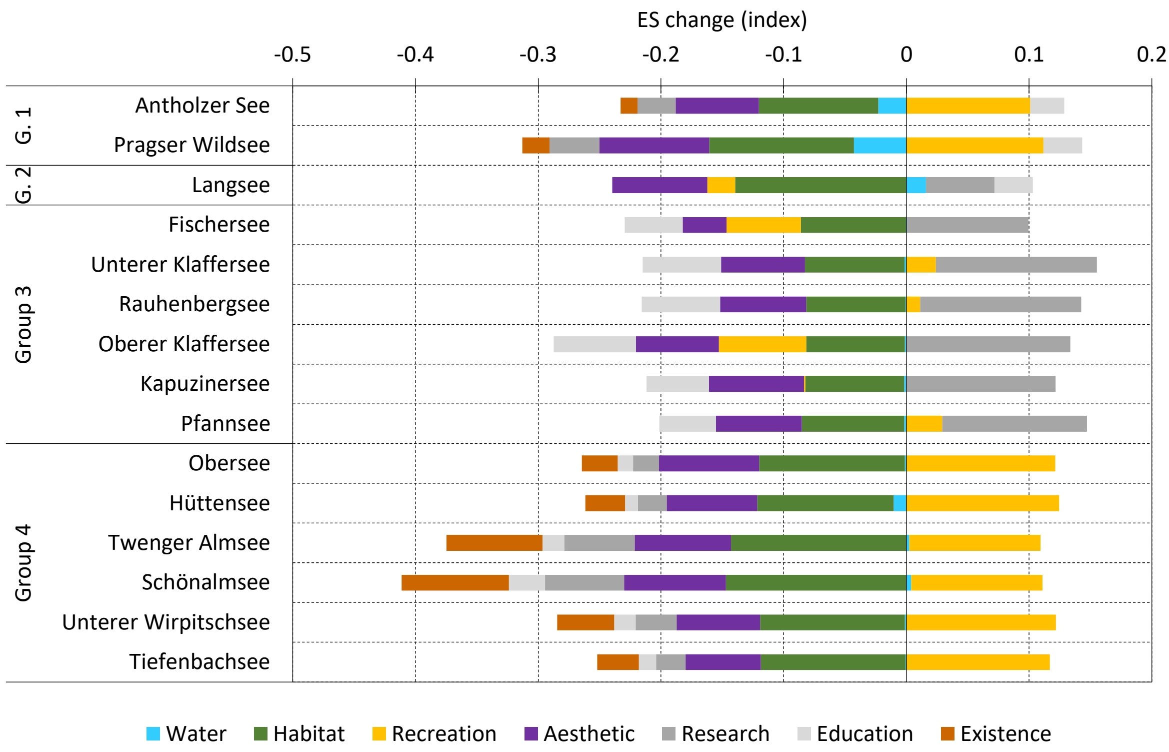

Figure 23: Estimated changes of selected ES of the study lakes under future scenarios (2081-2100). Representation was excluded from the potential impacts analysis, as future scenarios were not applicable to the indicators.

3.3 Evaluation of ES provision and policy advices

3.3.1 Evaluation of ES

In South Tyrol, 43 stakeholder representatives responded to the weighting questionnaire, of which 39 (see Table 7 for further details on respondents in both study regions) were satisfying the consistency thresholds and used in the MCDA. The highest weighting was attributed to ES for habitat, followed by aesthetics, water, recreation and entertainment (Table 8). While the priorities of each stakeholder group were broadly consistent with the ES ranking derived from the sectoral aggregated weightings, there was some dispersion, particularly for water and recreation, which was reflected in the standard deviation of the individual weightings. The sensitivity analysis (i.e., stability intervals of the MCDA results by perturbing the ES weights) showed that the ranking of the individual mountain lakes was stable with respect to the ES for habitat, recreation and representation. Surface water and aesthetics were more sensitive and resulted in a reversal of the ranking (i.e., changes in the order of the lakes according to their ES provision/performance) for the weight interval between 49.53 and 1 and 73.46 and 1, respectively.

In the Niedere Tauern we received 22 stakeholder responses, of which 16 could be used for the MCDA. Habitat was weighted highest, followed by existence, aesthetics, research/education (here considered as a single ES) and recreation (Table 7). As in South Tyrol, the ranking of the ES resulting from the aggregated weights was found to be largely consistent with the weightings attributed by individual stakeholders, although dispersion was evident specifically for aesthetic and research/education. The sensitivity analysis showed that the MCDA results were sensitive to the ES weights used as importance coefficients, which were found to result in rank reversals of the evaluated lakes, partly already for minor deviations around the assigned values. Overall, this is consistent with the observation that the values of the ES indicators of the assessed mountain lakes in the Niedere Tauern are more similar compared to the stronger gradient in South Tyrol, which makes the overall assessment more sensitive to changes in the importance coefficients.

Table 7: Number of consistent weightings by stakeholders from different sectors in the study regions South Tyrol and Niedere Tauern used in the MCDA.

	Number of consistent weightings	
Sector	South Tyrol	Niedere Tauern
Environmental/water management and conservation	8	3
Local authorities	4	2
Economy and tourism	8	4
Research and education	7	3
Non-governmental organizations	12	3
Private owner	-	1
TOTAL	39	16

Table 8: Weighting (aggregated) by stakeholders attributed to the ES selected in each study region (South Tyrol, n = 39; Niedere Tauern, n = 16) and used as importance coefficients in the MCDA to evaluate the ES provision of the mountain lakes. Stability intervals show the range of weights that result in a stable ranking of the ES provision performance of the lakes in the MCDA.

Region	ES	Weighting (aggregated)	Standard deviation	Stability interval
South Tyrol	Water	0.13	0.13	0.00-0.44
	Habitat	0.45	0.12	0.00-1.00
	Recreation	0.10	0.07	0.00-1.00
	Aesthetic	0.26	0.10	0.00-0.89
	Representation	0.06	0.05	0.00-1.00
Niedere Tauern	Research/Education	0.13	0.12	0.09-0.15
	Habitat	0.46	0.14	0.45-0.48
	Recreation	0.06	0.04	0.05-0.08
	Aesthetic	0.15	0.11	0.10-0.17
	Existence	0.20	0.10	0.19-0.21

The evaluation of the current ES provision of the mountain lakes in South Tyrol revealed differences, i.e. PRA providing the highest amount of ES, followed by ANT, LAG, and FIS. A disaggregated view on the ES profiles based on the relative contribution of an ES to overall performance of a lake (i.e., positive or negative outranking flow of a respective ES) is presented in Figure 24a, which shows the ranking of lakes according to the relative weaknesses and strengths in ES provision. The comparison of the current and future ES provision performance based on the estimated changes of selected ES under future scenarios (until 2081-2100) reveals subtle differences, both positive and negative, in the overall performance in ES provision, but no changes in the ranking of lakes (Table 8). Regarding the relative contribution of individual ES, a change was observed for FIS, for which water went from the second most to the strongest weakness under the future scenarios (Figure 24b).

In the Niedere Tauern, the current ES provision of mountain lakes also varied, with PFA, OKL, and KAP ranking the highest and UKL, SCH, and TWA ranking the lowest, with the other lakes positioning in between. An overview of relative weaknesses and strengths of the lakes in terms of ES provision is shown in Figure 25a. The comparison of current and future conditions showed variability in ES provision in terms of positive and negative changes in the overall performance of lakes, resulting in changes in the overall ranking, especially for lakes that are in the middle ranks (Figure 25b, Table 9).

Considering the four lake groups more broadly and in relation to the respective study region that forms the context for the relative comparison of the ES provision of mountain lakes, the results (Table 9) indicate different trends: Negative changes in the performance of the lakes to provide ES for Group 1 (South Tyrol only), negative changes for Group 2 (South Tyrol only), positive changes for Group 3 (consistently in South Tyrol and Niedere Tauern), and negative changes for Group 4 (Niedere Tauern only).

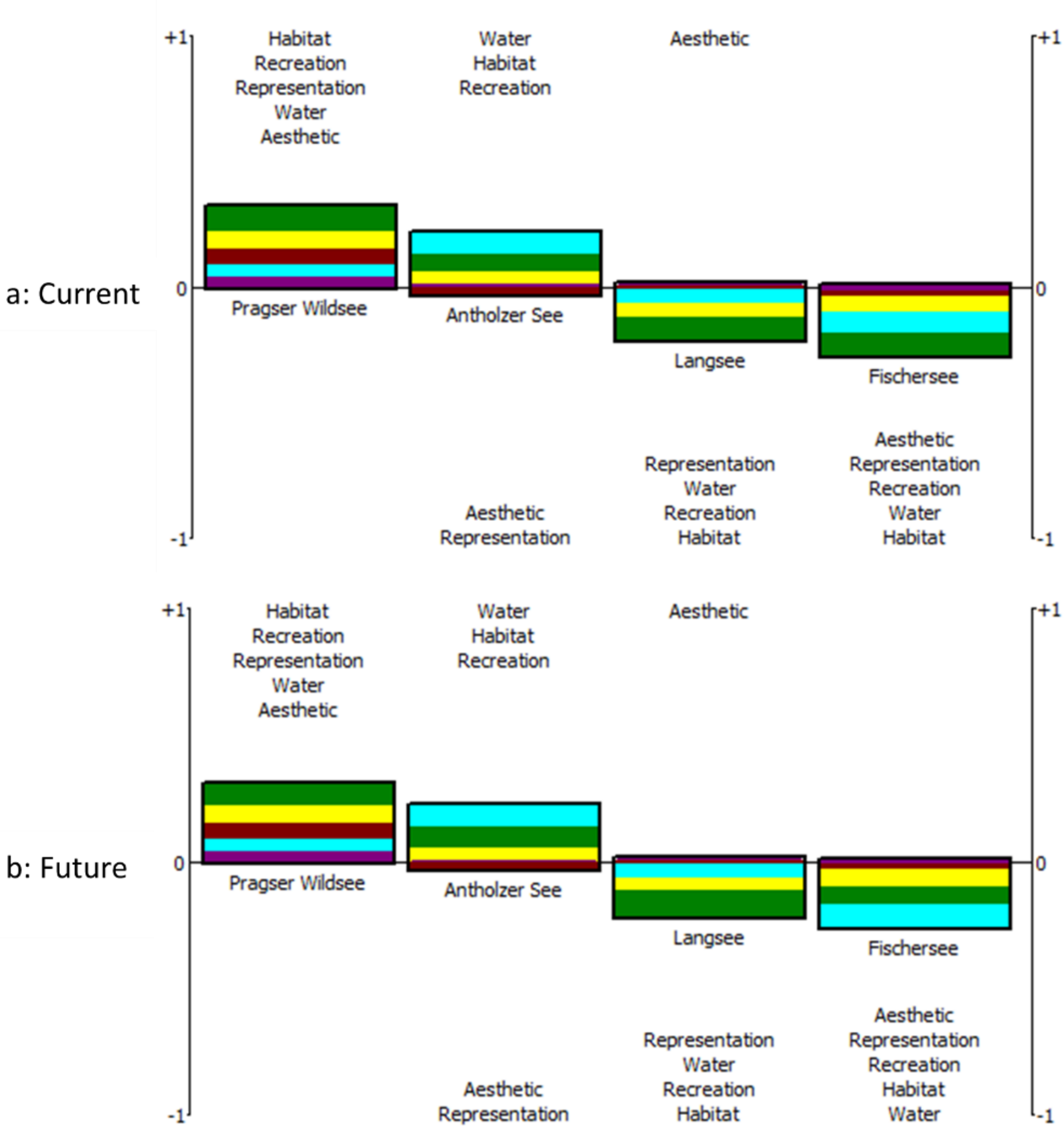

Figure 24: ES profiles (disaggregated outranking flows, phi-value: scaled from -1 to 1) of the mountain lakes in the study region South Tyrol (Italy). The profiles of the mountain lakes for the current ES provision are shown in the upper graph (a) and the future ES provision in the lower graph (b). Positive phi-values depict a positive contribution (i.e., strength) of the respective ES to the overall performance of an individual lake, while negative values depict the opposite (i.e., weakness). The net value for each lake then gives the complete ranking of all mountain lakes (highest net phi-values position in the first rank). The colors of the bars are congruent with the ES, which are shown either above or below the respective stacked bar chart and reflect the order of the phi values. Note that for representation no changes were imposed for the future conditions due to a lack of data.

