Supplementary Information

Varying ecological successions in lakes subdivided by volcanic eruption at Akan Caldera, Japan

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Lake	Elevation	Boundary length	LA	Shoreline development	Maximum depth	Mean depth	LV	Residence time	LWA	TWA	AWA
	(m)	(km)	(km^2)		(m)	(m)	(km^3)	(year)	(km^2)	(km^2)	(km^2)
L. Akan	420	30.3	13.261	3.3	44.8	15.8	0.21	1.0818	100.386	113.647	161.8
L. Taro	413	0.5	0.013	1.8	7.8	2.2	2.87763E-05	0.0001	0.070	0.083	163.0
L. Jiro	416	0.6	0.017	1.8	2.7	1.5	2.50968E-05	0.0001	1.149	1.166	162.9
L. Penke	511	3.9	0.331	2.7	39.4	14.3	0.0047188	0.4080	7.448	7.779	9.6
L. Panke	451	12.5	2.859	2.9	54	22.4	0.0641587	1.1112	35.616	38.476	48.1
P. Kyodai-kita	554	0.2	0.002	1.8	4.8	2.5	0.0000052	0.0023	0.386	0.388	1.9
P. Kyodai-naka	555	0.3	0.006	1.5	6	3.7	0.0000230	0.0130	1.385	1.392	1.5
P. Kyodai-minami	559	0.2	0.002	1.6	3.8	2.2	0.0000042	0.0439	0.078	0.080	0.1
P. Hyotan	447	2.1	0.094	2.7	4.4	1.3	0.0001204	0.0059	16.846	16.939	16.9
P. Junsai	403	0.4	0.011	1.5	5.7	2.4	0.0000268	0.0665	0.325	0.336	0.3

Table S1. Topography of Akan Caldera Lakes. Details of lake morphology were analyzed based on the lake chart drawn by depth sounding performed in October, 2014 as well as current topographic information. LA: lake area, LV: lake volume, LWA: land watershed area, TWA: total watershed area, AWA: accumulated watershed area.

Lake	pH	DO	EC	SS	Chl-a	DOC	COD	TP	TN
		(mg l^{-1})	(mS m^{-1})	(mg l^{-1})	(μg 1^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})
L. Akan	7.9	12.7	25.1	0.8	2.9	1.0	2.6	0.026	0.191
L. Taro	7.5	10.4	24.2	1.0	1.7	0.8	2.5	0.022	0.194
L. Jiro	7.1	8.7	24.0	0.7	0.6	0.4	1.0	0.036	0.235
L. Penke	7.6	11.1	5.8	0.4	1.3	0.7	1.6	0.006	0.081
L. Panke	7.4	12.7	8.3	0.4	1.0	0.6	1.1	0.007	0.074
P. Kyodai-kita	7.2	11.8	6.5	1.6	4.0	1.9	4.4	0.012	0.203
P. Kyodai-naka	7.2	12.3	5.8	0.2	0.9	0.9	1.6	0.013	0.113
P. Kyodai-minami	7.1	11.9	3.3	1.1	3.2	2.2	4.7	0.011	0.204
P. Hyotan	7.8	13.2	5.2	2.4	10.1	1.2	3.4	0.017	0.188
P. Junsai	6.9	10.3	3.0	2.4	12.5	7.1	15.0	0.014	0.438

Table S2. Water quality of the Akan Caldera Lakes. Data are shown as the mean of the data surveyed in October-November 2013 and July 2014. Observation and water sampling were performed at the lake center. DO: dissolved oxygen, EC: electrical conductivity, SS: suspended solids, Chl-a: Chlorophyll-a, DOC: dissolved organic carbon, COD: chemical oxygen demand, TP: total phosphorus, TN: total nitrogen.

Lake	Number of Species			
	Submerged	Floating-leaved	Free-floating	Total
L. Akan	9	1	0	10
L. Taro	1	0	0	1
L. Jiro	0	0	0	0
L. Penke	7	0	0	7
L. Panke	13	0	0	13
P. Kyodai-kita	0	0	0	0
P. Kyodai-naka	2	0	0	2
P. Kyodai-minami	0	0	0	0
P. Hyotan	1	0	0	1
P. Junsai	0	4	2	6

Table S3. Number of species of macrophyte observed in Akan Caldera Lakes. In total, 21 species of macrophytes were comprehensively collected by SCUBA diving or snorkeling in August and October 2012, October–November 2013, and July 2014.

