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SYNTHESIS

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Assessing ecosystem services of mountain lakes

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Abstract

From global to local scales, human-induced environmental changes can impact mountain lakes by, for example, altering species composition, trophic state, and thermal dynamics, thereby affecting ecosystem functions and processes. However, the consequences of these changes on ecosystem services (ES) of mountain lakes are unclear due to a lack of integrative assessments. Therefore, this dissertation adopts an interdisciplinary ES perspective to improve insight into human interactions with mountain lakes and the potential social and ecological impacts of anthropogenic pressures on them. Stakeholder consultations highlighted the importance of regulating, cultural, and provisioning ES of natural mountain lakes, emphasizing habitat, aesthetics, recreation, education and research, and surface water, with nature-based experiences as being a key aspect of human interaction with mountain lakes. Multiple indicators were proposed to quantify potential supply of these ES, revealing variations among case study lakes in the European Alps. These results informed an integrative valuation approach and exposure assessment to anthropogenic pressures, suggesting that ES by mountain lakes are sensitive to climate change-related and human use pressures. Overall, the findings advance a social-ecological understanding of mountain lakes and indicate towards the need for adaptive lake management to maintain ES under potential anthropogenic pressure.

Keywords:
freshwater, participatory, perceptions, global change, valuation, European Alps

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1 Introduction

Freshwater ecosystems are an integral landscape feature of mountain regions that contribute to the well-being of both mountain communities and those living outside these regions by providing ecosystem services (ES, Millennium Ecosystem Assessment, 2005). These ES include nursery populations, water for human consumption, recreational opportunities and aesthetic experiences, among others (Angradi et al., 2018; Grizzetti et al., 2016; Schirpke et al., 2019). However, (mountain) freshwater ecosystems face various pressures exerted by global change-related drivers, which can alter ecosystem conditions and functioning, ultimately leading to the degradation or loss of ES (Carpenter et al., 2011; Schmeller et al., 2018). Understanding these interactions and their potential impact on human well-being is therefore important for promoting sustainable management of freshwater ecosystems (Grizzetti et al., 2016; Heino et al., 2021; Ho and Goethals, 2019).

As typically pristine, oligotrophic, and small standing water bodies, natural lakes in the montane to alpine zones of the world's mountain regions are sensitive to global change-related and direct anthropogenic pressures (Moser et al., 2019; Rogora et al., 2018). For example, in response to climate warming, (atmospheric) nutrient inputs, or land/water use change, profound effects on species composition, biochemical properties, and thermal and hydrological conditions have been observed (e.g., Caldwell et al., 2021; Hundey et al., 2016; Moser et al., 2019; Oleksy et al., 2020; Weckström et al., 2016). Moreover, recreational use (e.g., Senetra et al., 2020; Tiberti et al., 2020) or local agricultural activities and water abstraction can alter mountain lake ecosystem conditions and functioning (e.g., Tiberti et al., 2020; Tiberti et al., 2014; van Colen et al., 2018). However, despite the range of potential pressures on mountain lakes, there is a lack of knowledge about how these changes may impact the provision of ES. Therefore, an integrative assessment of anthropogenic pressures and their impacts on the capacity of mountain lakes to generate ES can contribute to the social-ecological understanding required to support lake management, biodiversity protection, and maintenance of ES (Carpenter et al., 2009; Grizzetti et al., 2016; Heino et al., 2021; Rounsevell et al., 2010).

The urgency of such research is highlighted by the persistent and accelerating large-scale pressures such as climate change (Pepin et al., 2015; Roberts et al., 2017), as well as a potential for increased local human water use and demand for recreational opportunities in the future (e.g., Brunner et al., 2019; Pröbstl-Haider et al., 2021). In this vein, small lakes, which are abundant in higher-elevated regions (Verpoorter et al., 2014), may be overlooked in water management despite their ecological and social significance (Biggs et al., 2017). Furthermore, research on ES in freshwater systems is still limited (Vári et al., 2022), especially concerning mountain lakes. Only a few studies have evaluated ES of mountain lakes and associated societal perception (e.g., Angradi et al., 2018; Chiapella et al., 2018), compared to research on larger lowland or urban lakes (e.g., Hossu et al., 2019; Reynaud and Lanzanova, 2017; Sterner et al., 2020). This knowledge gap hinders our understanding of the social relevance and perceptions of ES provided by mountain lakes and their benefits to human well-being. However, this is essential for a context-specific evaluation of human interactions with mountain lakes, anticipating social responses to management actions (Bennett, 2016; Schmeller et al., 2018), and for a multi-faceted understanding of the importance of ES (Chan et al., 2012; Jacobs et al., 2016).

In this context, the dissertation (Ebner, 2022), as presented in this synthesis article, aims to advance the understanding of ES of mountain lakes, the associated benefits to human well-being, and the pressures affecting their provisioning in view of global change. Three research objectives were pursued to enable a coherent research progress: (I) exploring socio-cultural perspectives on ES provided by mountain lakes, (II) developing ES indicators and integrative valuation, (III) evaluating global change pressures and impacts on ES.

