Table S1. Detection Limits for Indoor Laboratory Testing Indicators

Testing items	Test method	Instrumentation	Detection limit
Total phosphorus Dissolved phosphorus Orthophosphate	Water and Wastewater Fourth Edition Determination of phosphorus in water quality Phosphomolybdate heteropoly acid Spectrophotometry	T6 New Century UV visible spectrophotometer	0.001
Total nitrogen	HJ 636-2012 Determination of total nitrogen in water quality Alkaline potassium persulfate digestion UV spectrophotometry	T6 New Century UV visible spectrophotometer	0.05
Nitrate nitrogen	Water quality - Determination of nitrate nitrogen Phenol disulfonic acid spectrophotometry HJ/T 346-2007	T6 New Century UV visible spectrophotometer	0.02
Ammonia nitrogen	HJ 535-2009 Water Quality Determination of ammonia nitrogen Hypobromate oxidation method	T6 New Century UV visible spectrophotometer	0.0008
Nitrite	water quality Nitrite nitrogen determination Spectrophotometry GB 7493-87	T6 New Century UV visible spectrophotometer	0.003
Chlorophyll-a	Determination of Chlorophyll a by the State Environmental Protection Administration in 2022 (B) 5.1.5 (1)	T6 New Century UV visible spectrophotometer	/

Table S2. Environmental Factor Measurements in Kuoqionggangri Proglacial Lakes

Site	TN (mg/L)	NO$_3$-N (mg/L)	NO$_2$-N (mg/L)	NH$_3$-N (mg/L)	TP (µg/L)	TDP (µg/L)	PO$_4^3$ (µg/L)	PP (µg/L)	Chla (µg/L)	WT (°C)	pH	EC (µs/cm)	SAL (‰)	TUR (NTU)	DO (mg/L)	Periods
S-NL	0.133	0.063	0.003	0.005	12.6	7.87	4.2	4.73	0.29	2.6	8.1	22	0.022	8	5.08	May
B-NL	0.193	0.048	0.005	0.005	16.03	8.6	5.17	7.43	0.83	1.8	8.1	23	0.023	10	3.14	May
S-EL	0.397	0.124	0.011	0.007	17.27	12.2	9.5	5.07	0.88	8.8	9.2	84	0.041	9.2	4.73	May
B-EL	0.43	0.126	0.013	0.012	19.3	14.23	11.17	5.07	1.53	8	9.3	78	0.041	22	4.1	May
S-NL	0.168	0.093	0.004	0.005	18.67	13	9.17	5.67	0.44	10.2	8.53	12	0.012	58	5.95	August
B-NL	0.24	0.073	0.007	0.009	19.67	15.3	9.7	4.37	1.17	6.8	8.62	10	0.01	96	3.76	August
S-EL	0.52	0.168	0.014	0.013	26.7	19.5	15.6	7.2	1.79	14.6	8.66	66	0.034	64	6.61	August
B-EL	0.59	0.202	0.017	0.012	29.47	20.63	17.6	8.83	2.67	13.8	8.7	76	0.035	110	5.35	August

(Note: "S-NL" denotes the surface layer of proglacial lakes, while "B-NL" refers to the bottom layer. This notation applies similarly throughout the study.)

Table S3. Environmental factors (mean ± standard deviation) at various classification levels of the Kuoqionggangri proglacial lake.

Environment factors	Different lakes			Different layers		Different periods	
	NL	ML	EL	pls	plb	May	August
TN (mg/L)	0.182±0.045	0.308±0.097	0.462±0.059	0.273±0.113	0.370±0.120	0.294±0.099	0.360±0.140