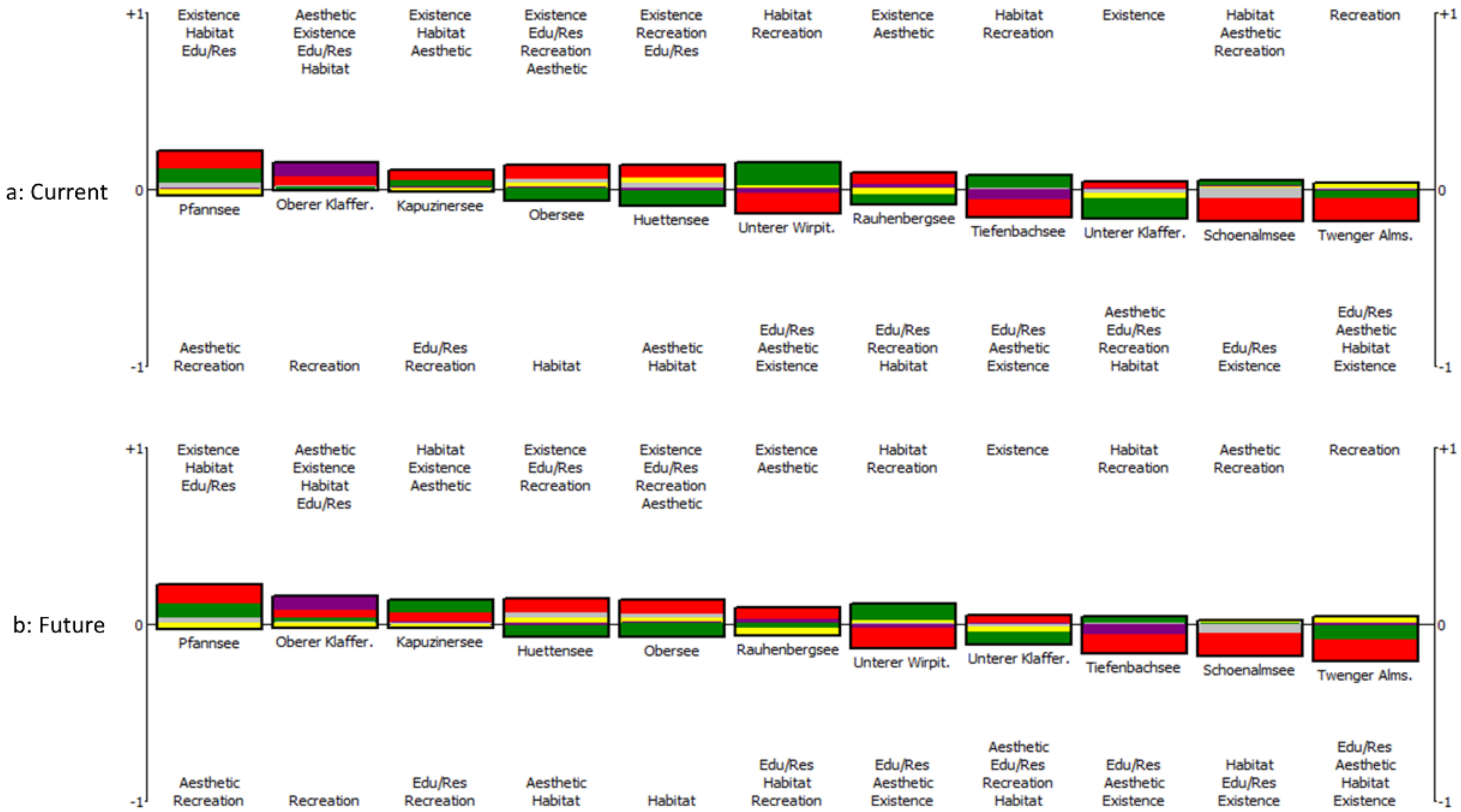

Figure 25: ES profiles (disaggregated outranking flows, phi-value: scaled from -1 to 1) of the mountain lakes in the study region Niedere Tauern (Austria). The profiles of the mountain lakes for the current ES provision are shown in the upper graph (a) and the future ES provision in the lower graph (b). Positive phi-values depict a positive contribution (i.e., strength) of the respective ES to the overall performance of an individual lake, while negative values depict the opposite (i.e., weakness). The net value for each lake then gives the complete ranking of all mountain lakes (highest net phi-values position in the first rank). The colors of the bars are congruent with the ES, which are shown either above or below the respective stacked bar chart and reflect the order of the phi values.

Table 9: Comparison of ES provision for mountain lakes in the two study regions South Tyrol and Niedere Tauern under current conditions and future scenarios of climate change (2081-2100). Phi-values represent the net outranking flows (multicriteria, PROMETHEE II, scaled from -1 to 1) and provide a complete ranking of the performance of mountain lakes in each study region, reflecting the respective ES selection and integrating indicator values and ES weights.

			Current		Future		Difference	
Region	Lake	Group	Phi	Rank	Phi	Rank	Phi	Rank
South Tyrol	ANT	1	0.18	2	0.18	2	0.00	0
	FIS	3	-0.28	4	-0.26	4	0.01	0
	LAG	2	-0.21	3	-0.22	3	-0.01	0
	PRA	1	0.31	1	0.30	1	-0.01	0
Niedere Tauern	HUS	4	0.04	5	0.06	4	0.02	1
	KAP	3	0.09	3	0.11	3	0.03	0
	OKL	3	0.13	2	0.13	2	0.00	0
	OBE	4	0.07	4	0.06	5	-0.01	-1
	PFA	3	0.18	1	0.19	1	0.01	0
	RAU	3	0.00	7	0.03	6	0.03	1
	SCH	4	-0.14	10	-0.17	10	-0.03	0
	TIE	4	-0.09	8	-0.13	9	-0.04	-1
	TWA	4	-0.15	11	-0.18	11	-0.03	0
	UKL	3	-0.13	9	-0.07	8	0.05	1
	WIR	4	0.01	6	-0.03	7	-0.04	-1

3.3.2 Policy recommendations

On the aggregate level, there was almost unanimous consensus that climate change *per se* does not require immediate regulatory intervention in the near future. Generally, the institutional framework currently in place seems apt to respond to potential regulatory concerns that might arise in the near future (i.e. the next 20 to 30 years) from climate change alone. However, if climate change coincides with increases in the use of mountain lakes for recreational, agricultural, or other human activities, additional instruments for resource management will be necessary. This holds in particular on the regional or even local level, where such issues might arise due to local specificities (like easy access due to pre-existing infrastructure).

Note that such regional issues should obviously also be addressed in national regulation, for example via a closer integration of the conservation management for protected areas into the water management plans that follow the EU framework directive on water use. Similarly, the integration of water management and risk-management tools is likely to become more important, in particular if not only drought and extreme heat events are of concern, but also flood risks for potential downstream water bodies. Such an integration of risk management tools is clearly beneficial when it comes to reducing potential conflicts of interests over water resources in general, and mountain lakes in particular.

In this context, many stakeholders were concerned that mountain lakes might come under increased pressure to also directly or indirectly function as water reservoirs. While such abstraction is clearly regulated for all types of water bodies in most alpine regions, climate change might lead to increased (political) pressure to expand the rights for abstraction in the future. Thus, regulations on water management should be upheld and their continuing enforcement should be ensured at all levels of government.

Note also that specific conservation management rules only apply to mountain lakes in protected areas, such that increases in nitrogen (or any other) immissions due to more extensive agriculture in adjacent areas are, at first, not easily discovered. A better integration of managing such risks with land use regulations would again be preferable to reduce the stress on mountain lakes. In this context, a large majority of experts were also calling for the intensification of research to better understand the interactions between the human system and mountain lakes. Specifically for unprotected lakes, they identified a lack of available data that could be used to support resource management decisions.

Yet, generally, neither regulators, nor other stakeholders identified large conflicts of interest between user groups that would be imminent for the entire set of mountain lakes in alpine regions. Thus, beyond the above-mentioned integration of national policies, there does not seem to be an urgent need for more restrictive national regulation. This might, however, not hold when it comes to regionalized overuse of mountain lakes. For example, an increase in average temperatures in the summer months might lead to additional stress on those lakes that are easily accessible for touristic or recreational uses. For these lakes, experts and stakeholders unanimously identified a need for active visitor management, as visitors are not only likely to increase in peak times in the summer, but also touristic use of such mountain lakes will expand further into the autumn, which was previously considered to be off-season for tourism. Clearly, such rules for visitor management would have to be taken at the regional and community level. Similarly, potential issues of illegal over-abstraction of water resources or the illegal introduction of a fish population for recreational fishing might become more frequent in the future and are best identified---and ultimately prevented---at the local level, as stakeholders indicated.

Thus, in summary, it can be stated that the effect of climate change on mountain lakes alone is slow enough that the necessity for drastic regulatory response is unlikely. Consequently, current institutions are likely to be able to respond in time to any severe issues that arise. Yet, the interaction of climate change with increased human use of mountain lakes as a resource, be it recreational or otherwise, might necessitate regulatory intervention even in the nearer future. While these negative effects are likely to be localized, and are hence to be addressed on a local level, a stronger integration of risk management approaches into water management plans is strongly advised, which also includes an increased effort in data collection and regional modeling by the scientific community.

4 Conclusions and Outlook

In alpine lakes, good water quality is due to low primary production which is essential for the existence of autochthonous communities, as well as the provision of cultural, regulating and provisioning ecosystem services from which we humans benefit. The goal of the CLAIMES project is to identify negative impacts on lakes and their ecosystem services at an early stage and to ensure intact ecosystems and sustainable provision of ecosystem services with transdisciplinary management plans. In order to identify problems at an early stage, the collection of raw data relevant to trophic conditions should be done on a regular basis, especially since smaller alpine lakes are often not included in the regulations for monitoring as are larger water bodies.

The effect of climate-induced warming can be summarized as follows: Despite extension of the growing season (by a maximum of 100 days), ice cover will remain for most alpine lakes in the near future and also in the distant future. Thus, an important stabilizing factor will remain.

However, due to the extended growth period, an increased primary production and a shift of the trophic state from oligotrophic to mesotrophic is likely. This, at first glance moderate shift of the trophic level would, however, already trigger a considerable reduction of the water transparency, so that a situation like currently observed in the larger lowland lakes of the Alps can be assumed. Increased primary production would have negative consequences for the oxygen content in the water column and thus for the overwintering of vertebrates (amphibians, fish) during the formation of the ice cover.

For lakes that are already considered warmer than average (Thompson et al. 2005), maximum temperatures are expected to exacerbate this trend in the future. This means that the already strikingly high variation in water temperature between lakes located at the same altitude will continue to increase and the response of lakes to climate warming will diversify even further.

Since the estimation of eutrophication due to climate warming, which was made, is to be regarded as rather conservative if the nutrient situation remains unchanged, it is essential to use measures for minimizing nutrient input and water protection in a controlling manner already now. For this reason, risks as well as potential measures for water protection were discussed during two workshops for the Niedere Tauern region (28.4.2022) and South Tyrol (5.5.2022). The minutes of these workshops are included in the Supplement (p.79-86).

In the stakeholder discussions, participants in South Tyrol and Austria were asked about their assessment of the risks arising from the interaction of human activity and climate change for mountain lakes. Risks for water protection, especially due to tourism and agricultural use, were identified. Here, particular attention should be paid to increased pressures on sensitive habitats due to higher nutrient inputs and high visitor numbers. Potentially higher water withdrawals could also become problematic in the future, which should be considered in the context of appropriate regulation.

A number of measures to reduce the identified risks were also discussed by workshop participants. Due to the regional specificity of potential human-mountain lake interactions, proposed measures are meaningful particularly at the community level. In particular, visitor management measures should be considered and implemented if the burden of tourism becomes too great in terms of excessive stress on the ecosystem, which is already under pressure from climate change. Both tourism and agricultural use could extend well into late fall due to climate change resulting in additional stress on the ecosystem. As a conclusion, both regulators and stakeholders do not initially expect any directly immanent catastrophic events. However, a gradual deterioration of the ecological condition of mountain lakes should be prevented in time.