2 Research approach and methods

This dissertation comprises seven articles published in scientific journals organized around the three re-

search objectives (Figure 1). To achieve these objectives, a variety of approaches and methods are employed, including participatory approaches, empirical studies, and conceptual analyses. The research primarily focuses on small (<50 ha) and natural lakes the European Alps ranging from local case studies to encompassing the entire mountain range (Figure 2a). Local case studies were conducted in South Tyrol/Alto Adige (Italy, Central/Southern Eastern Alps) and Niedere Tauern (Austria, Central Eastern Alps), comprising in total 15 case study mountain lakes, ranging from 1493 to 2758 m a.s.l. in elevation and between 0.54 and 43.24 ha in lake size (see Figure 2b for regional examples of case study lakes).

2.1 Exploring socio-cultural perspectives on ES of mountain lakes

Addressing objective I, three articles focus on socio-cultural (i.e., non-monetary) approaches to explore human perceptions of ES provided by mountain lakes. These approaches aim to better understand how ES are perceived, valued, or demanded (e.g., Scholte et al., 2015; Walz et al., 2019; Zoderer et al., 2019), and to capture related benefits to human well-being, which are relatively underexplored in ES assessments (Schmidt et al., 2016; Wang et al., 2021). **Article I** explores stakeholder perceptions of ES related to natural mountain lakes in South Tyrol based on a participatory workshop with twelve regional stakeholders from different sectors and a questionnaire-based survey (N = 184, stakehold-

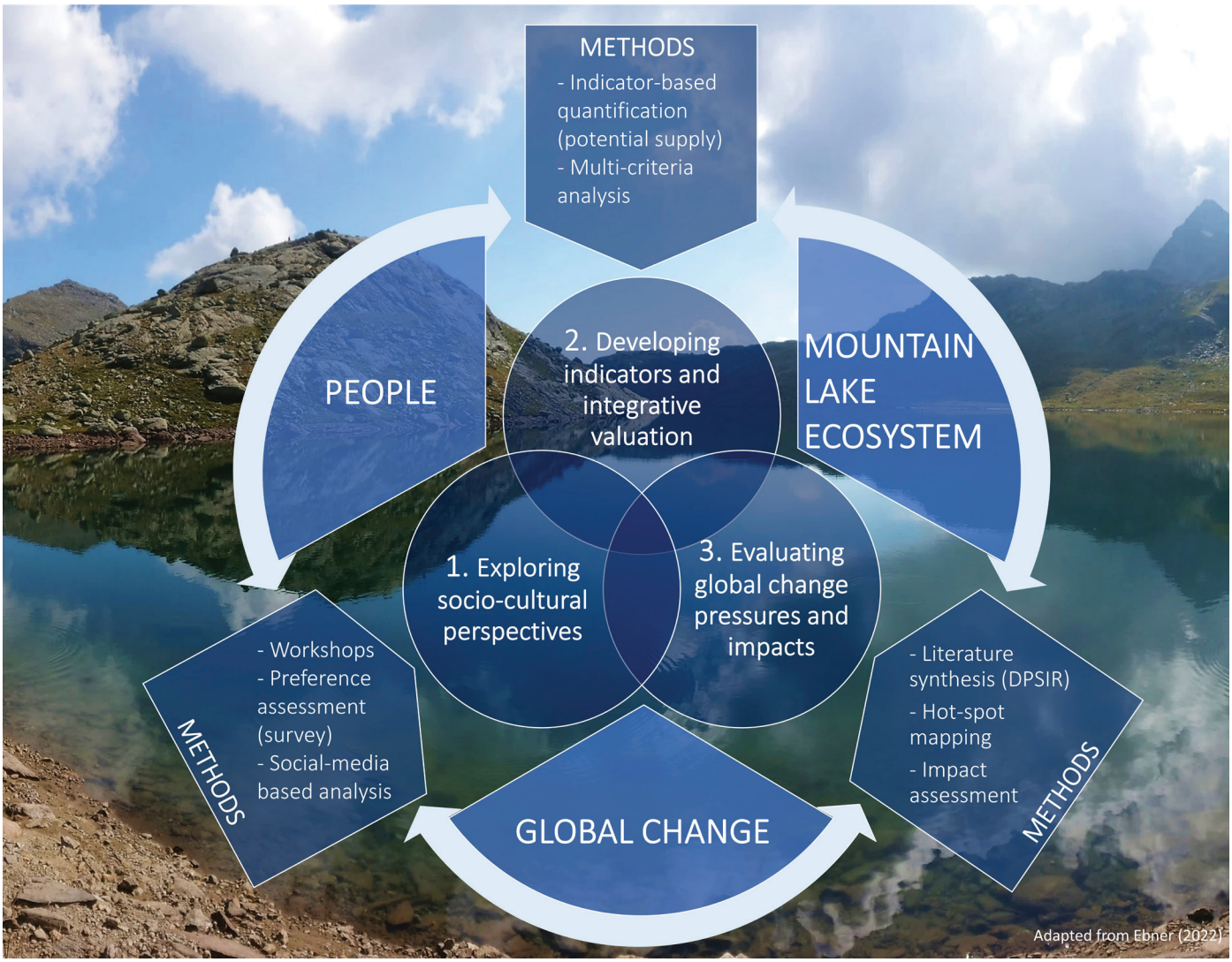

Figure 1. Conceptual framework, research objectives, and main methods. Abbreviations: DPSIR - Driver, Pressures, States, Impacts and Responses framework.