NO$_3$-N (mg/L)	0.069±0.013	0.120±0.025	0.149±0.026	0.117±0.029	0.116±0.042	0.101±0.026	0.135±0.041
NO$_2$-N (mg/L)	0.005±0.001	0.007±0.003	0.014±0.002	0.007±0.004	0.01±0.004	0.008±0.004	0.009±0.004
NH$_3$-N (mg/L)	0.006±0.002	0.008±0.002	0.01±0.002	0.007±0.003	0.009±0.002	0.007±0.002	0.009±0.003
TP (μg/L)	17.24±2.39	19.28±3.42	22.71±4.05	18.61±3.69	20.93±3.83	15.95±1.71	22.89±3.23
TDP (μg/L)	11.03±2.23	12.83±2.78	15.86±3.03	12.28±3.15	14.23±3.03	10.35±1.97	15.86±2.58
PO$_4^{3-}$ (μg/L)	6.86±1.89	9.80±2.81	12.46±2.76	8.95±3.11	10.81±3.16	7.46±2.40	12.29±2.63
PP (μg/L)	6.21±1.22	6.45±1.14	6.85±1.23	6.33±0.97	6.69±1.39	5.61±0.95	7.03±1.27
Chla (μg/L)	0.63±0.34	1.01±0.43	1.69±0.63	0.78±0.42	1.46±0.58	0.79±0.32	1.38±0.67
WT (°C)	3.31±2.81	8.72±2.62	10.78±1.97	8.64±3.87	7.46±3.35	6.89±3.24	10.1±3.44
pH	8.36±0.22	8.16±0.64	8.91±0.25	8.22±0.56	8.59±0.54	8.19±0.76	8.65±0.38
EC (μg/cm)	17.9±5.19	69.26±15.57	84.42±12.15	63.48±27.63	60.23±27.49	74.62±23.17	47.94±23.70
SAL (‰)	0.02±0.005	0.03±0.008	0.04±0.005	0.033±0.001	0.031±0.001	0.037±0.006	0.024±0.009
TUR (NTU)	38.05±29.1	109.6±74.56	40.93±31.23	52.07±38.58	99.82±80.73	35.32±27.94	129.81±77.5
DO (mg/L)	4.51±1.11	4.57±0.8	5.19±0.61	5.30±0.63	4.13±0.70	4.25±0.68	5.17±0.89

Table S4. Mann-Whitney U test and Wilcoxon Signed Rank Test results of environmental factors between different groups.

Environment factors	Different lakes			Different layers	Different periods
	NL-ML	NL-EL	ML-EL	Pls-plb	May-August
TN	0.000	0.000	0.000	0.032	0.020
NO$_3$_N	0.000	0.000	0.015	0.853	0.000
NO$_2$_N	0.002	0.000	0.001	0.020	0.051
NH$_3$_N	0.015	0.000	0.006	0.016	0.001
TP	0.130	0.009	0.015	0.137	0.000
TDP	0.034	0.009	0.034	0.094	0.000
PO$_4^{3-}$	0.002	0.000	0.023	0.163	0.000
PP	0.363	0.114	0.287	0.852	0.002
Chla	0.034	0.000	0.015	0.000	0.001
WT	0.000	0.002	0.288	0.026	0.000
pH	0.544	0.000	0.015	0.020	0.000
EC	0.000	0.000	0.762	0.577	0.000
SAL	0.000	0.000	0.225	0.780	0.000
TUR	0.002	0.295	0.002	0.026	0.000
DO	0.363	0.116	0.130	0.000	0.000

(*<0.05,**<0.01,***<0.001)

Table S5. SIMPER analysis of eukaryotic microbial community structure similarity across different spatial and temporal contexts.

classification	Groups	Major contributor taxa	Contribution rate (%)
		Bacillariophyta	35.12
	G(NL-ML)	*Chlorophyta*	34.73
		Gastrotricha	6.48
Different lakes		*Ciliophora*	34.14
	G(ML-EL)	*Chlorophyta*	30.21
		Bacillariophyta	6.35
	G(NL-EL)	*Cryptomycota*	34.84

		Chlorophyta	32.41
		Apicomplexa	5.39
		Chlorophyta	34.71
Different layers	G(pls-plb)	Cercozoa	32.18
		Nematoda	6.13

Table S6. Key topological characteristics of eukaryotic microbial symbiotic networks.