Between the two study regions, Niedere Tauern and South Tyrol the ranking of ES was largely overlapping, i.e. for both study regions the ES for habitat, recreation and aesthetic were selected. Additionally, stakeholders in South Tyrol selected water and representation, while stakeholders in Niedere Tauern indicated ES for research, education, and existence. A potential conflict is emerging in the future due to the top-ranked ES habitat (protection) vs. recreation and the current expectation that overexploitation resulting from recreation may become more frequent. Since the provision of ES relies on valuable and integer ecosystems the concept of evaluation of ES may become increasingly important for evaluation of stressors in the future. It has been argued previously that, even if changes in phytoplankton community composition are hardly visible to the public, they can have profound consequences as ecological endpoints affecting ES appreciated by beneficiaries (i.e. Rhodes et al. 2016). For example, nutrient loads exceeding critical levels have been linked to changes in planktonic diatom species composition, benthic macroinvertebrate abundance and composition, decrease in water clarity, and decreased probability and abundance of terrestrial consumers. In this study, a few alpine lakes with higher proportion (> 30%) of phototrophic phytoplankton exhibit a significantly reduced water clarity probably because of undergoing a process of eutrophication. While the reasons for this eutrophication process are not straightforward, recreational activities including fishing might be causal.

In this study, for the first time, the comparison of lake types (i.e. "highly accessible" vs. "remote") regarding their ES provision can provide a basis for management in the future. Notably the influence of aesthetics becomes relatively more important for the overall performance in MCDA the more remote the lakes are. From a management point of view, accessibility to alpine lakes has been and can be regulated in the future as it has been discussed during the second round of stakeholder workshops, i.e. including infrastructure development (e.g., adapted infrastructure (trails, resting places) for "intelligent" visitor guidance or hampering accessibility (i.e., no longer maintenance of hiking trails close to water bodies, relocation or complete deletion of trails in maps). On the other hand, it is not (anymore) so easy to reroute, because deleting hiking trails from maps is not enough, as people have GPS on their cell phones, and new orientation routes are constantly being set up. Thus, awareness raising (i.e., information boards at lakes that are already well visited with large parking lots, but not at remote lakes; rangers, social media, tourism associations) may become a more sustainable measure in the future to guide accessibility. In general, soft measures, such as information or visitor management are to be preferred over bans or price mechanisms. Nevertheless, current regulations in place must be maintained and enforced if access has been increased to such an extent that ecosystem integrity is endangered.

5 Outputs

Peer-reviewed publications

Enigl, K., Kurmayer, R. (in prep) Evolution of surface temperatures of high-altitude lakes in the European Alpine region under climate change. EarthArXiv. Preprint. https://doi.org/10.31223/X5NM28

Pritsch, H., Schirpke, U., Kurmayer, R. (submitted after revision) Plankton community composition in mountain lakes and consequences for ecosystem services. Ecological Indicators

Schirpke, U., Ebner, M., Fontana, V., Enigl, K., Ohndorf, M., Pritsch, H., Kurmayer, R. (to be submitted) Climate response of alpine lakes and impacts on ecosystem services. Landscape Online

Fontana, V., Ebner, M., Schirpke, U., Ohndorf, M., Pritsch, H., Tappeiner, U., Kurmayer, R. (2023) An integrative approach to evaluate ecosystem services of mountain lakes using multi-criteria decision analysis. Ecological Economics 204, 107678. https://doi.org/10.1016/j.ecolecon.2022.107678 .

Ebner, M., Schirpke, U., Tappeiner U. (2022) Combining multiple socio-cultural approaches – Deeper insights into cultural ecosystem services of mountain lakes? Landscape and Urban Planning 228, 104549. https://doi.org/10.1016/j.landurbplan.2022.104549

Schirpke, U., Ebner, M. (2022) Exposure to global change pressures and potential impacts on ecosystem services of mountain lakes in the European Alps. Journal of Environmental Management 318, 115606, https://doi.org/10.1016/j.jenvman.2022.115606 .

Ebner, M., Schirpke, U., Tappeiner, U. (2022) How do anthropogenic pressures affect the provision of ecosystem services of small mountain lakes? Anthropocene 38, 100336. https://doi.org/10.1016/j.ancene.2022.100336

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Schirpke U., Ebner M., Pritsch H., Fontana V., Kurmayer R. (2021a) Quantifying Ecosystem Services of High Mountain Lakes across Different Socio-Ecological Contexts. Sustainability 13(11):6051. https://doi.org/10.3390/su13116051

Schirpke U., Scolozzi R., Tappeiner U. (2021d) "A Gem among the Rocks"—Identifying and Measuring Visual Preferences for Mountain Lakes. Water 13(9), 1151. https://www.mdpi.com/2073-4441/13/9/1151

Using data from previous project:

Ma T., Jiang Y., Elbehery A.H., Blank S., Kurmayer R., Deng, L. (2019) Resilience of planktonic bacterial community structure in response to short-term weather deterioration during the growing season in an alpine lake. Hydrobiologia, 1-14, https://link.springer.com/article/10.1007/s10750-019-04118-8

Jiang Y., Huang H., Ma T., Ru J., Blank S., Kurmayer R., Deng, L. (2019) Temperature Response of Planktonic Microbiota in Remote Alpine Lakes. Frontiers in Microbiology 10: 1714. https://www.frontiersin.org/articles/10.3389/fmicb.2019.01714/full

Academic theses

PhD theses

Ebner M. (2022) Assessing ecosystem services of mountain lakes: An integrative approach to link socio-cultural perspectives, multi-metric indicators, and global change pressures, PhD Thesis, Universität Innsbruck (defended)

Enigl K. (ongoing) Impact of climate change on ecosytems, PhD Thesis, University of Vienna and ZAMG (now: GeoSphere Austria)

Pritsch H. (ongoing) Alpine Limnology and its relevance for Ecosystem Services under Climate Change, PhD Thesis, Universität Innsbruck

MSc theses

Kiessling A. (2021) Mountain lakes in the Alps: Identifying the perception of cultural services and benefits. M.Sc. Thesis, Universität Innsbruck

Pilgram J. (???) Environmental pressures on ecosystem services of mountain lakes, M.Sc. Thesis, SLU - Swedish University of Agricultural Science

Büchen S. (2020) Temperature anomalies of alpine lakes in the Lower Tauern Region, M.Sc. Thesis, Universität für Bodenkultur Wien – BOKU

BSc thesis

Dominik von Spinn (2021) Sequenzanalyse aus Umwelt DNA als Informationsquelle für den Naturschutz in alpinen Seen, B.Sc. Thesis, Universität Innsbruck, Forschungsinstitut für Limnologie, Mondsee

Science Transfer publications

Pritsch H., Enigl K., Ebner M, Kurmayer R. (2022) Studie zum Einfluss des Klimawandels auf Alpine Seen und deren Ökosystemleistungen -2. Bericht, Probenahme im September – Oktober 2020, Österreichs Fischerei 75: 61-67

Kurmayer R. (2021) Einfluss des Klimawandels auf alpine Seen, Salzburgs Fischerei 3: 35-40

Wanzenböck S., Kurmayer R. (2021) „Klimastress in den alpinen Seen“, „Handlungsempfehlungen für künftiges Management in den Alpenseen“, Klimaszenarien und ihre möglichen Auswirkungen“ Beitrag über das Projekt CLAIMES im Forschungsnewsletter 8/2021 des Forschungsinstituts für Limnologie, Mondsee, der Universität Innsbruck, https://www.uibk.ac.at/limno/files/pdf/fl8-19.04.21-ansicht-150-einzeln.pdf

„Wie sich der Klimawandel auf unsere Alpenseen auswirkt“ (2020) https://www.youtube.com/watch?v=TKEDnhqCgHc auf der Webseite der Universität Innsbruck (https://www.uibk.ac.at/de/newsroom/2021/limnologie-wie-wirkt-sich-der-klimawandel-auf-alpenseen-aus/)

Videobeitrag „Am Antholzer See – Was forschen Limnologen“ zu sehen auf der Webseite der Langen Nacht der Forschung digital zwischen 9.10. und 30.12.2020 https://www.youtube.com/watch?v=TKEDnhqCgHc

Radioserie „Vom Leben der Natur“ auf Ö1 ein Beitrag von Rainer Kurmayer mit dem Thema Algen in den Alpenseen. Die Serie läuft an den folgenden Tagen mit weiterführenden Algenthemen 2.8.-6.8.2021, https://oe1.orf.at/vomlebendernatur

Kurmayer R. (2022) Präsentation des Projekts CLAIMES bei der Langen Nacht der Forschung in Mondsee am 15.05.2022, Station „Welchen Einfluss hat der Klimawandel auf Gebirgsseen?“

Kurmayer, R., Pritsch, H., Schirpke, U., Fontana, V., Ebner, M., Enigl, K., Matulla, C., Ohndorf, M. (2022) Limnologische Studie zum Einfluss des Klimawandels auf Alpine Seen und deren Ökosystemleistungen. Final report for stakeholders, 37pp.

Stakeholder workshops

Workshop “Bergseen im Wandel – Südtirol” – am 05.05.2022, virtuell

Workshop “Bergseen im Wandel – Niedere Tauern” am 28.04.2022, virtuell

Stakeholder-Workshop (Niedere Tauern) am 04.08.2020, Radstadt

Stakeholder Workshop (Südtirol) am

Internships (FFG Talente Praktika für SchülerInnen

Elisabeth Brzon (Gymnasium Bad Ischl), 2022

Minou Yazdani (BORG Strasswalchen), 2022

Xaver Kopf (BORG Strasswalchen), 2021, (Prämierung Bester Praktikumsbericht "Algenentwicklung in Gebirgsseen unter dem Einfluss des Klimawandels")

Sebastian Prenneis (HLUW Yspertal), 2021

Julia Götsch (HBLA Ursprung), 2020

Marylin Danner (HBLA Ursprung), 2020

Margherita Capacci (EURAC), 2020

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Kurmayer, R., Pritsch, H. (2022) Phytoplankton community composition and response to climate warming in alpine lakes. SIL Austria 2022, Illmitz, 30.09.2022.

Pritsch, H., Enigl, K., Kurmayer, R. (2022) Warming of surface temperature in alpine lakes and consequence for productivity. 36th Congress of the International Society of Limnology (SIL 2022), Berlin, 10.08.2022.

Ebner, M., Schirpke, U., Pritsch, H., Fontana, V., Tappeiner, U., Kurmayer, R. (2021) An ecosystem service perspective on mountain lakes across socio-ecological contexts. 50th Annual Meeting of the Ecological Society of Germany, Austria and Switzerland (GfÖ), 30 August - 1 September 2021

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Pritsch, H., Enigl, K., Kurmayer, R (2022) Warming of surface water temperature in alpine lakes and consequence for productivity. 7th Nationalparks Austria Forschungssymposium, 7.-9. September, Vienna, Austria

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Social Media postings

Facebook https://www.facebook.com/Mondseelimnology/

22.09.2021 Tauchclub Delfin Sub-Brunico unterstützt das Projekt CLAIMES bei Freilandarbeit

20.01.2021 Posting zum Video des Projekts CLAIMES bei der digitalen Langen Nacht der Forschung 2020

17.11.2020 Posting zur Teilnahme an der Umfrage „Wie erlebt der Mensch die Natur?" im Projekt CLAIMES

07.10.2020 Kurzvideo des Projekts CLAIMES bei der digitalen Langen Nacht der Forschung

03.02.2020 Pressemeldung über das Projekt CLAIMES in der Kleinen Zeitung „Schladminger Tauern: Auf Tauchgang in heimischen Bergseen"

08.01.2020 Seminarankündigung H. Pritsch Climate response of alpine lakes: resistance variability and management consequences - Projekt CLAIMES am Forschungsinstitut für Limnologie, Mondsee

25.04.2019 PhD Stelle Eurac Research ausgeschrieben

11.04.2019 PhD Stelle Eurac Research ausgeschrieben

03.05.2019 – PhD Stelle am Forschungsinstitut für Limnologie, Mondsee, ausgeschrieben

15.04.2019 – PhD Stelle am Forschungsinstitut für Limnologie, Mondsee, ausgeschrieben

29.03.2019 Posting zur Verfügbarkeit von Sommerpraktika im Projekt CLAIMES

Project Websites

https://www.uibk.ac.at/projects/claimes/index.html.de

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https://www.researchgate.net/project/CLAIMES-CLimate-response-of-AlpIne-lakes-resistance-variability-and-Management-consequences-for-Ecosystem-Services

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7 Supplement

Identification of stakeholders

For both project regions, a list of approx. 60 persons for South Tyrol and a list of approx. 40 persons for the Niedere Tauern, from the fields of federal administration (nature conservation, water protection, environmental management), tourism, owners, research and NGOs, was compiled by reviewing media and spatial planning/management documents, informal interviews with key persons and applying the snowball method.