Correlation coefficient (r)

Statistical significance (*p*)

	Topographic characters																Water quality									Number of macrophyte species			
	Elevation	Boundary length	LA	Maximum depth	LV	LWA	Mean depth	Shoreline development	Residence time	TWA	AWA	LWA/LA	LWA/LV	TWA/LA	TWA/LV	AWA/LA	AWA/LV	pH	EC	DO	SS	Chl-a	DOC	COD	TP	TN	Submerged	Floating-leaved	Free-floating	Total
Elevation	---	-0.324	-0.311	-0.167	-0.316	-0.336	-0.112	-0.301	-0.249	-0.333	-0.654	0.530	0.200	0.530	0.199	-0.444	-0.455	-0.176	-0.581	0.351	-0.282	-0.300	-0.192	-0.229	-0.560	-0.430	-0.152	-0.449	-0.379	-0.322
Boundary length	n.s.	---	0.980	0.756	0.991	0.991	0.714	0.791	0.879	0.992	0.445	-0.400	-0.361	-0.400	-0.363	-0.265	-0.263	0.653	0.449	0.416	-0.232	-0.166	-0.215	-0.213	0.165	-0.206	0.735	0.058	-0.172	0.720
LA	n.s.	***	---	0.626	0.996	0.981	0.575	0.690	0.775	0.985	0.484	-0.353	-0.332	-0.353	-0.334	-0.221	-0.220	0.603	0.501	0.363	-0.179	-0.130	-0.159	-0.154	0.264	-0.099	0.595	0.105	-0.139	0.598
Maximum depth	n.s.	*	n.s.	---	0.675	0.690	0.991	0.821	0.950	0.684	0.164	-0.518	-0.538	-0.518	-0.540	-0.327	-0.339	0.573	0.146	0.369	-0.468	-0.346	-0.306	-0.327	-0.289	-0.517	0.983	-0.083	-0.203	0.924
LV	n.s.	***	***	*	---	0.987	0.632	0.713	0.824	0.990	0.474	-0.374	-0.356	-0.374	-0.358	-0.233	-0.232	0.598	0.485	0.384	-0.206	-0.153	-0.174	-0.171	0.228	-0.133	0.652	0.092	-0.146	0.651
LWA	n.s.	***	*	*	***	---	0.644	0.797	0.830	1.000	0.436	-0.324	-0.249	-0.324	-0.250	-0.279	-0.274	0.689	0.440	0.463	-0.149	-0.092	-0.211	-0.202	0.204	-0.176	0.676	0.055	-0.178	0.660
Mean depth	n.s.	*	n.s.	***	n.s.	*	---	0.773	0.948	0.637	0.105	-0.475	-0.527	-0.475	-0.530	-0.359	-0.363	0.496	0.085	0.384	-0.499	-0.370	-0.301	-0.331	-0.334	-0.539	0.991	-0.098	-0.201	0.928
Shoreline development	n.s.	**	*	**	*	**	**	---	0.812	0.786	0.254	-0.303	-0.089	-0.303	-0.091	-0.298	-0.296	0.885	0.236	0.517	-0.145	-0.100	-0.418	-0.398	-0.052	-0.470	0.808	-0.192	-0.341	0.703
Residence time	n.s.	***	**	***	**	**	***	**	---	0.825	0.257	-0.501	-0.498	-0.501	-0.501	-0.339	-0.337	0.541	0.234	0.425	-0.382	-0.274	-0.241	-0.261	-0.140	-0.388	0.953	-0.004	-0.161	0.921
TWA	n.s.	***	***	*	***	***	*	**	**	---	0.442	-0.328	-0.259	-0.328	-0.261	-0.272	-0.268	0.680	0.448	0.452	-0.152	-0.097	-0.205	-0.197	0.211	-0.167	0.668	0.061	-0.174	0.654
AWA	*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	---	-0.462	-0.314	-0.462	-0.313	0.732	0.741	0.283	0.991	-0.395	-0.271	-0.388	-0.392	-0.363	0.820	0.005	0.148	-0.141	-0.265	0.073
LWA/LA	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	---	0.839	1.000	0.838	-0.240	-0.213	-0.114	-0.390	0.309	0.176	0.133	-0.113	-0.114	-0.080	-0.121	-0.433	-0.270	-0.199	-0.529