Network topology indicators	NL	ML	EL	pls	plb	May	August
Number of connections	4392	4774	18262	7245	7014	4314	9236
Average degree	43.059	32.699	94.377	41.758	37.013	28.196	45.054
Network diameter	4	6	5	6	6	7	6
Mean path length	2.029	2.477	2.055	2.571	2.508	2.73	2.55
Density of figure	0.212	0.112	0.245	0.121	0.098	0.092	0.11
Modularity coefficient	1.419	0.655	0.214	0.5	0.795	0.786	0.64
Mean clustering coefficient	0.603	0.61	0.671	0.672	0.621	0.645	0.626
Positive correlation (%)	64.32	81.72	80.15	95.39	88.34	90.09	90.02
Negative correlation (%)	35.68	18.28	19.85	4.61	11.66	9.81	9.98

Table S7. Mantel test results for correlations between environmental variables.

/	Chla	TN	NO$_3$-N	NO$_2$-N	NH$_3$-N	TP	TDP	PO$_4^{3-}$	PP	WT	pH	EC	SAL	TUR	DO
Chla	0	0.79	0.66	0.83	0.86	0.78	0.80	0.77	0.38	0.41	0.71	0.01	-0.01	0.58	-0.02
TN		0	0.85	0.63	0.83	0.76	0.77	0.85	0.33	0.57	0.65	0.25	0.20	0.45	0.10
NO$_3$-N			0	0.59	0.76	0.82	0.83	0.91	0.46	0.86	0.60	0.17	0.09	0.59	0.48
NO$_2$-N				0	0.67	0.55	0.60	0.61	0.28	0.42	0.60	0.33	0.30	0.33	0.19
NH$_3$-N					0	0.74	0.79	0.79	0.12	0.48	0.70	0.02	0.03	0.52	0.10
TP						0	0.97	0.94	0.59	0.75	0.74	-0.28	-0.37	0.70	0.37
TDP							0	0.96	0.46	0.76	0.72	-0.20	-0.32	0.76	0.37
PO$_4^{3-}$								0	0.45	0.79	0.67	-0.04	-0.17	0.72	0.39
PP									0	0.59	0.31	-0.14	-0.17	0.32	0.33
WT										0	0.40	0.07	-0.08	0.59	0.75
pH											0	-0.28	-0.27	0.39	0.16
EC												0	0.95	-0.17	-0.06
SAL													0	-0.38	-0.17
TUR														0	0.16
DO															0

Table S8. Mantel test results for correlations between environmental variables and βNTI. Significant environmental factors (p < 0.05) are highlighted in bold.

Environment factors	NL		ML		EL		pls		plb	
	r	p	r	p	r	p	r	p	r	p
TN (mg/L)	0.1077	0.09	0.0016	0.43	-0.0405	0.588	0.0016	0.433	0.0817	0.126
NO$_3$-N (mg/L)	-0.0363	0.591	**0.2683**	**0.002**	-0.0884	0.878	**0.2683**	**0.005**	-0.0721	0.799
NO$_2$-N (mg/L)	-0.0284	0.601	-0.0420	0.701	-0.0168	0.526	-0.0420	0.713	-0.0308	0.619
NH$_3$-N (mg/L)	0.0564	0.188	0.0410	0.276	0.0780	0.159	0.0410	0.237	0.0763	0.113

TP (µg/L)	-0.1029	0.899	-0.1344	0.982	-0.0875	0.915	-0.1344	0.984	-0.1304	0.983
TDP (µg/L)	-0.1133	0.956	0.0224	0.353	-0.1049	0.974	0.0224	0.349	-0.1447	0.994
PO$_4^{3-}$ (µg/L)	-0.1221	0.968	0.0259	0.331	-0.0859	0.864	0.0259	0.358	-0.1464	0.99
PP (µg/L)	-0.1084	0.962	0.0462	0.255	-0.0835	0.895	0.0462	0.259	-0.1335	0.99
Chla (µg/L)	0.0296	0.284	-0.1338	0.972	-0.0557	0.679	-0.1338	0.971	0.0125	0.37
WT (°C)	-0.1366	0.976	**0.3287**	**0.003**	-0.0312	0.524	**0.3287**	**0.003**	-0.1390	0.963
pH	-0.0938	0.858	-0.1387	0.982	0.0654	0.25	-0.1387	0.979	-0.0560	0.727
EC (µg/cm)	**0.2348**	**0.002**	**0.3481**	**0.001**	-0.0926	0.982	**0.3481**	**0.001**	**0.1841**	**0.009**
SAL (‰)	**0.2539**	**0.002**	0.1822	0.007	**-0.0166**	**0.0498**	0.1822	0.005	**0.2327**	**0.005**
TUR (NTU)	0.0048	0.416	-0.0716	0.696	0.0072	0.306	-0.0716	0.679	-0.0050	0.46
DO (mg/L)	0.0706	0.216	**0.2769**	**0.001**	0.0219	0.353	**0.2769**	**0.001**	0.0739	0.191