In the course of the first half of the project, one focus group meeting for both regions (South Tyrol and Niedere Tauern), (10-12 participants, each) was subsequently organized with the aim of actively involving all relevant stakeholders/interest groups in the discussion of relevant ES. In the course of the two focus group meetings, current problems or conflicts of use were also addressed from the stakeholders' point of view, as well as their visions of future sustainable development were elicited. Finally, the same people defined the list of relevant ES for both project regions. In addition, the 40 to 60 stakeholders in both regions were sent a weighting questionnaire, which, in addition to the importance of the individual ES, also contained open questions on the perception and importance of the services, as well as general information about the project. This information is an essential part of the further environmental-economic evaluation in the project.

Supplementary Tables

Suppl. Table 1: Anonymized list of participants of the focus group meeting in Bozen (South Tyrol)

Institution	Sektor	No of persons
Amt für Landwirtschaft	Governmental	1
Amt für Naturparke - Außenstelle Bruneck (Naturpark Riesenferner- Ahrn.; Antholzer Tal)	Governmental	1
Amt für Naturparke - Texelgruppe	Governmental	1
Gemeinde Tirol	Governmental	1
Gemeinde Rasen-Antholz	Governmental	1
Gemeinde Prags	Governmental	0
Landesagentur für Umwelt und Klimaschutz - Biologisches Labor	Governmental	1
Alpenverein Südtirol	NGO	1
Naturtreff Eisvogel	NGO	1
Fischreiverband/Dachverband Umwelt	NGO	0 (Interview)
EURAC - Alpine Environment	Research/Edu	1
EURAC, Universität Innsbruck	Research/Edu	1
IDM Südtirol - Alto Adige	Tourism/Econ	2

Suppl. Table 2: Anonymized list of participants of the focus group meeting in in Radstadt (Niedere Tauern)

Institution	Sektor	No of persons
Salzburger Gewässerschutz	Governmental	2
Referat Gewässeraufsicht und Gewässerschutz STMK	Governmental	0
ÖAV Schladming	NGO	1
Landesfischerreiverband	NGO	1
Pächter/Besitzer/Hüttenwirt_2	Private/Tourism/Econ	1
Forstgut Rink	Private/Tourism/Econ	0
Universität Innsbruck	Research/Edu	1
Nationalpark Salzburg	Research/Edu	1
Österreichische Bundesforste AG	Tourism/Econ	1
Tourismusverband Mondsee	Tourism/Econ	1
Tourismusverein Schladming	Tourism/Econ	1

Suppl. Table 3: Anonymized list of participants in questionnaire for ES weighting in South Tyrol

Stakeholder	Sektor
Amt für Landwirtschaft - ländliches Bauwesen	Governmental
Gemeinde Mals	Governmental
Gemeinde Meran	Governmental
Gemeinde Prags	Governmental
Gemeinde Rasen Antholz	Governmental
Amt für Gewässerschutz	Governmental

Amt für Jagd und Fischerei	Governmental
Amt für öffentliches Wassergut	Governmental
Landesagentur für Umwelt und Klimaschutz - Biologisches Labor	Governmental
Amt für Natur - Naturpark Fanes-Sennes-Prags	Governmental
Amt für Natur - Außenstelle Bruneck (Naturpark Riesenferner- Ahrn.; Antholzer Tal)	Governmental
Amt für Natur	Governmental
Amt für Natur - Naturpark Texelgruppe	Governmental
Heimatpflegeverband Südtirol1	NGO
Heimatpflegeverband Südtirol2	NGO
Landesfischereiverband Südtirol - Gewässerreferent Bachforellengewässer und Gebirgsseen	NGO
Lia per natura y usanzes	NGO
Naturtreff Eisvogel	NGO
Heimatpflegeverband Südtirol3	NGO
Alpenverein Südtirol	NGO
Dachverband für Natur- und Umweltschutz	NGO
Umweltgruppe Olang	NGO
Umweltschutzgruppe Vinschgau	NGO
Heimatpflegeverband Südtirol4	NGO
Plattform Pro Pustertal	NGO
EURAC	Research/Edu
Naturmuseum	Research/Edu
Naturparkhaus Puez Geisler	Research/Edu
Nationalparkhaus Aquaprad	Research/Edu
EURAC, Uni Innsbruck	Research/Edu
Südtiroler Biologen	Research/Edu
EURAC, Uni Innsbruck	Research/Edu
Bürgergenossenschaft Obervinschgau	Tourism/Econ
Tourismusverein Obervinschgau	Tourism/Econ
Funktionsbereich Tourismus	Tourism/Econ
Bootsverleih Pragser Wildsee	Tourism/Econ
IDM Südtirol - Alto Adige	Tourism/Econ
Südtiroler Bauernbund	Tourism/Econ
Tourismusverein Antholzertal	Tourism/Econ
Tourismusverein Prags	Tourism/Econ
Tourismusverein Olang	Tourism/Econ
Hotel Pragser Wildsee	Tourism/Econ
Tourismusverein Dorf Tirol (Langsee)	Tourism/Econ

Suppl. Table 4: Anonymized list of participants in questionnaire for ES weighting in Niedere Tauern

Stakeholder	Stakeholder_sektor
Gemeinde Lessach	Governmental
Gemeinde Krakau	Governmental
Salzburg Gewässerschutz	Governmental
Salzburg Gewässerschutz2	Governmental
Gemeinde Aich	Governmental
Referat Gewässeraufsicht und Gewässerschutz STMK	Governmental
Almgemeinschaft	NGO
OEAV Schladming	NGO
Landesfischereiverband	NGO
Naturpark Sölktäler GmbH	NGO
Pächter/Besitzer/Hüttenwirt_8	Private/Tourism/Econ
Pächter/Besitzer/Hüttenwirt_5	Private/Tourism/Econ
Pächter/Besitzer/Hüttenwirt_2	Private/Tourism/Econ
Universität Salzburg1	Research/Edu
Universität Salzburg2	Research/Edu
Universität Innsbruck	Research/Edu
Universität Salzburg3	Research/Edu
Tourismusverband Mondsee	Tourism/Econ
Tourismusverband Schladming	Tourism/Econ
Tourismusverband Schladming	Tourism/Econ
Österreichische Bundesforste AG	Tourism/Econ

Suppl. Table S5: Characteristics of the 27 mountain lakes in two study regions of the Eastern Alps: Niedere Tauern (NT) in Austria (22 lakes), South Tyrol (ST) in Italy (5 lakes), (from Kamenik et al. 2001; Schmidt et al. 2004, Thompson et al. 2005)

Lake	Acronym	Study region	Elevation [m a.s.l.]	Surface area [ha]	Volume [m3]	Maximum depth
Antholzersee	ANT	ST	1642	43.3	11040000	38
Eiskarsee	EIS	NT	1940	2.3	107416	14.2
Elendbergsee[2]	ELE	NT	2215	2.8	188884	21
Fischersee	FIS	ST	2754	0.5	30000	8.5
Hinterkarsee	HIN	NT	2074	1.9	96333	11.3
Hüttensee	HUS	NT	1502	4.6	166128	7.7
Kapuzinersee	KAP	NT	2147	1.2	91039	20
Knappenkarsee	KNA	NT	2257	1.4	41322	8
Langsee	LAG	ST	2384	20.1	2580000[1]	45
Landauersee	LAN	NT	1653	3.6	271563	16.6
Mittlerer Landschitzsee	MLA	NT	1940	6.6	626650	20.3
Obersee	OBE	NT	1672	7.2	801790	23.4
Oberer Giglachsee	OGIG	NT	1930	3.5	182827	10.5
Oberer Klaffersee	OKL	NT	2309	5.1	573844	32.5
Oberer Landschitzsee	OLA	NT	2067	8.9	509710	13.6
Oberer Saldursee	OSAL	ST	2922	0.4	n.d.	8.9
Pfannsee	PFA	NT	1967	1.3	24832	7.7
Pragser Wildsee	PRA	ST	1496	33.4	5300000	36
Rantensee	RAN	NT	1880	2.3	77856	7.6
Rauhenbergsee	RAU	NT	2263	2.8	246078	26.3
Oberer	SCH	NT	2110	5.1	186167	21.6
Tiefenbachsee	TIE	NT	1844	3.2	130028	8
Twenger Almsee	TWA	NT	1950	3.1	399160	33.6
Unterer	UGIG	NT	1922	16.8	1285012	18
Unterer Klaffersee	UKL	NT	2103	3.9	502862	39.6
Unterer Landschitzsee	ULA	NT	1782	12	997087	15.8
Unterer Wirpitschsee	WIR	NT	1700	2.7	121038	8

[1] data from Schirpke et al. 2021a; [2] ELE was sampled but not included in LST modeling.

Suppl. Table S6: Ranges for limnological parameters according to trophic state as observed during the study period (details are given in Suppl. Table S7). Proportions for eukaryotic phytoplankton were calculated from rarefied read numbers from 18S rDNA or 16S rDNA sequencing. N = Number of measurements/samples. Results are shown in this order: Minimum – Average +- Standard Error – Maximum