LWA/LV	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	**	---	0.839	1.000	-0.136	-0.089	0.091	-0.292	0.289	0.486	0.387	-0.109	-0.075	0.099	0.010	-0.465	-0.248	-0.181	-0.552
TWA/LA	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	**	---	0.838	-0.240	-0.213	-0.114	-0.390	0.309	0.176	0.133	-0.113	-0.114	-0.080	-0.121	-0.433	-0.270	-0.199	-0.529
TWA/LV	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	**	***	**	---	-0.134	-0.086	0.090	-0.290	0.286	0.487	0.388	-0.108	-0.074	0.102	0.012	-0.468	-0.248	-0.180	-0.554
AWA/LA	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	*	n.s.	n.s.	n.s.	n.s.	---	0.975	-0.149	0.720	-0.692	-0.151	-0.331	-0.278	-0.247	0.665	0.100	-0.329	-0.220	-0.176	-0.408
AWA/LV	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	*	n.s.	n.s.	n.s.	n.s.	***	---	-0.205	0.726	-0.763	-0.166	-0.341	-0.291	-0.266	0.751	0.123	-0.338	-0.218	-0.175	-0.417
pH	n.s.	*	n.s.	n.s.	n.s.	*	n.s.	***	n.s.	*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	---	0.294	0.569	-0.090	-0.107	-0.533	-0.490	0.007	-0.517	0.555	-0.362	-0.507	0.384
EC	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	***	n.s.	n.s.	n.s.	n.s.	*	*	n.s.	---	-0.384	-0.303	-0.430	-0.424	-0.395	0.821	-0.025	0.124	-0.175	-0.308	0.035
DO	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	*	*	n.s.	n.s.	---	0.048	0.113	-0.186	-0.185	-0.515	-0.445	0.436	-0.226	-0.301	0.330
SS	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	---	0.940	0.667	0.720	0.015	0.729	-0.500	0.550	0.579	-0.269
Chl-a	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	***	---	0.783	0.818	-0.115	0.732	-0.370	0.713	0.735	-0.076
DOC	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	*	**	---	0.996	-0.198	0.864	-0.358	0.927	0.958	0.023
COD	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	*	**	***	---	-0.168	0.884	-0.384	0.923	0.951	-0.004
TP	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	**	n.s.	n.s.	n.s.	n.s.	*	*	n.s.	**	n.s.	n.s.	n.s.	n.s.	n.s.	---	0.297	-0.290	-0.023	-0.111	-0.308
TN	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	*	*	**	***	n.s.	---	-0.575	0.837	0.840	-0.231
Submerged	n.s.	*	n.s.	***	*	*	***	**	***	*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	---	-0.133	-0.245	0.919
Floating-leaved	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	*	***	***	n.s.	**	n.s.	---	0.969	0.260
Free-floating	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	*	***	***	n.s.	**	n.s.	***	---	0.149
Total	n.s.	*	n.s.	***	*	*	***	*	***	*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	***	n.s.	n.s.	---