Fig. S1.
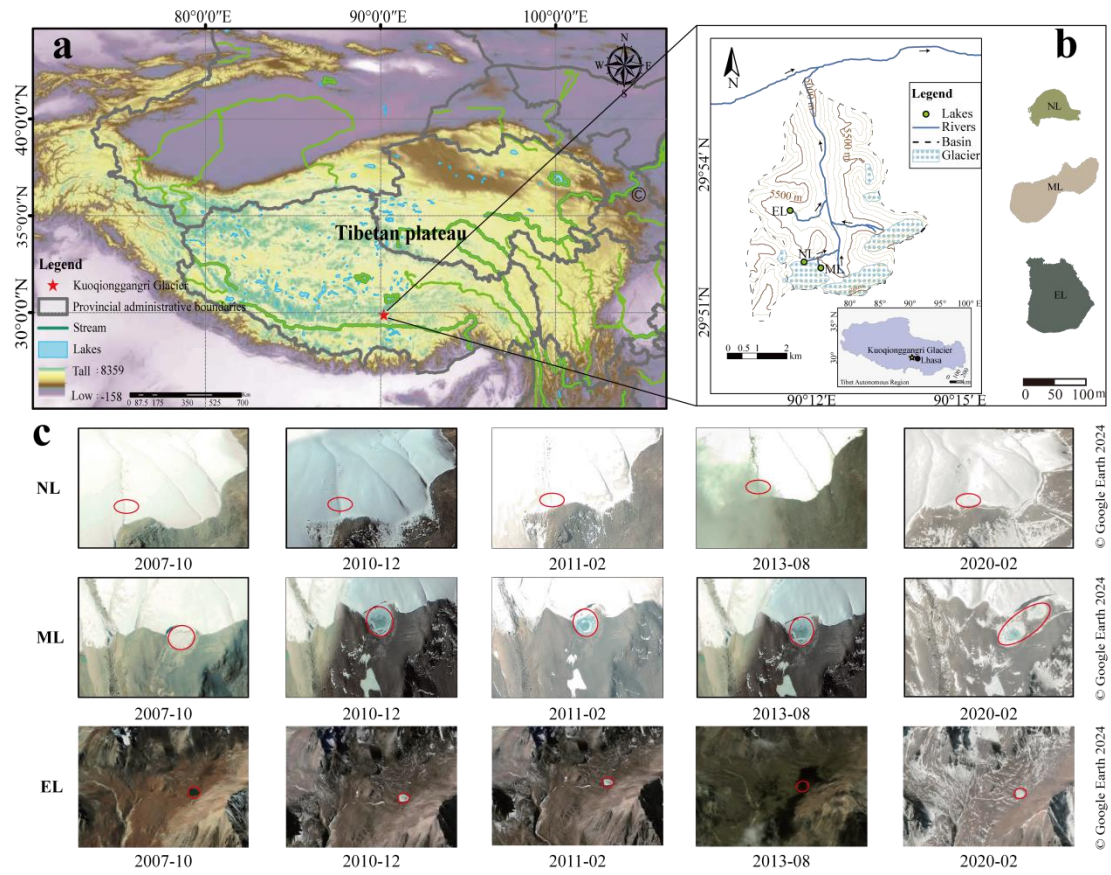
Fig. S1. Study area location and images showing changes in the three proglacial lakes (highlighted with red circles) sourced from © Google Earth.