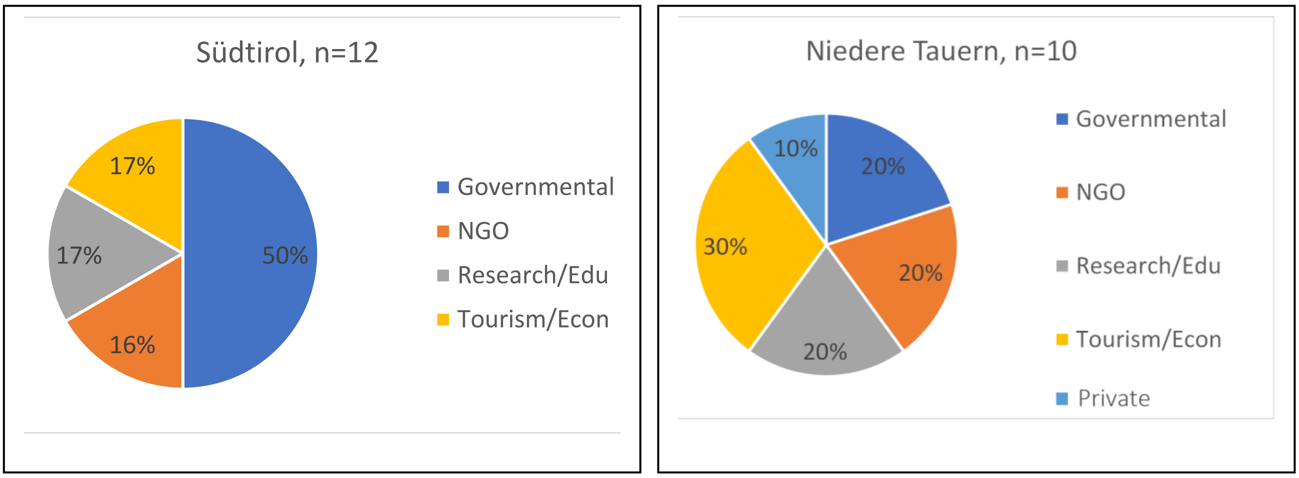
Limnological parameter	**N**	**ultra-oligotrophic (6 lakes)**	**N**	**oligotrophic (19 lakes)**	**N**	**oligo-mesotrophic (2 lakes)**	**p-value[1]**
Chlorophyll a [μgL^{-1}]	24	0.2 – 0.9 ± 0.1 – 2.4[a]	132	0.3 – 2.3 ± 0.1 – 5.9[b]	27	0.7 – 5.7 ± 0.7 – 13.8[c]	<0.001
Total phosphorus [μgL^{-1}]	34	1.1 – 3.0 ± 0.1 – 4.6[a]	145	1.2 – 4.8 ± 0.2 – 14.2[b]	29	3.1 – 5.5 ± 0.3 – 9.0[c]	<0.001
Secchi depth [m]	25	6 – 8.9 ± 0.4 – 12.5[a]	134	1.2 – 6.0 ± 0.2 – 13.0[b]	14	2.0 – 5.3 ± 0.5 – 9.0[b]	<0.001
Phytoplankton groups							
Green algae [%]	13	1.7 – 7.9 ± 2.2 – 28.5[a]	39	0.7 – 7.9 ± 1.4 – 38.6[a]	5	19.8 – 36.6 ± 8.8 – 66.1[b]	0.003
Bacillariophyceae [%]	13	0 – 1.6 ± 0.7 – 9.7	39	0 – 6.3 ± 1.7 – 35.5	5	0.1 – 4.7 ± 1.9 – 9.9	0.395
Cryptophyceae [%]	13	6.1 - 21.9 ± 4.1 – 51.2	39	1.1 – 27.3 ± 3.2 – 76.5	5	6.2 – 14.1 ± 4.4 – 29.4	0.217
Chrysophyceae [%]	13	6.1 – 31.8 ± 4.5 – 56.8	39	2.3 – 27.5 ± 2.5 – 79.1	5	7.3 – 18.9 ± 3.3 -26.4	0.28
Dinoflagellata [%]	13	13.0 – 34.2 ± 4.9 – 66.5	39	2.4 – 29.5 ± 3.0 – 77.4	5	11.6 – 18.3 ± 2.3 – 24.6	0.24
Others [%]	13	0.1 – 2.5 ± 1.6 – 20.9	39	0 – 1.5 ± 0.3 – 9.8	5	0 – 7.4 ± 3.6 – 16.1	0.483
Cyanobacteria [%]	19	0.1 – 0.7 ± 0.4 – 4.6[a]	37	0 – 6.0 ± 1.7 – 43.9[b]	5	0 – 0.2 ± 0.1 – 0.4[a]	0.002
Indicator taxa							
Enterococci [%]	12	0	37	0 – 0.002 ± 0.001– 0.03[a]	5	0 – 0.01 ± 0.008 – 0.04[a]	0.044
Escherichia coli [%]	12	0 – 0.009 ± 0.004 – 0.4	37	0 – 0.01 ± 0.003– 0.07	5	0 – 0.02 ± 0.02 – 0.1	0.828
Bloom-forming cyanobacteria [%]	13	0 – 0.03 ± 0.02 – 0.28	39	0 – 0.06 ± 0.03 – 1.1	5	0 – 0.002 ± 0.002 - 0.01	0.269
Asterionella formosa [%]	13	0 – 0.9 ± 0.9 – 11.5	37	0 – 0.7 ± 0.4 – 13.5	5	0	0.339
Coccal green algae [%]	13	0 – 2.8 ± 1.1 – 15.6[a]	39	0.03 – 2.0 ± 0.4 – 11.9[a]	5	9.5 – 28.5 ± 8.9 – 56.6[b]	<0.001
Phototrophic algae [%]	13	2.6 – 12 ± 2.6 – 29.1[a]	39	1.5 – 15.7 ± 2 – 43[a]	5	34.5 – 48.6 ± 5.3 – 66.8[b]	0.001
Zooplankton groups							
Rotifera [%]	6	0.5 – 52.5 ± 19 – 100	18	0.1 – 30 ± 7 – 96	2	13 – 100	0.328
Cladocera [%]	6	0 – 21.5 ± 13 – 67	18	0 – 41 ± 8 – 95	2	0.2 – 0.5	0.176
Cyclopoid Copepoda [%]	6	0 – 26 ± 15 – 96	18	0 – 29 ± 7 – 83	2	0 – 87	0.894
Daphnia spp. [%]	6	n.d.	18	0 – 5.2 ± 2.6 - 42	2	n.d.	0.196
Bosmina spp. [%]	6	0 – 20.6 ± 13 - 67	18	0 – 36 ± 8 - 93	2	0 - 0.2	0.247

[1] Kruskal–Wallis one-way ANOVA on ranks ([a,b,c] superscripts indicate subgroups not significantly different at $p < 0.05$ according to Dunn's method).

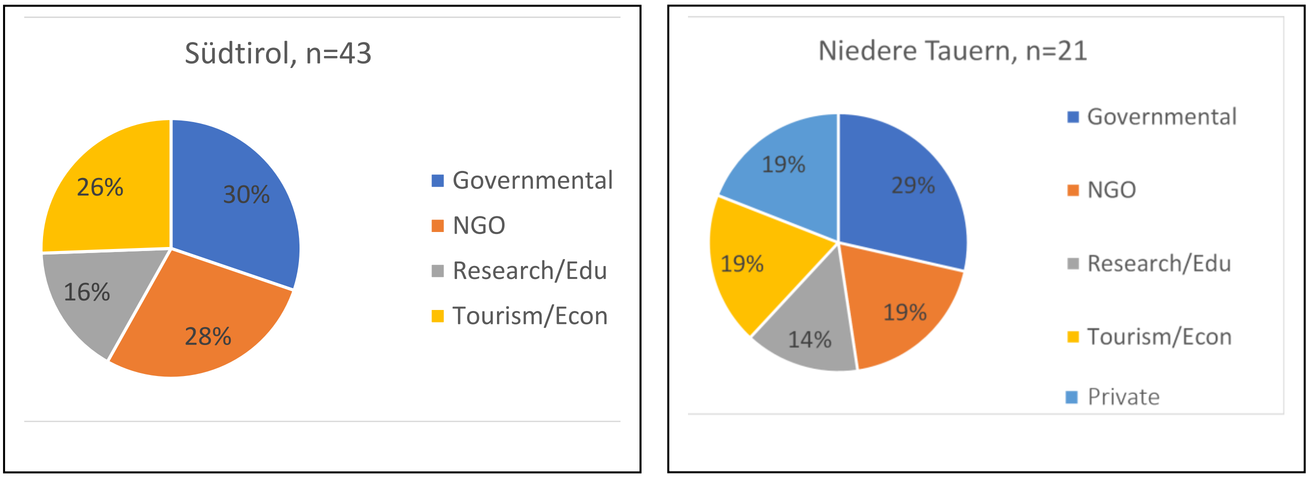
Suppl. Table S7: Number of measurements (N), average ± standard error (SE), minimum (min), maximum (max.) of total phosphorus (TP) and chlorophyll a (Chl. a) concentration and Secchi depth in the studied lakes and the assigned trophic state according to OECD.

	TP [µgL^{-1}]					**Chl-a [µgL^{-1}]**					**Secchi depth [m]**					**Trophic state**
	N	**Avg.**	**SE**	**min**	**max**	**N**	**Avg.**	**SE**	**min**	**max**	**N**	**Avg.**	**SE**	**min**	**max**	
WIR	8	3.3	0.3	2.3	4.6	8	0.4	0.1	0.2	0.7	8	6.7	0.2	6	7.6	ultra-oligotrophic
MLA	3	2.5	0.9	1.1	4.3	2	0.8	0.1	0.6	0.9	2	12.5	0.1	12.4	12.5	ultra-oligotrophic
OSAL	8	3.0	0.2	2.0	3.8	2	0.8	0.2	0.6	1.1	2	9.2	0.3	8.9	9.5	ultra-oligotrophic
OLA	8	2.8	0.1	2.2	3.4	7	0.9	0.2	0.3	1.6	8	9.2	0.2	8.5	10	ultra-oligotrophic
KAP	3	3.1	0.1	2.9	3.4	2	1.8	0.7	1.1	2.4	2	11.4	0.6	10.8	12	ultra-oligotrophic
HIN	4	3.2	0.2	2.6	3.7	3	1.7	0	1.6	1.8	3	9.8	1.1	8.5	12	ultra-oligotrophic
KNA	3	3.8	1.6	1.7	7.0	2	1.9	0.5	1.4	2.4	2	6.0	1.5	4.5	7.4	oligotrophic
TWA	8	4.5	0.6	2.1	7.3	8	1.3	0.2	1.1	2.4	8	10.8	0.6	8.2	13	oligotrophic
ULA	3	4.5	1.3	3.1	7.0	2	1.2	0.3	0.9	1.5	2	10.6	1.4	9.2	12	oligotrophic
OKL	3	4.4	0.4	4.0	5.3	2	1.4	0.1	1.3	1.5	2	9.9	1.7	8.2	11.5	oligotrophic
PFA	2	5.7	2.9	2.8	8.6	2	1.0	0.6	0.4	1.6	2	7.2	0.2	7	7.4	oligotrophic
EIS	3	2.8	0.9	1.8	4.6	2	1.6	0	1.6	1.6	2	9.7	1.7	8	11.4	oligotrophic
UGIG	8	7.1	1.1	4.4	12.8	8	1.6	0.2	0.7	2.4	8	7.8	0.8	5.9	12.7	oligotrophic
OGIG	4	6.6	1.0	4.9	9.5	2	1.5	0.3	1.2	1.7	2	7.9	1.4	6.5	9.3	oligotrophic
HUS	3	4.2	0.7	2.8	5.2	2	1.3	0.5	0.8	1.8	2	6.0	0	6	6	oligotrophic
ANT	46	5.6	0.4	2.1	14.2	50	2.0	0.2	0.3	5.9	51	5.3	0.3	1.2	10.6	oligotrophic
LAN	4	5.2	1.8	2.8	10.4	3	1.1	0.5	0.4	2.0	3	7.9	0.6	6.8	9	oligotrophic
TIE	3	7.5	1.4	4.7	8.9	2	1.4	0.7	0.7	2.2	2	5.5	1.0	4.5	6.5	oligotrophic
SCH	3	4.0	0.5	3.5	4.9	2	1.9	0.7	1.2	2.6	2	9.4	0.6	8.8	10	oligotrophic
RAN	4	3.5	0.9	1.7	5.8	3	1.4	0.7	0.4	2.8	3	6.3	0.3	6	7	oligotrophic
OBE	3	5.3	1.0	3.4	6.9	2	2.1	0.7	1.4	2.8	2	8.9	0.7	8.2	9.5	oligotrophic
UKL	3	3.6	1.2	1.2	5.3	1	3.3	n/a	n/a	n/a	1	11.0	n/a	n/a	n/a	oligotrophic
RAU	3	4.4	0.3	4.0	4.9	2	3.4	0.5	3.0	3.9	2	9.0	0.2	8.8	9.2	oligotrophic
PRA	44	3.6	0.2	2.1	6.6	42	3.2	0.2	1.0	5.5	44	4.4	0.2	1.9	7.6	oligotrophic
FIS	9	4.6	0.5	3.1	7.8	7	3.4	0.5	2.0	5.7	4	5.6	1.0	3.8	8.5	oligo-mesotrophic
LAG	20	5.9	0.3	3.3	9.0	20	6.5	0.9	0.7	13.8	10	5.1	0.7	2	9	oligo-mesotrophic
ELE	2	4.6	0.3	4.3	4.9	1	3.0	-	-	-	0	-	-	-	-	n.d.