ers and lake visitors) including qualitative inquiries on the perceived importance of ES and benefits to well-being (Ebner et al., 2022a). Recognizing the generally limited representation of cultural ES (CES) in ES assessments (Cheng et al., 2019), and aiming to capture the perceptions of diverse beneficiary groups and expand the spatial scale of assessment, **Article II** focuses on CES of lakes in the European Alps (Schirpke et al., 2021a). This study utilizes social media data from the photo sharing platform Flickr, analysing photo-user-days as proxy for visitor activities, photo content, and user-generated tags for 2,807 lakes. In **Article III** (Ebner et al., 2022b), a follow-up study was conducted to enhance the understanding of human interactions and perceptions of mountain lakes. To achieve a comprehensive understanding of human interaction with these lakes from a CES perspective, a mixed methods approach was employed: This involved combining the findings from the social media-based approach with insights from an online survey targeting lake visitors (N = 526; Schirpke et al., 2022) and two participatory stakeholder workshops held in Niedere Tauern, and South Tyrol, allowing for triangulation of findings and comparative evaluation of the approaches. Overall, the Common International Classification of Ecosystem Services (CICES, v5.1; Haines-Young and Potschin, 2018) was used throughout the thesis to provide consistent ES terminology.

2.2 Developing ES indicators and integrative valuation

ES indicators for lakes are relatively underrepresented compared to other aquatic or terrestrial systems (Feld et al., 2009; Heino et al., 2021), which is particularly true for mountain lakes. To address this gap, objective II focuses on developing multi-metric indicators to quantitatively assess the ES of mountain lakes. These indicators were not only aimed to provide a measurable account of the current potential supply of ES but also to allow estimation of potential changes under future conditions. In **Article IV** (Schirpke et al., 2021b), indicators for eight ES of mountain lakes are presented based on the stakeholder workshops conducted in South Tyrol and Niedere Tauern as pursued during objective I. For each ES, multiple indicators were proposed, considering both natural capacity and human-derived capital and preferences. These indicators were quantified using a combination of limnological, socio-economic, and spatial data for the case study mountain lakes in both study regions. Furthermore, the results were compared to variables characterizing the lake's socio-ecological setting (i.e., lake characteristics, environmental setting, land cover, accessibility, beneficiaries) to characterize context-dependency of potential ES supply. Recognizing the multidimensional nature of ES (Jacobs et al., 2016; Tasser et al., 2020; Vári et al., 2022), **Article V** highlights the importance of integrating various data and information strands on ES (Fontana et al., 2023). To this end, multi-criteria (decision) analysis (MCA) is considered a suitable framework (Langemeyer et al., 2016; Saarikoski et al., 2016), and is increasingly applied in water-related management contexts (e.g. Castro-Pardo et al., 2021; Martínez-López et al., 2019; Marttunen et al., 2022). Drawing on such approaches, this article presents a conceptual framework for ES valuation in the context of mountain lakes using the PROMETHEE method. This framework integrates the outcomes of stakeholder consultations and the developed ES indicators, describing a participatory process to evaluate ES provision comparing different mountain lake types.

2.3 Evaluating global change-related pressures and impacts on ES

Objective III aimed to integrate the findings from the previous studies with cross-disciplinary evidence on global change-related and anthropogenic pressures affecting mountain lakes. The aim was to understand the potential impacts of such pressures on current and future ES provision. This approach contributes to the ongoing research on pressure-impact relationships in the ES context to identify the social-ecological consequences (e.g., Carpenter et al., 2009; Grizzetti et al., 2016; Rounsevell et al., 2010). Focusing on a subset of seven ES identified by stakeholders as described above, **Article VI** presents a synthesis of peer-reviewed research articles (Ebner et al., 2022c), adopting the Driver-Pressure-State-Impact-Response (DPSIR) framework to conceptualize the potential impacts of global change-related and anthropogenic pressures on ES provided by moun-