Fig. S2.
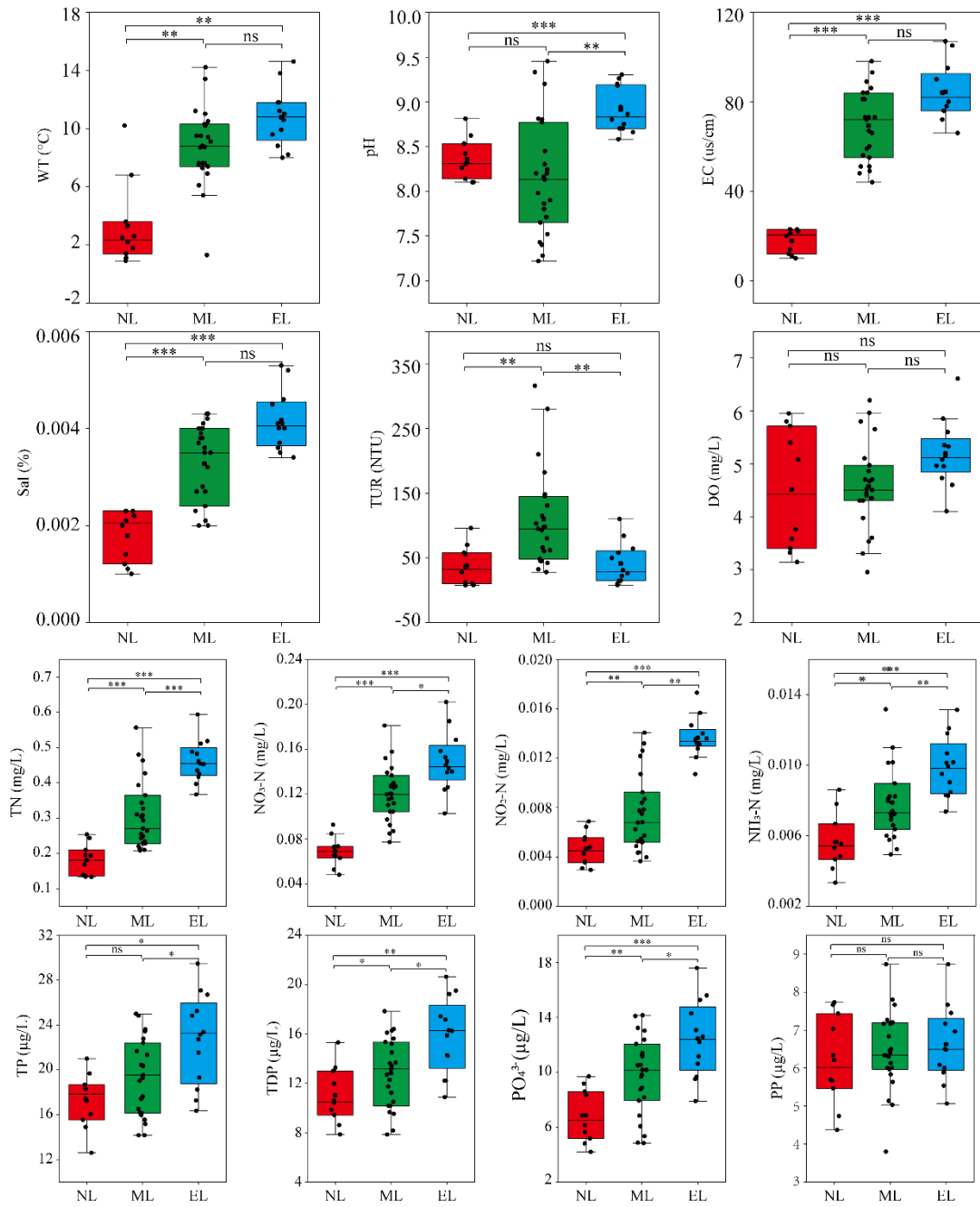
Fig. S2. Environmental characteristics of proglacial lakes across different historical development periods.
(Note: * *, extremely significant difference; *, significant difference; ns, no statistically significant)