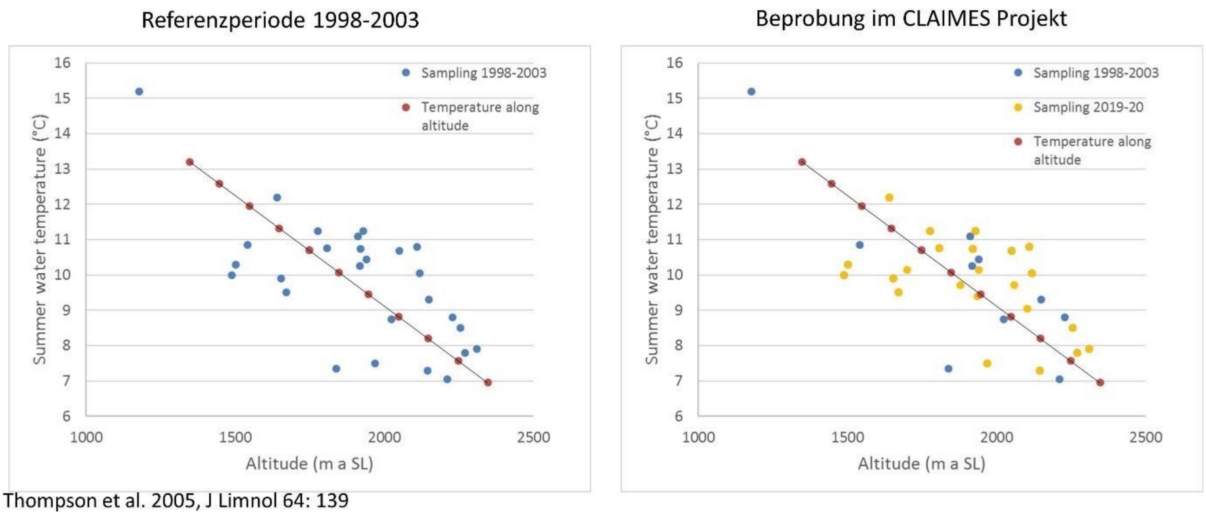
Supplementary Figures



Suppl. Fig. S1. Number of participants and share of the respective sectors at the focus group meetings in Bozen (9.1.2020) and Radstadt (4.8.2020).

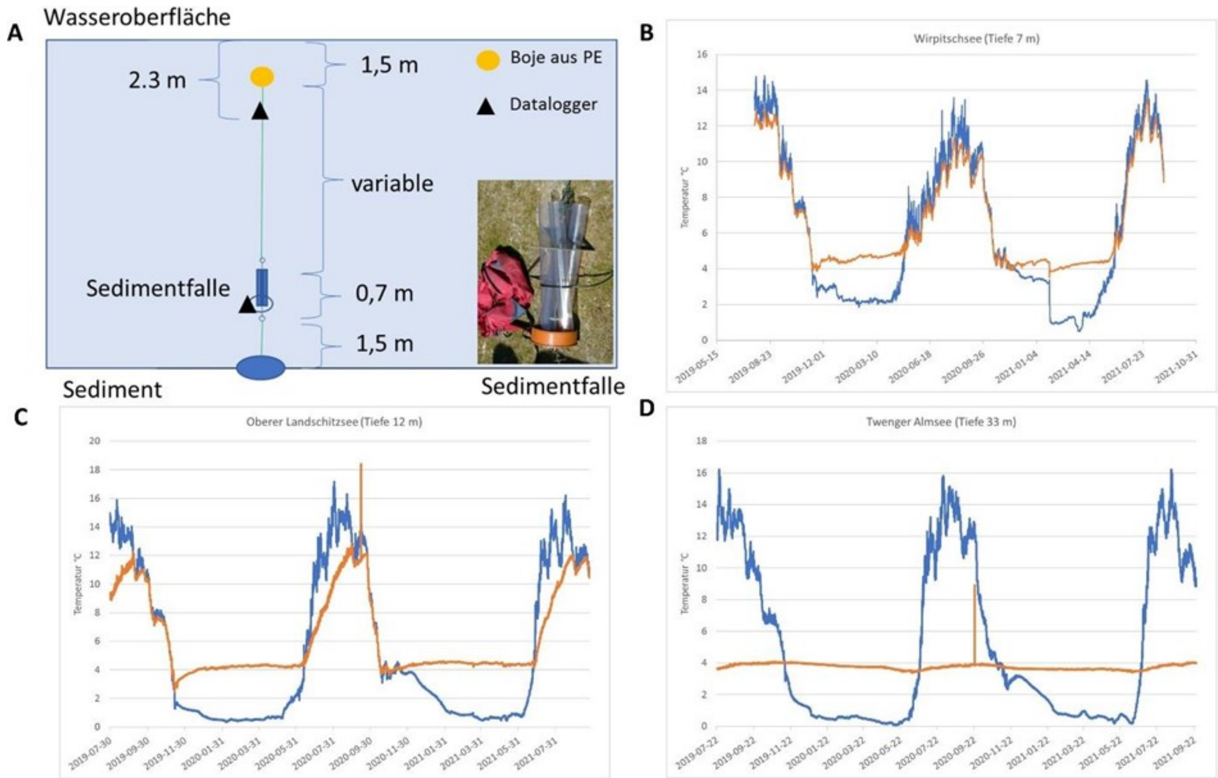


Suppl. Fig. S2. Number of participants and share of the respective sectors in the questionnaires on the weighting of ES.

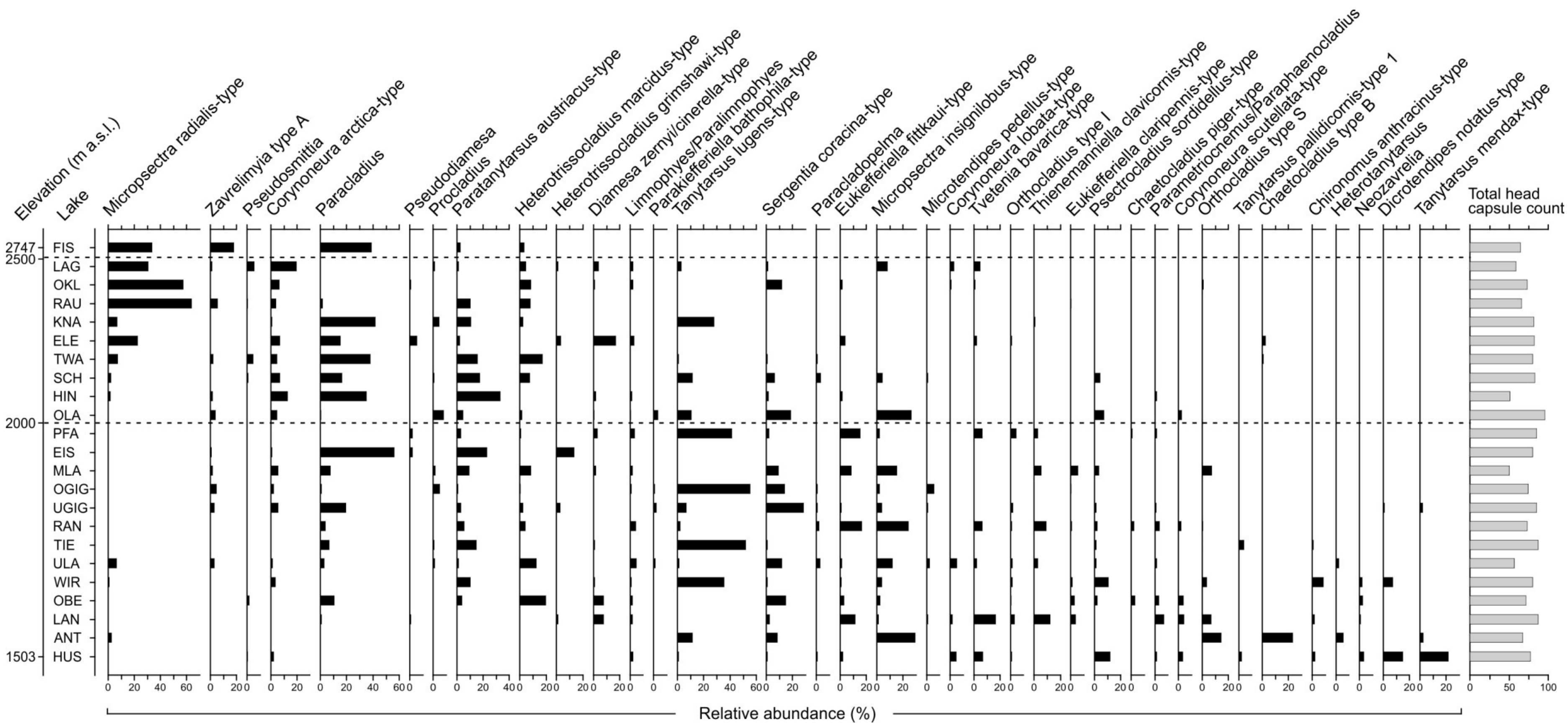


Thompson et al. 2005, J Limnol 64: 139

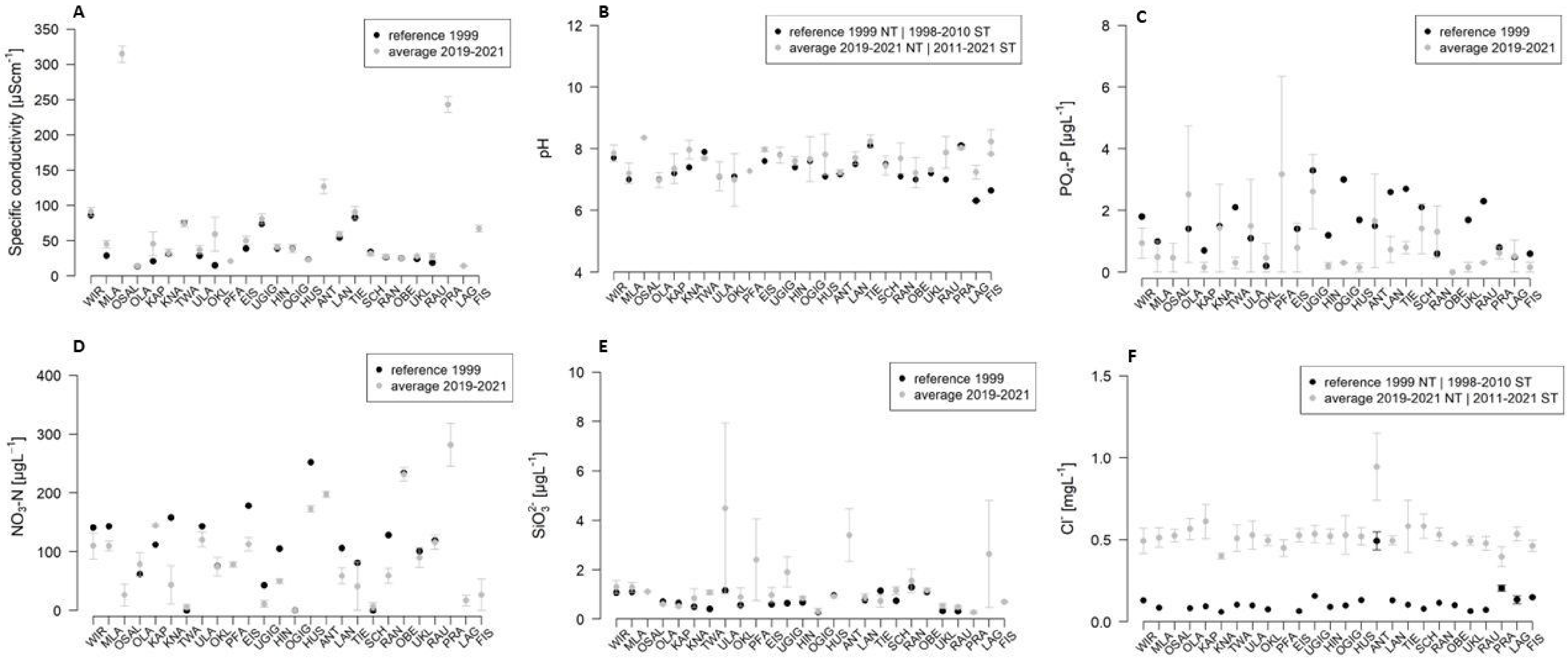
Suppl. Fig. S3: Relationship between mean summer epilimnion temperature values (ice-free period) and altitude (m a SL). The solid line shows the decrease in mean temperature due to the atmospheric influence alone (so called environmental lapse rate, 0.65°C per 100 m a.s.l.). Left: Data from Thompson et al. 2005, which were collected in 1998-2003; Right: Data collected as part of this study. Either undercooled or relatively warm lakes, show 7.5 or 11.3°C, respectively within a minor change in altitude from 1929 or 1970 m a.s.l.