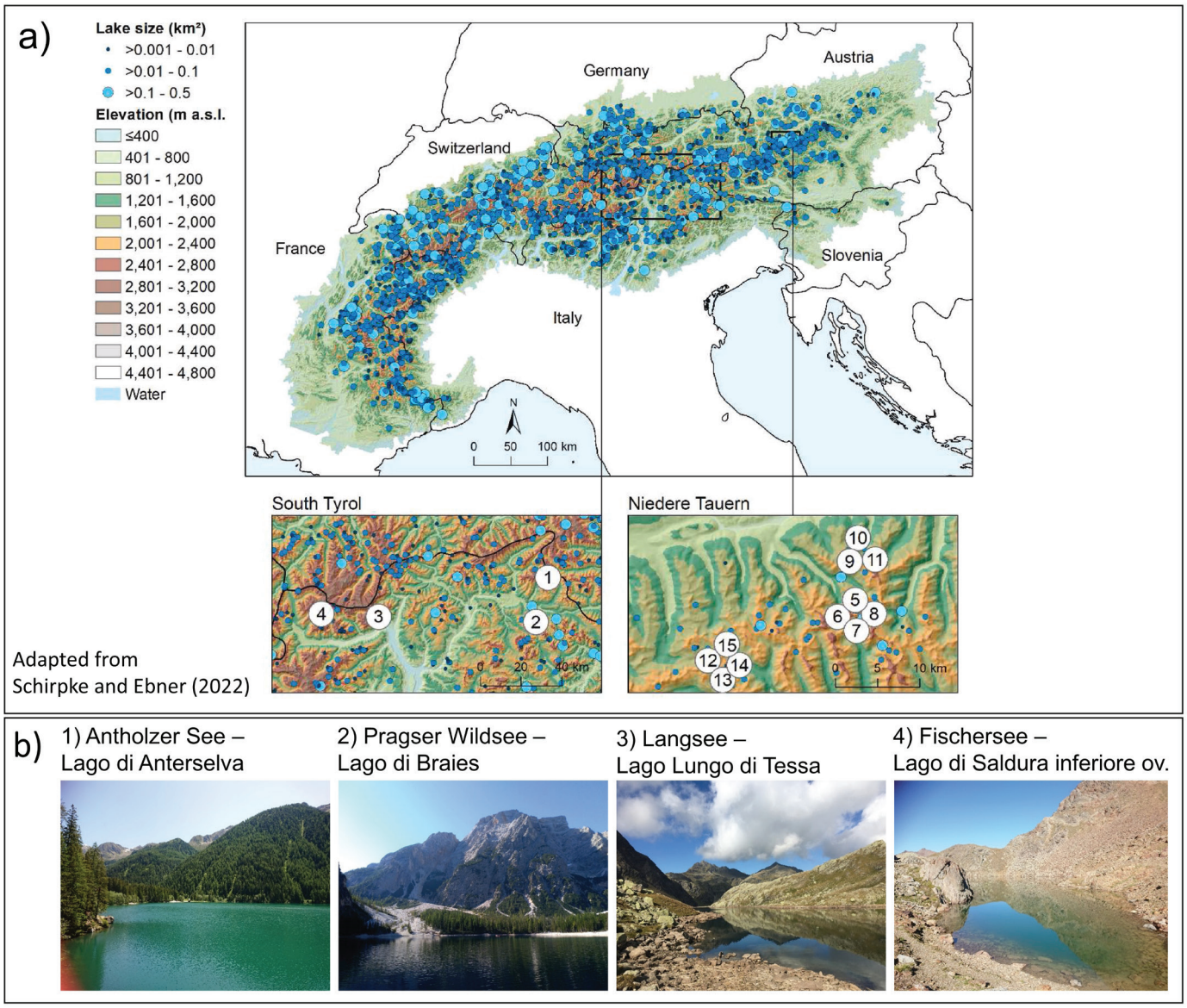

Figure 2. Map of the study area and location of the case study lakes (a, adapted from Schirpke and Ebner, 2022), with exemplary photographs of the case study lakes in the study region South Tyrol/Alto Adige, Italy (b, source: M. Ebner).

tain lakes. In **Article VII** (Schirpke and Ebner, 2022), a further study builds on these findings and focuses on small and natural mountain lakes in the European Alps (N = 2,455). This study pursues a spatially explicit hotspot mapping of nine key indicators for global change-related pressures relevant to ES of mountain lakes to assess scenarios of current and future exposure and potential impacts. To estimate potential changes in ES provision under these hypothetical pressures, the current state of ES provision was compared to a projected future situation (until 2100) for the 15 case study lakes using scenario-based change rates or data projections under the representative concentration pathway 8.5 (RCP8.5) scenario.

3 Key findings

3.1 Mountain lakes offer various ES

The findings of the stakeholder workshop in South Tyrol showed that relevant ES of mountain lakes in this region include provisioning ES, i.e., surface water for non-drinking purposes (*surface water*); regulation and maintenance ES, i.e., maintenance of nursery populations and provision of suitable habitats for plant and animal species (*habitat*); and cultural ES, i.e., aesthetic value (aesthetics), outdoor recreation (*recreation*), entertainment & representation

(*representation*). The broader survey on perceptions of these ES revealed that overall respondents attributed the highest importance to habitat and aesthetics, followed by the other ES (Figure 3a; Ebner et al., 2022a). The qualitative perceptions of respondents provided a more nuanced representation of the benefits associated with these ES (Figure 3b; Ebner et al., 2022a), for example, 'Very pleasuring to see them in the landscape, [they] convey tranquillity and serenity (…)' (related to *aesthetics*) or 'A high biodiversity contributes to the well-being of an ecosystem. High mountain lakes are "islands" of this biodiversity' (related to *habitat*). Additionally, notions of stewardship for mountain lakes were expressed, particularly concerning the commodification of mountain lakes, touristic activities and potential impacts on ecosystem integrity and perceived benefits. For the latter, a quote exemplifies a potential disruption of personal relationships to specific lake places: 'You can see from the example of Pragser Wildsee what advertising does. I detest this example that I loved in my childhood; and now you cannot even visit this jewel. I say less is more' (related to *representation*).

On a larger scale, the analysis of social media data for lakes in the European Alps revealed that spatio-temporal accessibility to lakes significantly influences visitor activities. Higher activity levels were found directly at lake sites and the adjacent areas, gradually decreasing with distance from the lake. Analysing 20,448 photos taken at lake sites indicated that aesthetic and recreational experiences were generally prevalent in CES context. Higher-elevated (mountain) lakes were particularly important for aesthetic experiences and recreational activities near the water, while lower-elevated lakes were associated with water-based activities (Schirpke et al., 2021a).