Fig. S3.
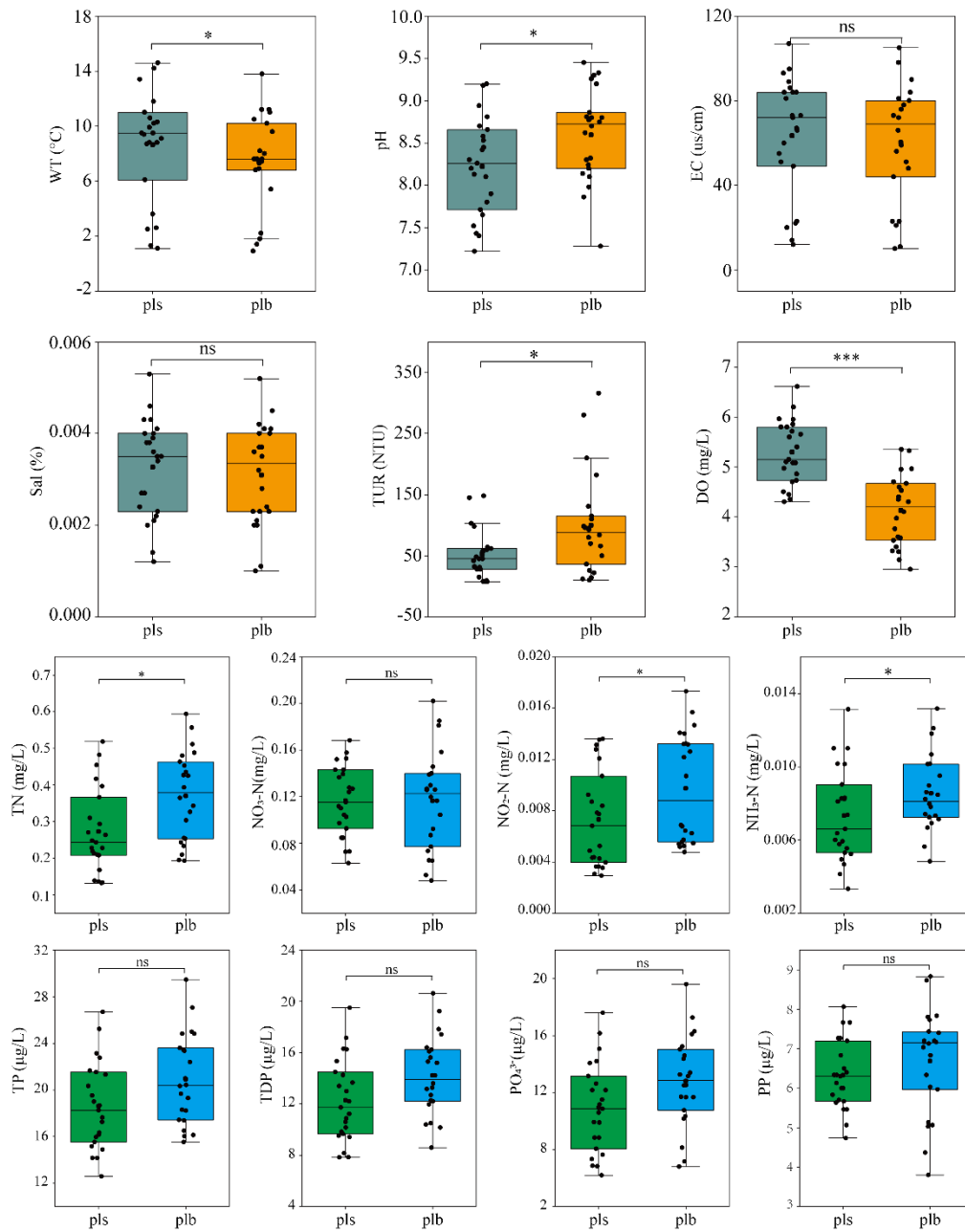
Fig. S3. Characteristics of Environmental Factors in the Surface and Bottom Layers of Proglacial Lakes.
(Note: * *, extremely significant difference; *, significant difference; ns, no statistically significant)

