

Climate response of alpine lakes and impacts on ecosystem services

Supplementary material

Table S1: Socio-ecological characteristics of the 15 study lakes. Table modified from Schirpke et al. (2021a).

Variable	Unit	Group 1		Group 2		Group 3					Group 4					
		Antholzer See—Lago di Anterselva	Pragser Wildsee—Lago di Braies	Langsee—Lago Lungo	Fischersee (Saldurseen)	Unterer Klaffersee	Rauhenbergsee	Oberer Klaffersee	Kapuzinersee	Pfannsee	Obersee	Hüttensee	Twenger Almsee	Oberer Schönalmsee	Unterer Wirpitschsee	Tiefenbachsee
		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 SL	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	609	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

Table S2: Definition and selection of ES used in CLAIMES based on the Common International Classification of Ecosystem Services (CICES, Haines-Young and 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	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	Other biotic characteristics that have a non-use value	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				
				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	
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 S3: 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 and 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 and Kerekes, 1980)	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 and 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 and 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., 2021d)	M, S	index	DEM ¹ , CLC ⁴
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

ES	Indicator	Description	Method Unit		Data Sources
Research	Instagram (+)	Number of posts using the lake names at Instagram	D	n	Instagram ⁷
	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
Education	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
	Littoral substrate complexity (+)	Mean index of major substrate classes ranked by size, with higher complexity supporting the potential presence of observable species (Mocior and 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
Existence	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
	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 and 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).

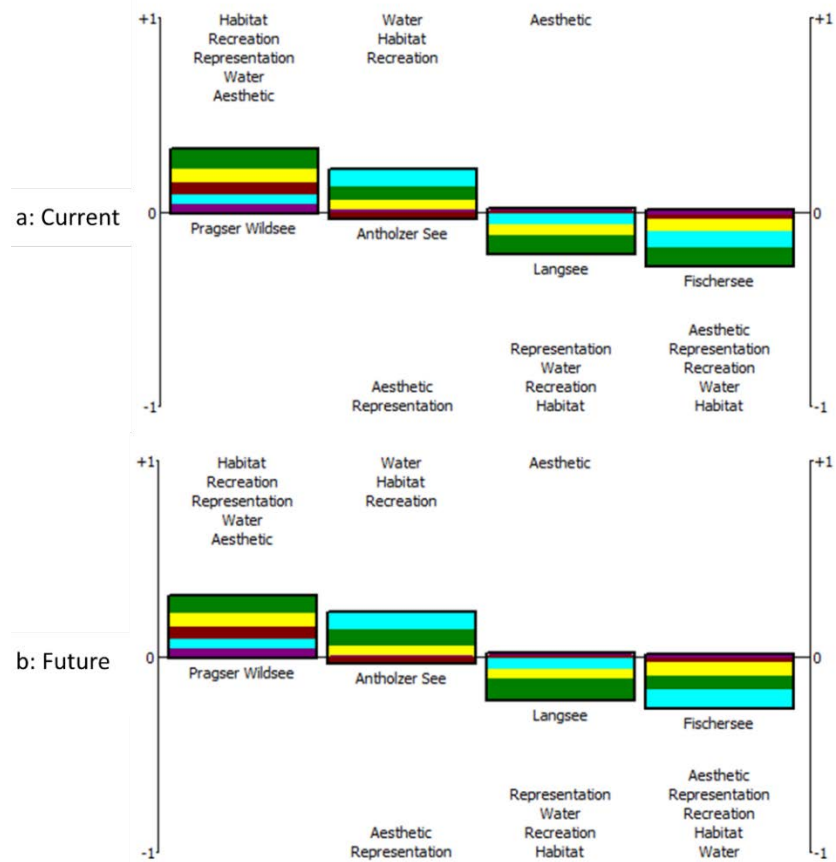


Figure S1: ES profiles (disaggregated outranking flows, phi-value: scaled from -1 to 1) of the mountain lakes in the model region South Tyrol (Italy). The profiles of the mountain lakes for the current ES provision are shown in the upper graph (a) and the future ES provision in the lower graph (b). Positive 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 colours 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 S2: ES profiles (disaggregated outranking flows, phi-value: scaled from -1 to 1) of the mountain lakes in the model 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 colours 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.