Beyond identifying relevant CES, combining the approaches provided deeper insights by unveiling various aspects of human interactions with mountain lakes, especially in regard of their natural assets (e.g., visual quality, scenic characteristics), and experienced benefits to subjective well-being (e.g., connection to nature, relaxation). These aspects emerged as key experiences as reflected in various quotes from the study participants, for example, 'Mountain lakes are an eye into the uniqueness of

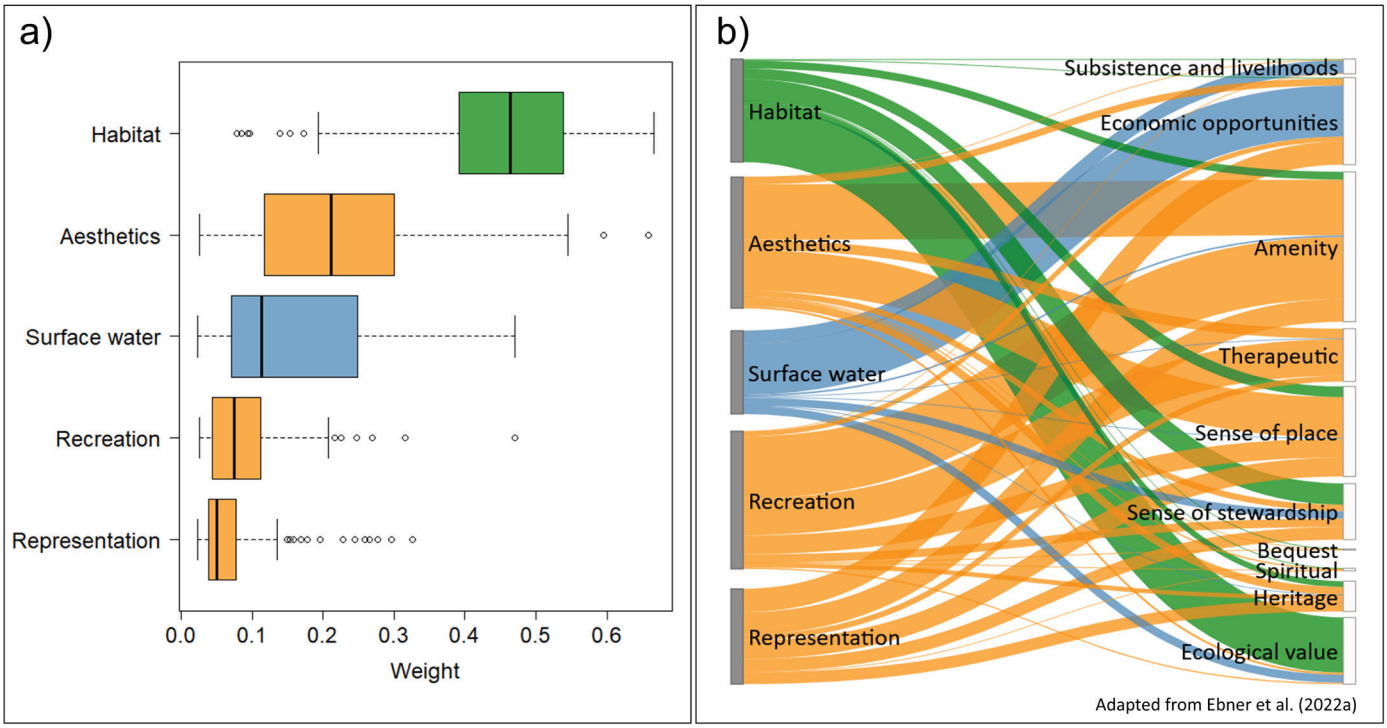

Figure 3. a) Relative weighting by stakeholders of five key ecosystem services of mountain lakes identified in the case study region South Tyrol/Alto Adige, Italy; data source: Ebner et al. (2022a). Perceptions (right) resulting from content analysis of stakeholder-identified contributions to human well-being in connection with these ecosystem services (left). The node sizes represent the proportional frequency of categorized perceptions (N = 1347 perceptions in total, right), adapted from Ebner et al. (2022a). Ecosystem services categories are differentiated by colour: green - regulating, blue- provisioning, orange – cultural.

mountain-nature', 'Nature connectedness is maintained and passed on to the next generations', '… [we] are always reminded of how uniquely beautiful and beneficial our mountain lakes are to our psyche, having a lasting effect', or 'Oasis of tranquillity'. These aspects were corroborated by the quantitative results from the online survey, finding highest importance attributed to the benefit categories of connection to nature, freedom, relaxation, peace, and memories. In sum, comparing the findings between the approaches affirmed the significance of mountain lakes as important landscape features, and nature experiences enabled through active and passive interaction with mountain lakes. This study also identified pressures mainly related to CES use, such as crowding, which could negatively impact the quality of these experiences (e.g., 'the way it is at the moment [at some lakes], you have to take flight during the daytime because it simply gets out of hand with the hikers - you no longer have any peace at the lake …'). The results highlight the importance of employing multiple socio-cultural approaches to enhance knowledge generation in CES assessments, as the combined approaches featured complementary characteristics (Ebner et al., 2022b).

