Supplementary Material: Seasonal dynamics of eutrophication in human-impacted rivers

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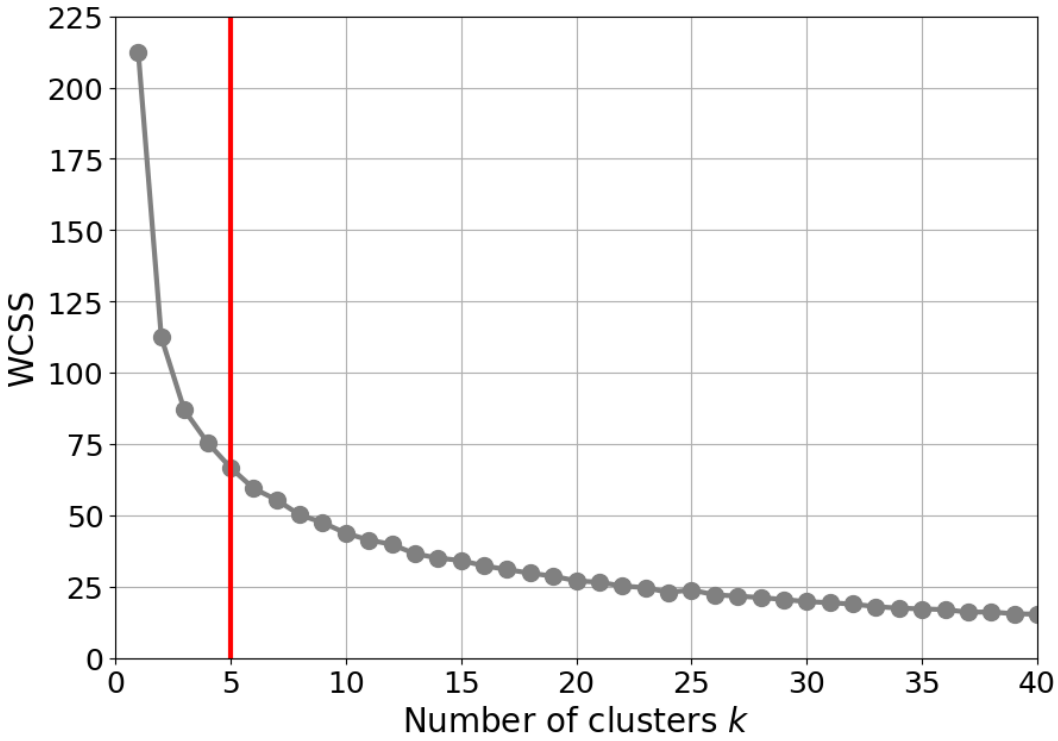

Figure S1. Elbow plot showing the within-cluster sum of squares (WCSS) for different values number of clusters (k). By visual inspection of the plot, we decided for $k = 5$ as the optimal number of clusters for our $\alpha_{realized}$ dataset.