Table S4. Correlation matrix of topography, water quality and number of species of aquatic macrophytes in Akan Caldera Lakes. Correlation coefficients and statistical significance are listed at the top right and at the bottom left of the table, respectively. LA: Lake area, LV: Lake volume, LWA: Land watershed area, TWA: Total watershed area, AWA: Accumulated watershed area, DO: Dissolved oxygen, EC: Electrical conductivity, SS: Suspended solids, Chl-a: Chlorophyll-a, DOC: Dissolved organic carbon, COD: Chemical oxygen demand, TP: Total phosphorus, TN: Total nitrogen, ***: $p < 0.001$, **: $p < 0.01$, *: $p < 0.05$, n.s.: not significant.

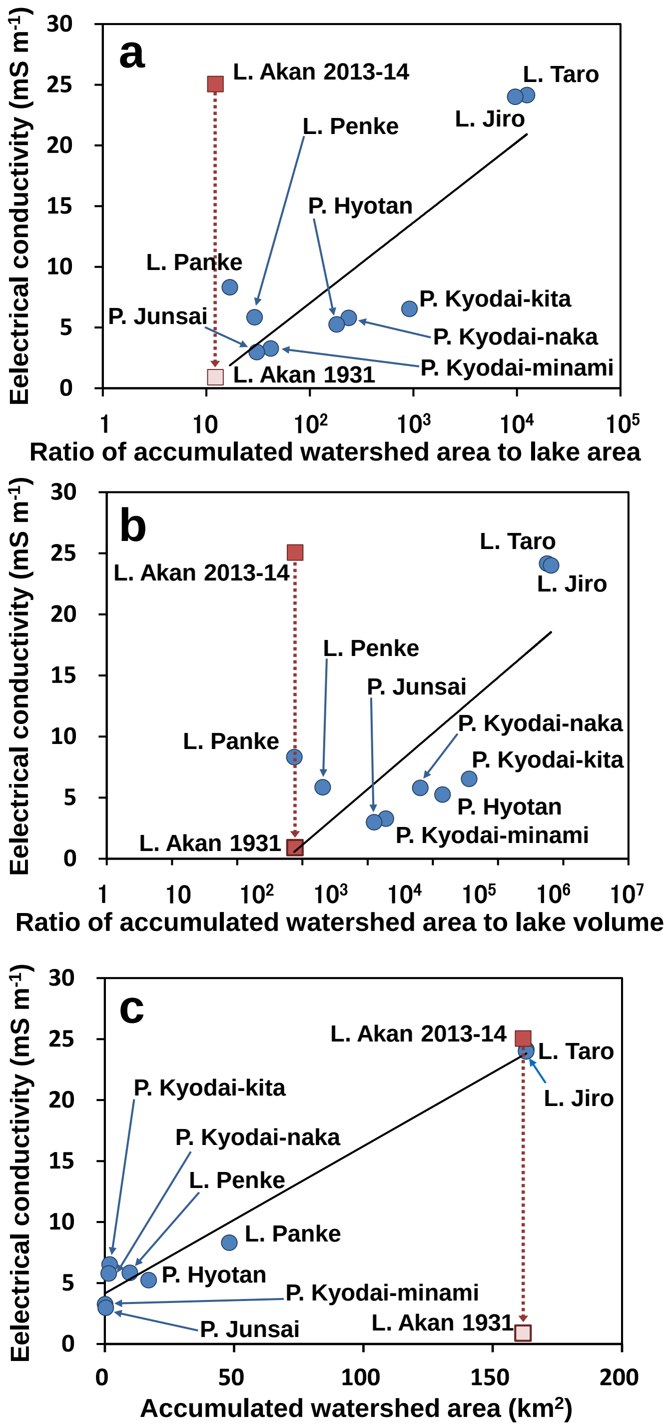

Figure S1. Estimation of electrical conductivity (EC) in Lake Akan before eutrophication. Since phosphorus concentration in Lake Akan was estimated to be significantly lower before eutrophication in the second half of the 20th century (Fig. 3), EC showing a high correlation with total phosphorus (TP) was also examined.

The EC for 1931 was calculated at 0.933 mS m^{-1} by substituting the estimated phosphorus concentration for 1931 (0.004 mg l^{-1}) into the regression formula for EC and TP (y = 819.023x - 2.343). Each regression line in the graphs is drawn for nine lakes of Akan Caldera Lakes (blue circles) except for Lake Akan. In **(a)** relationship between ratio of accumulated watershed area (AWA) to lake area and EC, and in **(b)** relationship between ratio of AWA to lake volume and EC, the 1931 estimate of EC for Lake Akan (light red square) is significantly lower than the 2013–14 EC data (dark red square), and is close to the regression lines, similar to the case of phosphorus in Fig. 3. Conversely, in **(c)** the relationship between AWA and EC, the same 1931 estimate is distant from the regression line, as in the case of phosphorus.