3.2 Mountain lakes differ in their capacity to supply ES

The integration of the findings from the two case study regions South Tyrol and Niedere Tauern revealed overlaps in the stakeholder-based identification of relevant ES, with stakeholders in Niedere Tauern additionally identifying the CES of scientific research (*research*), educational value (*education*) and existence, option or bequest value (*existence*), while *surface water* was not deemed as being relevant in this region. Quantifying the potential supply of these eight ES for the case study lakes based on 28 indicators (Suppl. Mat., Table S1) and comparing the outcomes to socio-ecological variables charac-

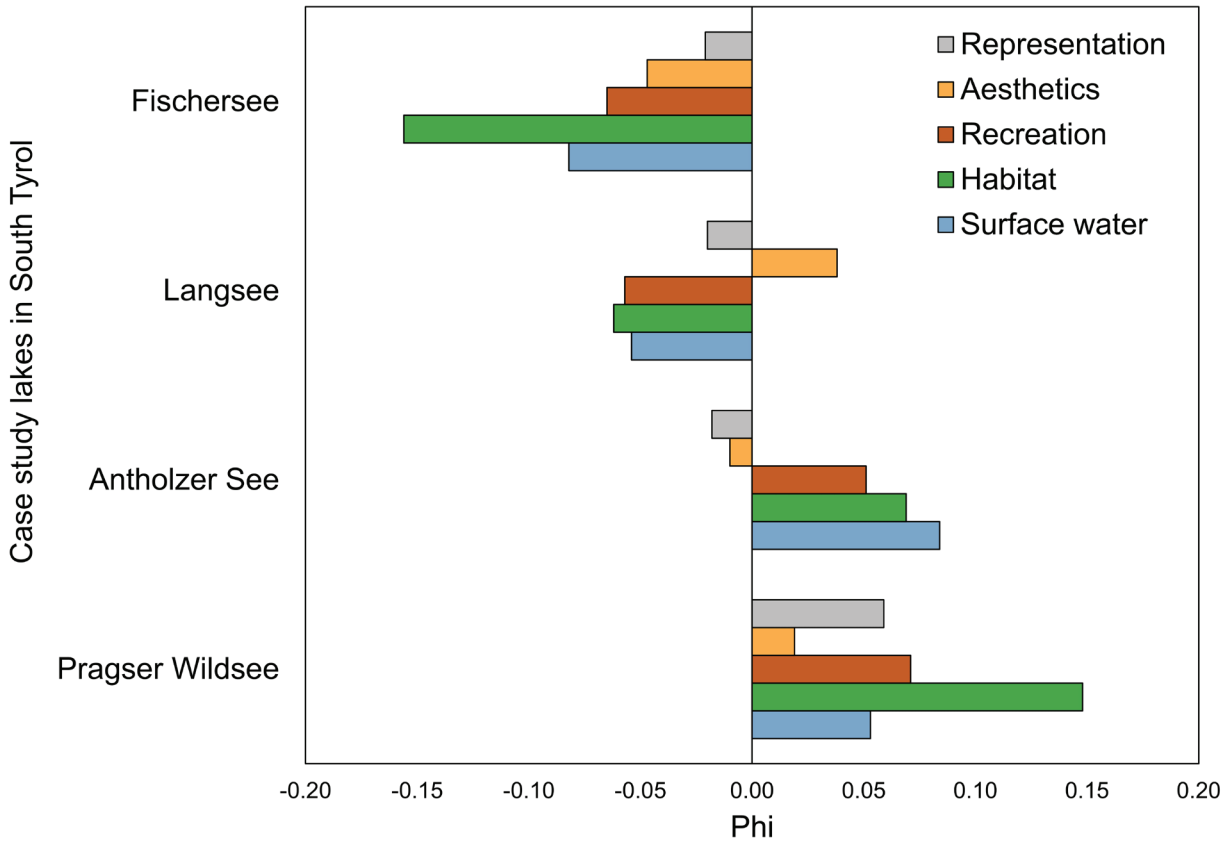

Figure 4. Ecosystem service profiles of four lakes in the case study region South Tyrol/Alto Adige, Italy, depicting the relative level of potential supply of five ecosystem service (unicriterion net flow – Phi, PROMETHEE II), integrating respective weights and indicator values. Positive phi-values represent a positive contribution of the given ecosystem service to the overall provision of an individual lake, compared to the other lakes. Conversely, negative values indicate a negative contribution the overall provision. Data source: Fontana et al. (2023).

terizing the lake's socio-ecological setting revealed that mean ES indices varied across the study lakes: Larger and lower-elevated lakes showed higher potential supply of ES compared to smaller and higher-elevated lakes, especially for *surface water* and *recreation*, with *habitat* and *aesthetics* showing the least difference. Overall, the ES *habitat*, *aesthetics*, and *existence* appeared relatively independent from the socio-ecological context (Schirpke et al., 2021b).

To elaborate on a conceptual framework for the valuation of ES in the context of mountain lakes based on these data, the outcomes of stakeholder consultations in South Tyrol including the weighting of ES and the multi-metric indicators were integrated. The evaluation procedure was tested using data from four mountain lakes in South Tyrol (Figure 1b), providing a basis for a broader discussion on applied aspects. The results regarding the ES provision of mountain lakes were generally consistent with those described above. However, using ES weights as importance coefficients allowed for a more contextual view when comparing individual lakes (Figure 4): Well-accessible and larger lakes (such as Pragser Wildsee and Antholzer See) currently offer, from a quantitative perspective, a higher level of ES in high demand, such as *habitat* and *recreation*. However, smaller, and remote alpine lakes (such as Langsee) also feature a significant level of *aesthetics*, while harbouring very specialized ecosystems of high conservation value as discussed in the stakeholder workshop. This finding suggests, taking also into account the stakeholder workshops, that lakes with different characteristics can play distinct roles in providing ES, and their contributions are not solely determined by their size or accessibility but are to be considered in the context of social demands and perceptions, as well as broader ecological relevance. Overall, the findings underline that the valuation of ES is highly context-dependent. Therefore, factors such as the social-ecological situation, lake characteristics, stakeholder opinions and priorities, potential trade-offs in the assessment or decision-making context, and specifications used in the valuation method necessitate careful consideration (Fontana et al., 2023).