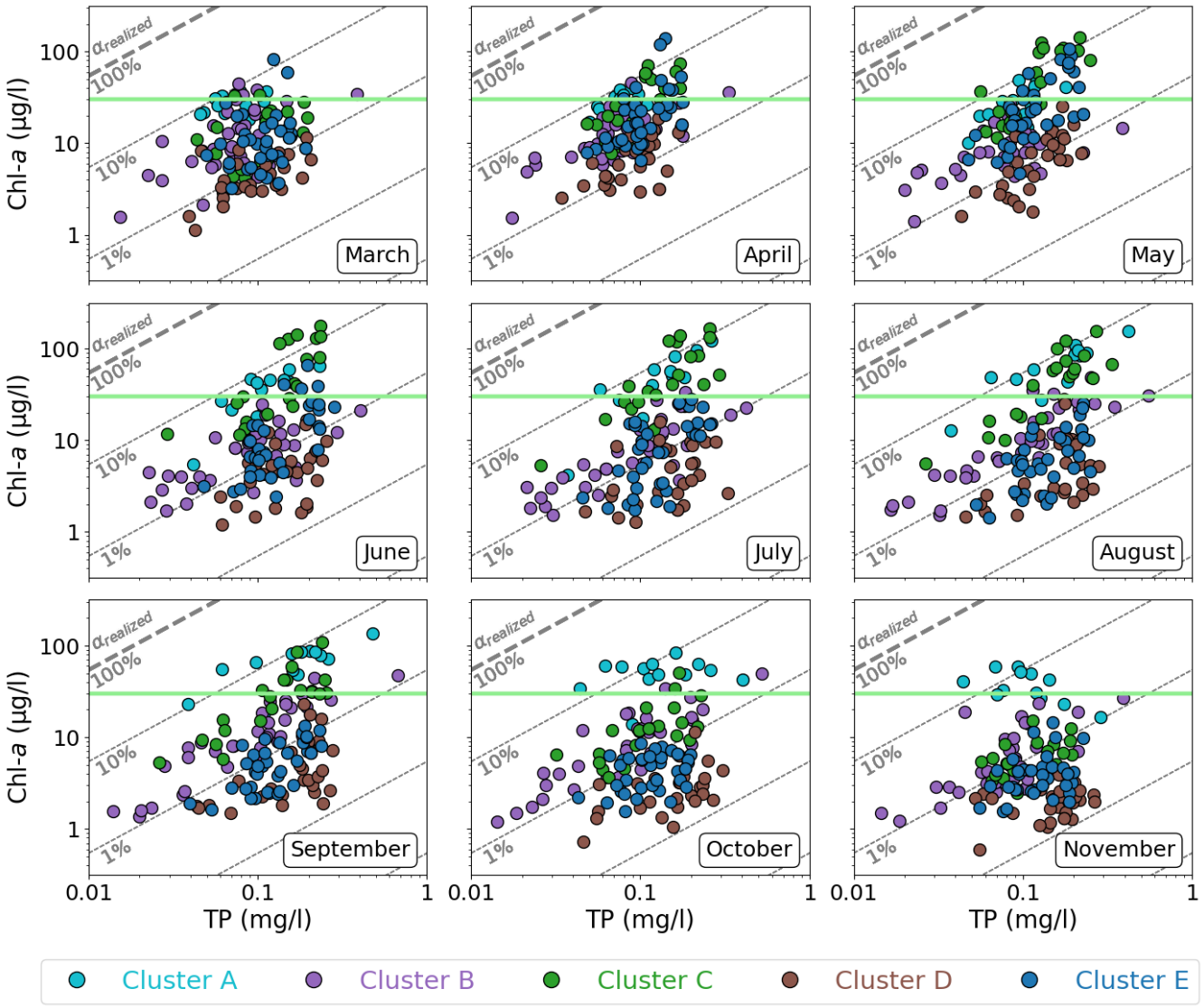

Figure S2. Monthly scatter plots of TP and Chl-a sorted by clusters with the dotted background lines indicating $\alpha_{realized}$. The green lines mark a threshold of 30 µg/l for phytoplankton blooms (Dodds et al., 1998).

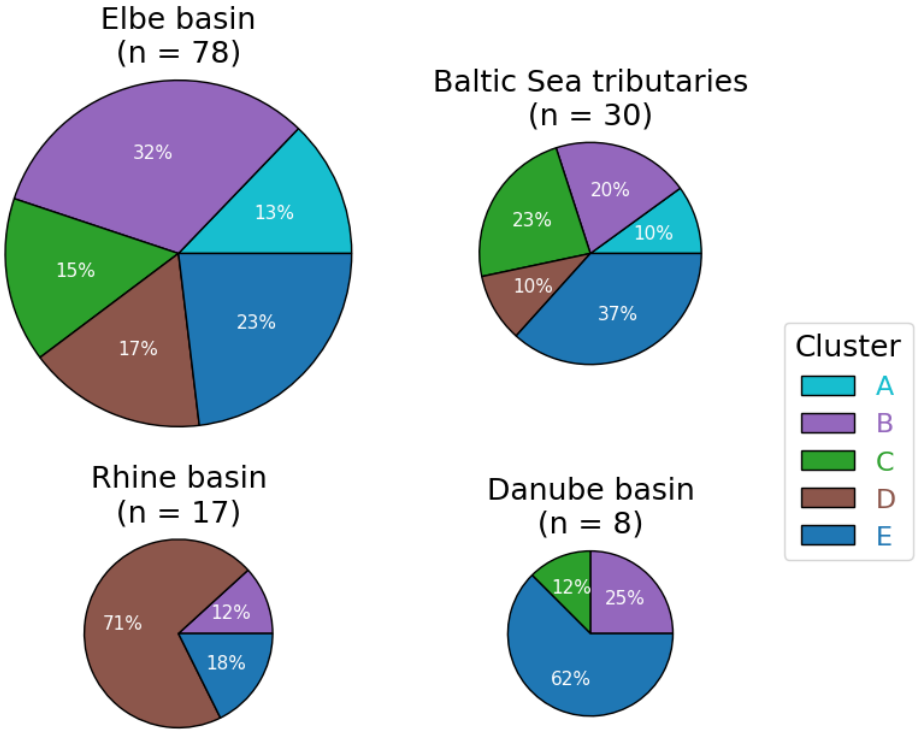

Figure S3. Fraction of the five cluster in stations of the Elbe basin, the Baltic Sea tributaries, the Rhine basin, and the Danube basin.