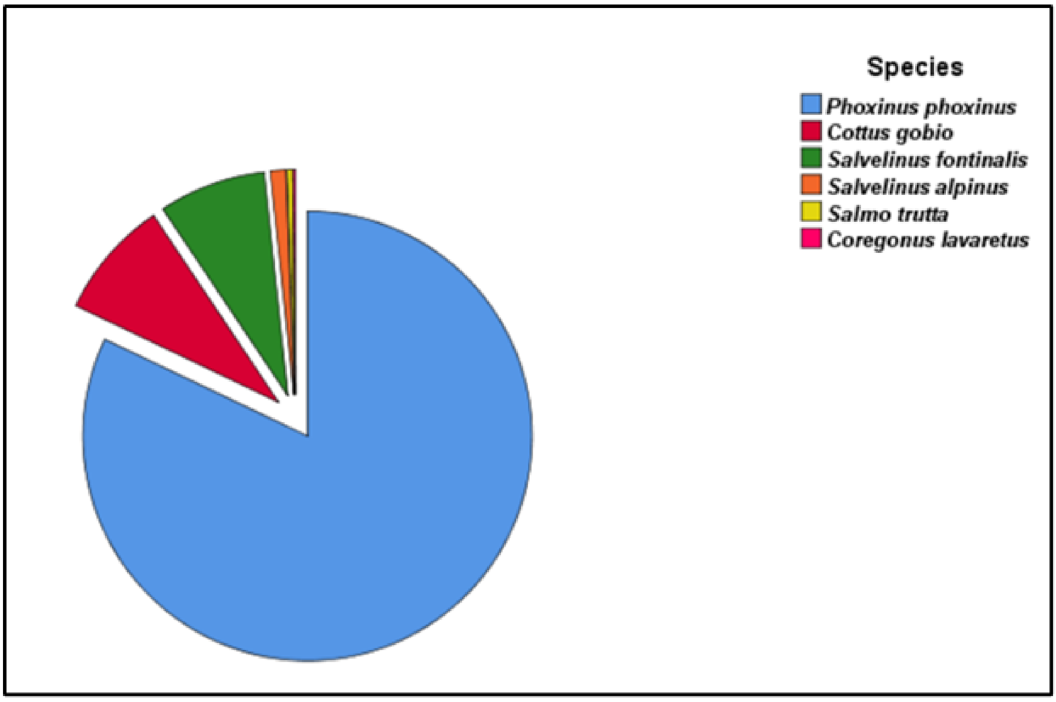
Suppl. Fig. S4: A) Scheme of the installation of the temperature dataloggers in the lakes (2019-2021). The first datalogger was installed in about 1-1.5 m water depth below the buoy to record surface temperature and the second datalogger was installed directly at the sediment trap about 1 m above the bottom. (B), (C), (D) Temperature curves in three different lakes varying in max. depth (blue line, buoy temperature; orange line, bottom temperature).



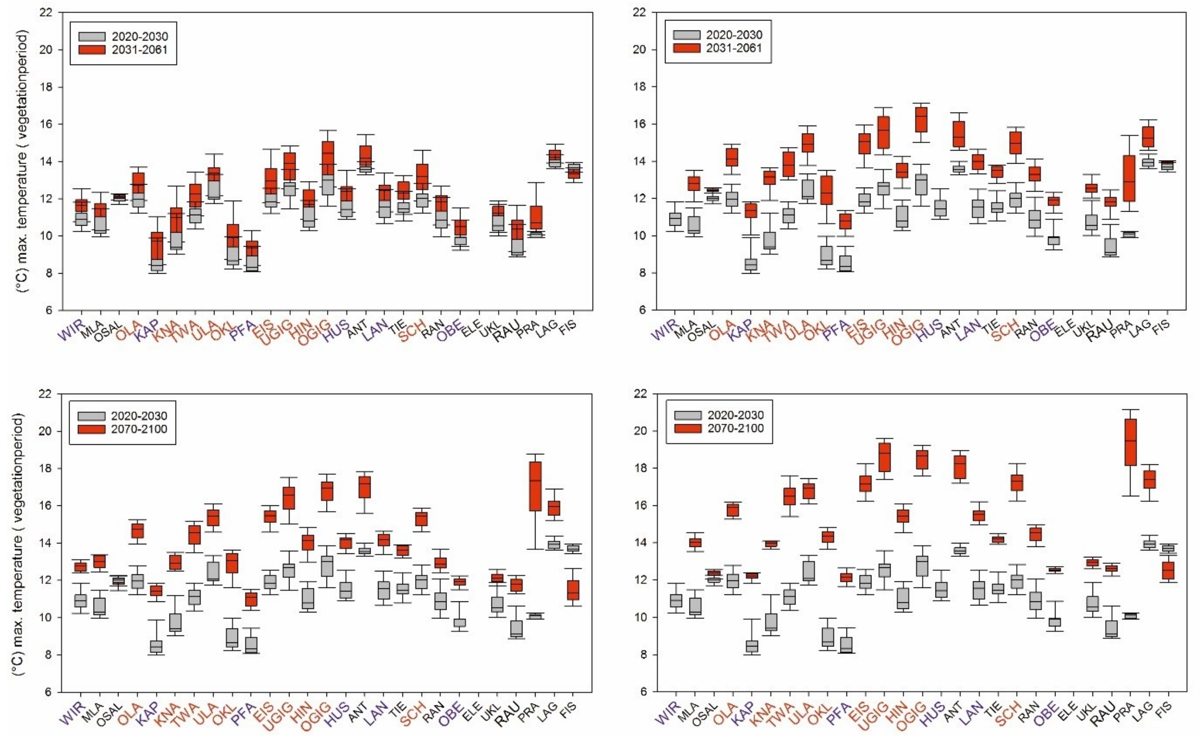
Suppl. Fig. S5: Subfossil chironomid assemblages in surface-sediment samples from the 23 lakes in the Niedere Tauern and South Tyrol. Only taxa with the relative abundance of >2% in at least two samples are shown.



Suppl. Fig. S6: Comparison of change in water chemistry (2019-2021) compared to reference sampling (October 1998) or reference period (LAG, ANT, PRA, 1985-1999) for (A) specific conductivity, (B) pH, (C) dissolved reactive phosphate, D) dissolved reactive nitrate, E) dissolved reactive silicate, F) chloride. Full names of lakes and corresponding abbreviations and topographic characteristics are given in Suppl. Table S5.



Suppl. Fig. S7: Fish species frequency of detection across all samples (>10000 reads) taken from shore. Overall, 81.8 % of all reads originated from Phoxinus phoxinus, 8.6 % from Cottus gobio, 7.8 % from Salvelinus fontinalis, 1.3% from Salvelinus alpinus, 0.4 % from Salmo trutta and 0.2 % of Coregonus lavaretus.



Suppl. Fig. S8: Projection of maximum surface temperatures for the near (2031-2060) and distant (2071-2100) future compared to the reference (2021-30). Left: at the median; right, at the 85% quantile. Average warm lakes are indicated by red font and average under-cooled lakes in blue font.

Minutes of the two stakeholder workshops on potential risks for water protection, identifying potential measures and evaluating the feasibility of individual measures (28.4.2022, 5.5.2022).

Appendix Protokoll no1,

Niedere Tauern Stakeholder Diskussion, 28.04. 2022

Teilnehmer:

Thomas Battisti, Steiermark Gewässerschutz

Michael Jesner, Gemeinde Lessach

Harald Ficker, Salzburger Landesregierung

Hr Klipp, Nationalpark Hohe Tauern

Josef Nothdurfter, Landesfischereiverband

Andreas Unterweger, Salzburg Gewässerschutz

Stephen Wickham, Forschungsprojekt Alpine Seen Uni Salzburg

Es wurden insgesamt zwei Diskussionsrunden durchgeführt, moderiert von jeweils einem Mitglied des CLAIMES-Projekt Teams.

In der ersten Diskussionsrunde, welche in zwei separaten Gruppen geführt wurde, wurden Risiken für den Gewässerschutz eruiert. In der zweiten Diskussionsrunde in einer einzelnen Gruppe wurden Maßnahmen, Konflikte und Lösungen bezüglich dieser Risiken diskutiert, welche sich aus der Interaktion von menschlicher Aktivität und dem Klimawandel für Bergseen ergeben.

Diskussionsrunde 1: Risiken für den Gewässerschutz (naturnaher Zustand)

Nennungen von Risiken in beiden Diskussionsgruppen jeweils aus Sicht

Gewässerschutz & Forschung

- Nährstoffeintrag (aus Landwirtschaft, Fischerei)
- Fischbesatz
- Klimaveränderung
- Energiewirtschaft
- Neobiota (e.g., Wasservögel)

Landwirtschaft, Jagd, Fischerei

- Zu dichte Viehhaltung
- Nährstoffeinträge aus Landwirtschaft (Viehwirtschaft)
- illegaler Fischbesatz

Tourismus

- Vermüllung (achtloses Benehmen)

- Erschließung der Bergseen durch (Forst-) Wege
- Beschneiung
- Neobiota

Kommunale Sichtweise

- Errichtete Infrastruktur (z.B. Toiletten, Müllsammelbehälter) kann wiederum mehr Besucher anziehen und dadurch das Risiko erhöhen

Diskussionsrunde 2: Maßnahmen und Lösungen für Risiken aus Touristischer Nutzung:

Die Diskussionsteilnehmer haben sich zu Beginn der Diskussion darauf geeinigt, sich aus Zeitgründen auf Risiken ausschließlich zur touristischen Nutzung zu konzentrieren.

Grundsätzliche Lösungsansätze zu Risiken aus Tourismus

- Lokale Besucherlenkung:
- Wie gut ist die Infrastruktur (Wege, Zugänglichkeit zu sensitiven Bereichen)

Potentielle Konflikte:

- Mehr Nutzung
- Längere Nutzung
- Müll
- Anthropogener Druck am und im See
- Hohe Besucherkonzentration (leicht zugängliche Regionen)
- Soziale Medien, digitale (GPS) Daten
- Versteckte Werbung
- Gezielte Bewerbung, z.B. 9 Plätze – 9 Schätze Aktion sollte nicht mehr stattfinden
- Lokaler Tourismus eingeschränkt, Wertschöpfung durch Tagestourismus geringer
- Widerstand vom Tourismusverein

Maßnahmen:

- Bewusstseinsbildung (Infotafeln an Seen die schon gut besucht sind mit großem Parkplatz, aber nicht an entlegenen Seen; Ranger, soziale Medien, Tourismusvereine)
- Gezielte und angepasste Infrastruktur (Wege, Bänke) zur "intelligenten" Besucherlenkung
- Zugänglichkeit erschweren (Wanderweg nicht mehr betreuen, aus Karte streichen bzw. weiter weg vom Gewässer führen)
- Sensibilisierung der Akteure und der Besucher (z.B. durch die Tourismusinformation)
- Lokalspezifische Maßnahmen

Offene Diskussion im Plenum

Zum Abschluss und zur Synthese wurden die genannten Maßnahmen im Beisein und mit Partizipation aller anwesenden CLAIMES-Projektmitglieder diskutiert.

Stichwort Besucherlenkung: Wege-Umleiten ist nicht (mehr) so leicht möglich, weil nur von der Landkarte wegnehmen zu wenig ist, die Leute haben GPS bzw. ihre Handy Maps, und es werden laufend neue Orientierungsrouten eingerichtet, z.b. im Lessachtal

Die Teilnehmer sprechen sich zur Lösung für Risiken aus Tourismus insbesondere für weiche Maßnahmen wie Information oder das Management zur Besucherlenkung aus. Es wurden keine Maßnahmen wie Verbote oder Preismechanismen präferiert. Die Teilnehmer legen Wert darauf, dass der Fokus auf Tourismus in der Maßnahmen-Diskussion nicht notwendigerweise das größte Problemfeld für die Bergseen im Wandel darstellt, aber als solches im Rahmen der Diskussionen identifiziert wurde.