3.3 Pressures and their potential impacts on ES provided by mountain lakes

The DPSIR analysis based on 112 articles revealed several global change-related and direct anthropogenic pressures and related state changes potentially impacting on ES of mountain lakes. These pressures were identified to be driven both large-scale (e.g., climate change, atmospheric depositions) and on regional to local scales (e.g., water use, agricultural activities, tourism). Climate change-related pressures were found to have effects on all ES categories considered, particularly negatively impacting those with high societal relevance, such as *habitat* and *aesthetics*. Changes in water use affecting ecological conditions were also identified to impact on these ES. In contrast, infrastructure developments were found to have the potential to enhance some CES like *recreation* and *education*. The study further differentiated mountain lakes based on their social-ecological characteristics as described above. The findings indicated varying levels of exposure to pressures. Lakes with lower suitability for human use (i.e., high and remote lakes) are more likely to be pressured by large-scale drivers, while lakes with higher suitability for human use may experience pressure primarily from local water use changes (Figure 5). However, the potential co-occurrence of pressures highlights the need for site-specific assessment and management strategies (Ebner et al., 2022c; Schirpke and Ebner, 2022).

Conducting a spatially explicit mapping of nine indicators describing the current and future exposure of 2,455 lakes in the European Alps to the identified pressures revealed that more than half of the considered lakes may be significantly exposed, with spatially clustered differences at regional scales. Spatial analysis revealed that 23.7% of all lakes exhibited above-average exposure levels, with most of them concentrated in the central part of the Alps. On the other hand, lakes with below-average exposure levels were predominant in the south-western (19.3%) and eastern (10.6%) parts of the Alps (Suppl. Mat., Figure S1, Schirpke and Ebner, 2022). Under future scenarios of potential pressures, the findings indicated potential negative changes in *habitat* and *aesthetics*. On the other hand, potential positive changes were found for *recreation*, *research*, and