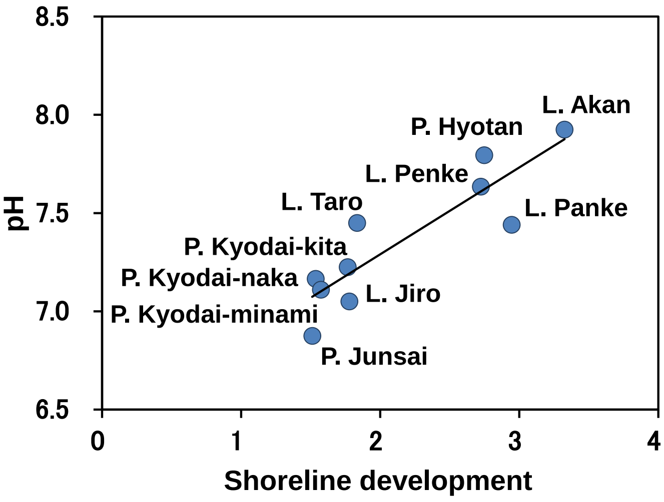

Figure S2. Relationship between shoreline development and pH in Akan Caldera Lakes.

Despite the lakes having a rich diversity of lake basin sizes (Supplementary Table S1 online) and water qualities including trophic levels (Supplementary Table S2 online), shoreline development, a degree of flexion of shoreline, is strongly correlated with lake water pH (Table 1).

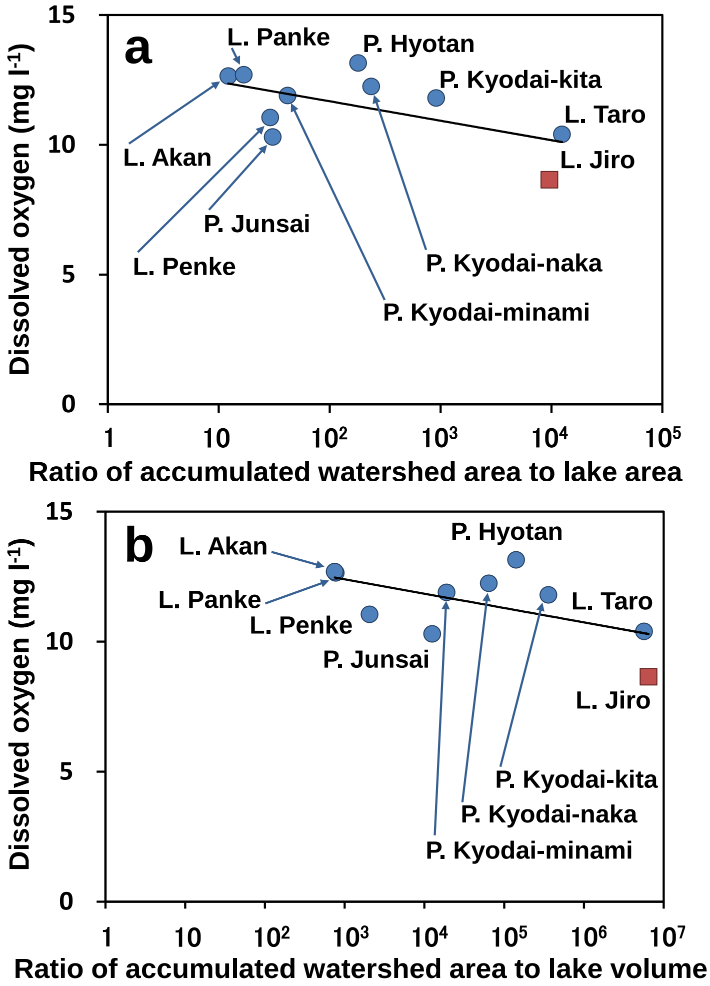

Figure S3. Relationships **(a)** between ratios of accumulated watershed area (AWA) to lake area and dissolved oxygen (DO), and **(b)** between ratios of AWA to lake volume and DO. In spite of the high correlation coefficients (Table 1), each regression line may not indicate an environmental gradient of DO, because its slight negative slope is given by the uniquely low DO data for Lake Jiro (red square) with a relatively heterogeneous water quality (Supplementary Table S2 online).