Fig. S4.
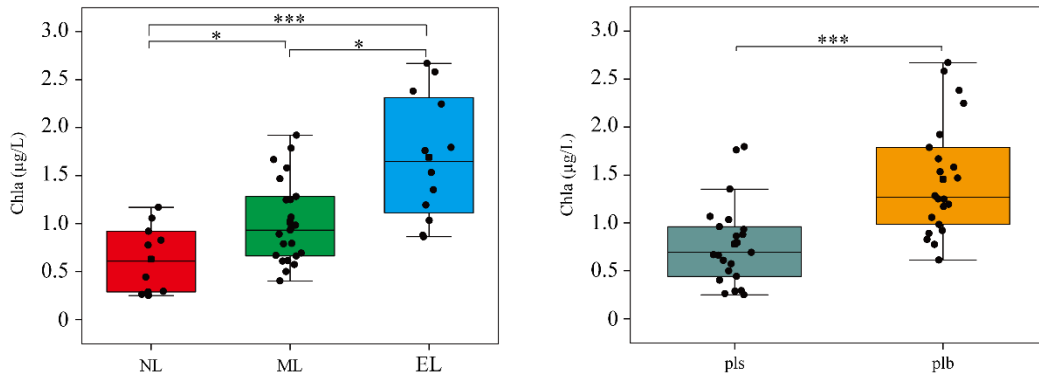
Fig. S4. Chlorophyll-a (Chla) Characteristics in Different Proglacial Lakes and Between Surface and

Bottom Layers.

(Note: * *, extremely significant difference; *, significant difference)

Fig. S5.
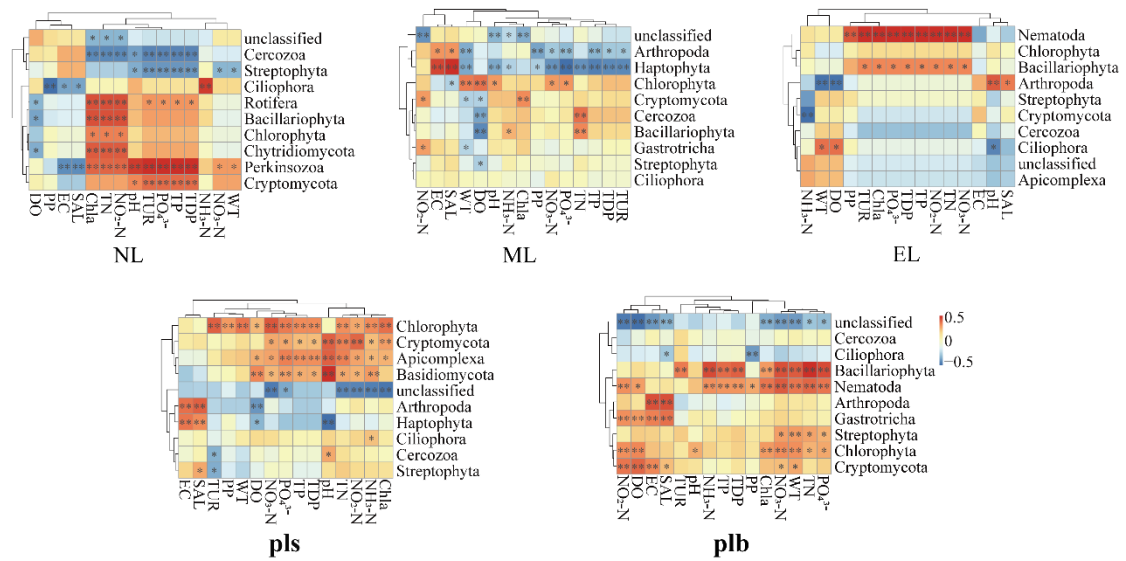
Fig. S5. Correlation Analysis Between Key Species and Environmental Factors in Proglacial Lakes.