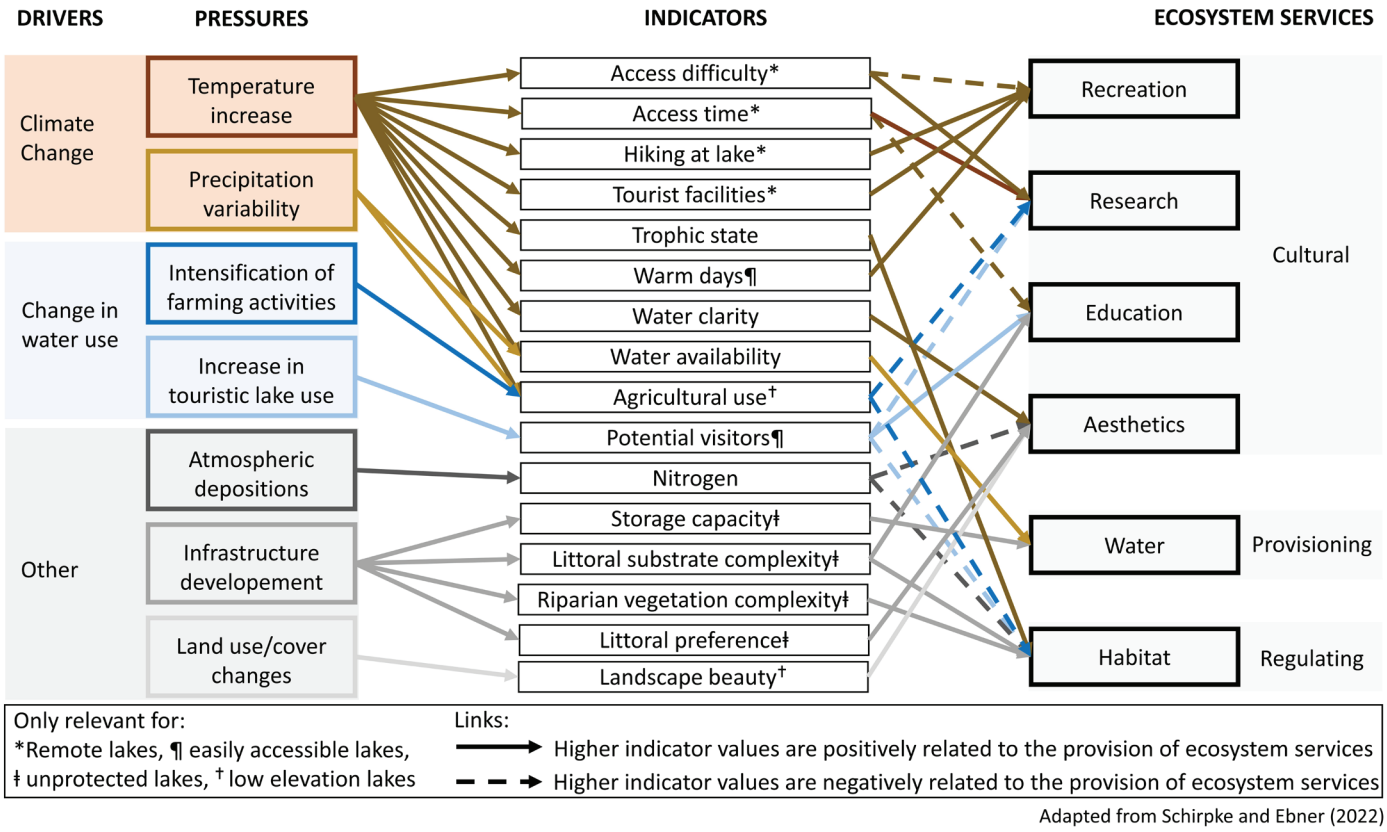

Figure 5. Identified links between global change and anthropogenic pressures (left) and indicators (middle) utilized for the quantification of ecosystem service provision by mountain lakes are illustrated. Certain pressures were exclusive to lakes possessing distinct socio-ecological attributes tied to factors such as accessibility, elevation, and protection status. Adapted from Schirpke and Ebner (2022).

education. The mountain lakes potentially affected the most were located in areas with above-average exposure levels, suggesting the importance of targeted monitoring and management efforts in these areas (Schirpke and Ebner, 2022).

4 Conclusion and outlook

This dissertation has demonstrated that mountain lakes offer a variety of ES with societal relevance, from providing habitats for animals and plants to aesthetic, recreational, and nature experiences that contribute to human well-being. However, these ES can be affected by global change-related pressures as well as human use. Given these emerging challenges, integrating social and ecological perspectives is critical for the sustainable use and protection of these freshwater ecosystems. In this sense, the findings of this dissertation contribute to research on mountain lakes and ES in the several ways:

First, an identification and characterization of relevant ES of mountain lakes and associated benefits to human well-being through empirical investigation was realized, highlighting the appreciation of nature-based experiences and intrinsic values associated with mountain lakes. This suggests that management aiming at protecting mountain lake ecosystems and their natural characteristics could support both ecosystem integrity and human-lake interactions and associated benefits to well-being.

Second, a comprehensive set of indicators was proposed that allows quantitative assessment of ES and potential changes. This standardized set of ES indicators could potentially be adapted and applied in other regional or assessment contexts to support the management of mountain lakes under current or future conditions. Furthermore, relationships between ES of mountain lakes and social-ecological characteristics could be identified, contributing deeper insights into contextual factors associated with ES generation and use. To operationalise the evaluation of

ES provided by mountain lakes, a valuation approach was elaborated that integrates stakeholder perspectives and ES indicators, which could be adapted to different management or decision-making contexts. These approaches can enable the consideration of not only ES but also non-ES criteria that may be essential in the practical context. This can contribute to more comprehensive and well-informed decision-making regarding the management and conservation of mountain lakes, considering the diverse needs and values of stakeholders and the broader social-ecological context.

Third, conceptual links could be established between global change-related and direct anthropogenic pressures exerted on mountain lakes and associated ES, providing a first indication of the societal consequences in terms of potential ES changes, which complements the scientific knowledge on ecological impacts. By mapping the current and future exposure of mountain lakes in the European Alps to these pressures, the findings can aid in identifying specific lake sites or districts that may require particular attention from managers and decision-makers in the face of future developments. This information is essential for developing targeted and effective management strategies to safeguard the ecological integrity and the provision of ES in these sensitive freshwater ecosystems.

To further advance the understanding of ES of mountain lakes more broadly, there are several future research perspectives. These include conducting a more sophisticated investigation of the pathways that link human interactions with freshwaters to well-being and health outcomes, as well as exploring the mediating factors that influence ES and benefit generation, also integrating a deeper limnological perspective. While this dissertation has shed first light on human perception and interaction with mountain lakes, a casual understanding remains to be further elucidated. Furthermore, focus needs to be given to assessing the relationship between ES demand and supply, particularly in the context of potential future changes. To align these outcomes with conservation and water management objectives, a greater consideration to aspects such as biodiversity, ecological functioning, and connectivity, as well as catchment characteristics will be key, which has not been in the focus of this dissertation. Identifying trade-offs or synergies and understanding competing stakeholder priorities will also be important in this vein. Therefore, to support the practical management of mountain lakes the potential of MCA as a decision-support tool could further be tested, which could involve explicit management alternatives or future scenarios. Ultimately, achieving a balanced and equitable consideration of values and objectives under potential future changes, including those related to ES, will require deliberative and transdisciplinary processes. Adopting such approaches could contribute to the sustainable management and protection of mountain lake ecosystems, for which this dissertation presents a first step.

5 About this work

This work is a synthesis of a cumulative dissertation for the degree of Doctor of Philosophy (PhD) entitled "Assessing ecosystem services of mountain lakes: An integrative approach to link socio-cultural perspectives, multi-metric indicators, and global change pressure", submitted to the Faculty of Biology at the Universität Innsbruck in 2022. This synthesis article presents an edited extract from the dissertation. It comprises the results of seven published articles:

- 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, 204A, Article 107678. https://doi.org/10.1016/j.ecolecon.2022.107678
- Ebner, M., Schirpke, U. & Tappeiner, U. (2022). Combining socio-cultural approaches – deeper insights into cultural services of mountain lakes?. Landscape and Urban Planning, 228, Article 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, Article 115606. https://doi.org/10.1016/j.jenvman.2022.115606

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Declaration of Competing Interest

The authors declare no conflict of interest.

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