Appendix Protokoll no2,

Südtirol Stakeholder Diskussion, 5.5.2022

Teilnehmer/innen:

Edit Bucher, Amt für Natur

Alex Festi, Fischereiverband

Dominik Gastel, Schutzgebietsverantwortlicher

Max Gruber, Fischereiverband

Caroline Heiss, Hotel Pragser

Deimichei Kager Miran, Gewässerschutz

Karin Sparber, Amt für Gewässerschutz

Roman Spechtenhauser, Amt für Jagd & Fischerei

Erich Tasser, Eurac Bozen

Barbara Vidoni, Amt für Gewässerschutz

Samuel Vorhauser, Biologisches Labor, APPA Bolzano

Es wurden insgesamt zwei Diskussionsrunden durchgeführt, moderiert von jeweils einem Mitglied des CLAIMES Projekt-Teams.

In der ersten Diskussionsrunde, welche in zwei separaten Gruppen geführt wurde, wurden Risken für den Gewässerschutz aus verschiedenen Perspektiven eruiert. In der zweiten Diskussionsrunde in einer einzelnen Gruppe wurden Maßnahmen, Konflikte und Lösungen bezüglich dieser Risken diskutiert, welche sich aus der Interaktion von menschlicher Aktivität und dem Klimawandel für Bergseen ergeben.

Diskussionsrunde 1: Risiken für den Gewässerschutz (naturnaher Zustand)

Nennungen von Risiken in beiden Diskussionsgruppen jeweils aus Sicht

Gewässerschutz & Forschung

- Lebensraum verschwindet durch max. Temp.erhöhung (Amphibien könnten aber profitieren)
- Gletscherwasser als Stabilisator für Temperatur fällt weg, durch die wegfallende Trübung könnte die Trophie zunehmen
- Wasserstand könnte niedriger werden, und damit Lebensraum verloren gehen
- Klimaerwärmung & Zunahme von Extremwetterereignissen (Starkregen)
- Eintrag von Nährstoffen aus Atmosphäre/Niederschlag
- Touristische Nutzung (Boote, Baden, Angeltätigkeit)
- Einfluss auf Ökosystem durch Sauerstoffzehrung im Tiefenwasser verringern (Temperaturanstieg und Trophiezunahme)
- Veränderung des Artenspektrums
- Reduktion der Eisdecke? Eisfläche -> Änderung des Nährstoffzyklus, Zufuhr der Wassermenge reduziert, Konzentration der Nährstoffe höher
- Erhöhte Wasserentnahme
- (Kunstschnee nicht aus natürlichen Seen)
- Hydroelektrische Nutzung ist bislang nicht zugelassen…
- Wege zu nah am Ufer
- Badeseepotential muss gemanagt werden
- Fischbesatz ist Genehmigungspflichtig (vor allem illegal ist ein Problem)

Landwirtschaft, Jagd, Fischerei

- Wasserentnahme für die Bewässerung
- Gesteigertes Wachstum der Vegetation -> Zunehmende Verlandung (vor allem bei seichten Seen)
- Umzäunung notwendig
- Interesse an Besatz steigt mit Temperatur
- Eher geringes Risiko durch Jagd
- Wasserentnahme für Energienutzung
- Intensivierung der Viehwirtschaft durch verlängerte Vegetationsperiode auch in der Höhe
- Wachstum der Fische könnte von verlängerter Vegetationsperiode profitieren (z.B. auch durch die Ansiedlung von Wasserpflanzen)
- Niedrigere Wasserstände durch Niederschlagsrückgang – Wasserfläche wird geringer
- Einfluss auf Ökosystem durch Sauerstoffzehrung verringern (Temperaturanstieg und Trophie) – Beeinflussung Reduktion der Fangzahl

Tourismus

- Seenutzung aus Sicht der Gemeinde
- mehr Touristen in sensiblen Lebensraum
- Rückgang Ästhetischer Wert (durch Algenwachstum in Folge von erhöhten Nährstoffeinträgen)
- Niedrigere Wasserstände durch Niederschlagsrückgang – Landschaftsbild
- Reduktion der Eisdecke – Einfluss auf Freizeitaktivitäten (Eislaufen)
- Extremwetter (Starkregen) Einfluss auf Wegenetze – Sperrung von Wegen
- Erhöhte Nutzung eher wahrscheinlich (Beispiel Pragser Wildsee)
- Längere Nutzung im Herbst
- Kunstschnee (auch Langlauf, Antholzer See)
- Badepotential steigt
- Fischbesatz als zusätzliche Attraktion
- Tretboote und Standup-Paddeling problematisch -> Sedimente aufgewirbelt

Kommunale Sichtweise

- Seenutzung aus Sicht der Gemeinde
- mehr Touristen in sensiblen Lebensräumen
- Rückgang Wasserangebot (Trinkwasserversorgung auch für Schutzhütten und Brauchwasser für Landwirtschaft)
- Reduktion der Eisdecke – öffentliche Sicherheit, behördliche Anordnungen, vermehrter Aufwand (Beschilderung, Absicherung)
- Vermehrter Aufwand für Aufklärungsarbeit, Umweltbildung
- Umwidmung Bsp. Gewerbezone interagiert mit Gewässerschutz
- Wasserverfügbarkeit
- Nichteinhalten von Regulierung Problem bei Durchsetzung
- Lenkung Tourismus sollte vorgesehen sein (Pragser Wildsee als abschreckendes Beispiel)

2**) Diskussionsrunde Maßnahmen und Lösungen für Risiken aus Touristischer Nutzung:**

Die Diskussionsteilnehmer haben sich zu Beginn der Diskussion darauf geeinigt, sich aus Zeitgründen auf ausgewählte Risikokategorien zu konzentrieren.

Maßnahmen und Lösungen zu Risiken durch Klimaerwärmung allgemein

Grundsätzliche Lösungsansätze zu Risken durch Klimaerwärmung allgemein:

- Lenkung der Beweidung im unmittelbaren Umfeld des Gewässers – Abstand zum Gewässer, Viehtränken

- Individuelle Lösungen bei Bedarf/je nach See, abhängig von Topographie, Bewirtschaftung im Umfeld
- Einschränkung der Landwirtschaft im Tal (Pestizideinsatz, Düngung) Zur Verringerung des potenziellen atmosphärischen Eintrags
- Seen müssen individuell betrachtet werden!

Potentielle Konflikte zu Risken durch Klimaerwärmung allgemein:

- Übertourismus
- Großevents – Ressourcennutzung/ -verteilung
- Änderung des Landschaftsbildes durch Besucherlenkung, Weideumzäunung, Beschilderung
- Seilbahnbetreibern – Tourismusverbände
- Wassernutzung – Konfliktparteien: LWS, Viehwirtschaft, Trinkwasser, Beschneiung, Energie

Maßnahmen zum Management von Risiken durch Klimaerwärmung allgemein:

- Besucherlenkung & Beschilderung, rechtliche Maßnahmen
- Ausweisung neuer Schutzgebiete / Verbote intensive Nutzung (Großevents)
- Einschränkung der Freizeitaktivitäten in gewissen Bereichen/Formen der Nutzung, Ruhezonen schaffen
- Nachhaltiger Tourismus – Förderung nachhaltiger Mobilität, Einschränkung touristischer Aufstiegsanlagen
- Viehtränken
- Rechtliche Maßnahmen bezüglich Wasserentnahme
- Nachschärfung vorhandener rechtlicher Maßnahmen

Maßnahmen und Lösungen Risiken zum Lebensraumverlust

Grundsätzliche Lösungsansätze zu Risiken aus Lebensraumverlust

- Frage: wie reagieren die versch. Organismen, z.B. Insekten auf Lebensraumverlust?
- Überzeugungsarbeit in der Öffentlichkeit für die Erhaltung fischfreier Gewässer
- keine zusätzlichen Konzessionen zur Wasserentnahme, um den Zufluss im Einzugsgebiet zu erhalten
- keine neue Erschließung von unbesiedelten und neu besiedelbaren Regionen um Wasserentnahme nicht noch zu fördern

Potentielle Konflikte bei Risken aus Lebensraumverlust:

- Wassernutzer (Landwirtschaft, etc.)
- wie weit darf der Wasserstand gesenkt werden

Maßnahmen zum Management von Risiken aus Lebensraumverlust:

- nachhaltige Bewässerung (Tropfsysteme)
- zeitliche Regelung der Bewässerung
- Anpassung der Kulturen
- Pegelstand regulieren
- Speicher nicht im Gewässer selbst, sondern künstliche Speicher errichten

Maßnahmen und Lösungen Risiken im Kontext von Tourismus

Grundsätzliche Lösungsansätze zu Risken im Fremdenverkehrskontext:

- Niedrig gelegene Seen:
- Zugangsbeschränkungen
- Höher gelegene Seen;
- Verbot von E-Bikes? Zugang zu höher gelegenen Seen wird schwieriger.
- Möglichkeit zur Besucherlenkung: Versicherung nicht gewährleistet bei Unfällen auf Forststraßen, Wegen... (Ist in Ö reguliert, in Südtirol bislang Grauzone…)
- Beschränkung der Wege, für welche Bikes erlaubt sind.

Potentielle Konflikte zu Risiken im Fremdenverkehrskontext:

- Fremdenverkehr: Konflikte eigentlich überschaubar,
- Hütten haben Interesse an hoher Besucherzahl
- Landwirtschaft und Tourismus (Kuhattacken, Herdenschutzhunde)
- Zielkonflikt Biodiversität: Wolf und Bär

Maßnahmen zum Management von Risiken im Fremdenverkehrskontext:

- Niedrig gelegene Seen:
- Tickets -> Parkplatz; Frequenz der Busfahrten,
- Preissteuerung (Parkplatz, Busticket)
- Höher gelegene Seen;
- Verbot von E-Bikes? Zugang zu höher gelegenen Seen wird schwieriger.
- Versicherung nicht gewährleistet bei Unfällen auf Forststraßen, Wegen... (Ist in Ö reguliert, in Südtirol bislang Grauzone…)
- Hüttenkonzessionen abhängig von Besucherzahl
- Umzäunung? Muss im Verhältnis zum Risiko stehen.
- Management-Plan für Wolf und Bär
- Baden regulieren (Schilder, Zuchttier-Gebote für Almen?)

Maßnahmen und Lösungen Risiken im Kontext von Gewässerschutz

Grundsätzliche Lösungsansätze zu Risken im Kontext von Gewässerschutz:

- Reduktion des Stresses für Uferbewuchs
- Beibehalten der Regulierungen für natürliche Seen

Potentielle Konflikte zu Risiken im Kontext von Gewässerschutz:

- Konflikt mit Landwirtschaft, auch Wasserentnahme
- Potentielle Hydroelektrische Nutzung
- Ästhetik leidet unter künstlichen Reservoirs => Richtlinien im Genehmigungsprozess.
- Nährstoffeintrag erhöht bei längerer Bewirtschaftung der Almen
- Milchkühe sind nährstoffintensiver

Maßnahmen zum Management von Risiken im Kontext von Gewässerschutz:

- Separate Trinkmöglichkeiten, Vorschrift
- Beibehalten der Regulierungen für natürliche Seen
- Ausschließlich künstliche Speicherbecken für Kunstschnee, hydroelektrische Nutzung
- Beobachten der Interaktion zwischen der Menge der künstlichen Reservoirs und der Wassermenge in natürlichen Seen.
- Primäre Einzugsgebiete des Sees gesondert schützen
- Pufferzonen berücksichtigen Hydrologie
- Menge des Viehs beschränken
- Subventionen anpassen? Besser Prämien für gewünschtes Verhalten.

Offene Diskussion im Plenum

Zum Abschluss und zur Synthese wurden die genannten Maßnahmen im Beisein und mit Partizipation aller anwesenden CLAIMES-Projektmitglieder diskutiert.

Die Teilnehmer sprechen sich generell für weiche Maßnahmen (Management zur Besucherlenkung, aus und wo erforderlich auch für strikte Regulierungen aus, respektive deren Beibehaltung. Besonders betont wurde letzteres beim Management von Wasserspeichern für Kunstschnee und hydorelektrische Nutzung. Die bestehende Regulierung sieht vor, dass natürliche Seen in einer solchen Form nicht genutzt werden dürfen. Beobachtbaren Tendenzen, diese Regulierung zu verwässern, ist entgegenzuwirken.