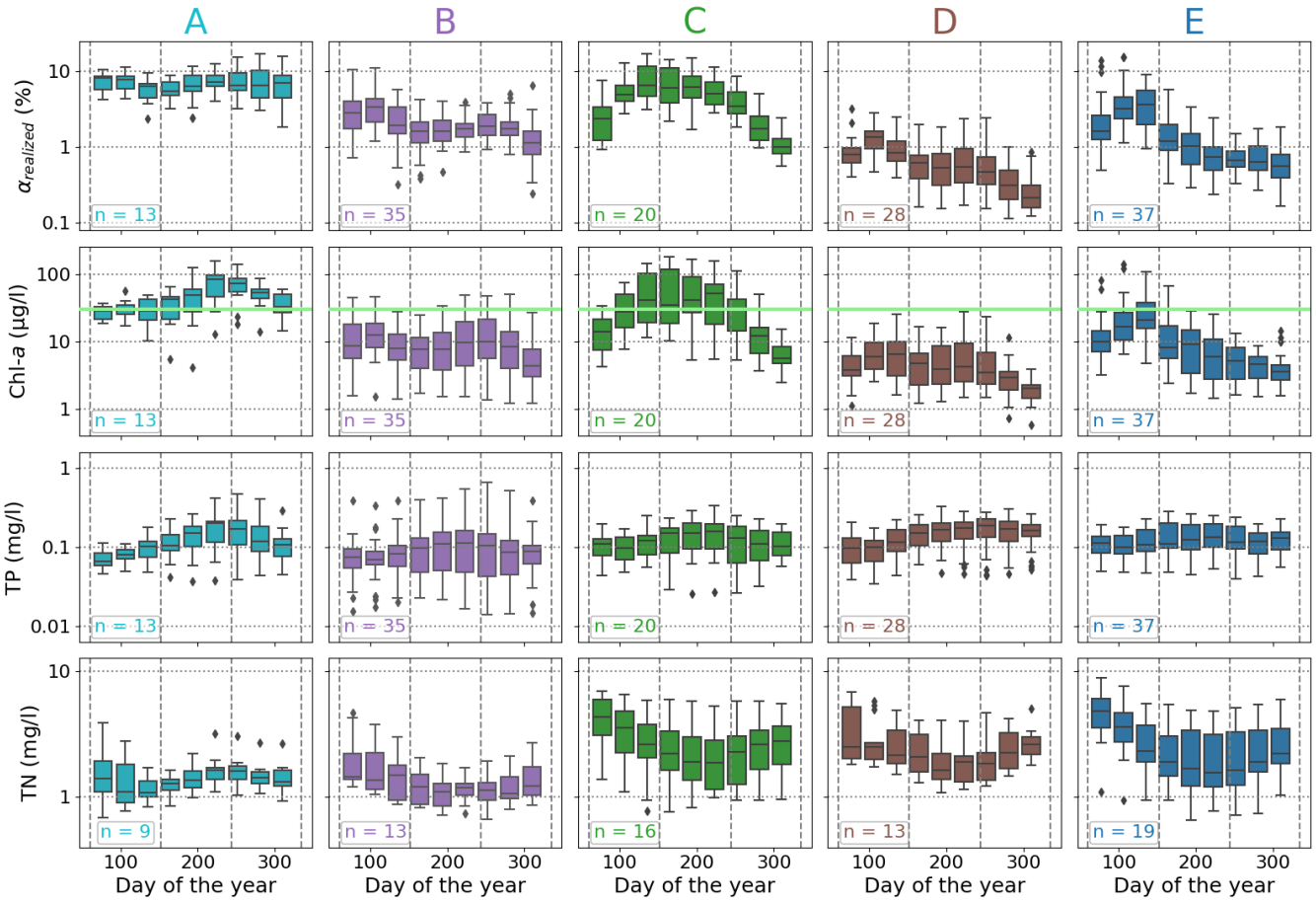

Figure S4. From top row to bottom row: Cluster-wise boxplots of $\alpha_{realized}$ and the concentrations of Chl-a, TP, and TN with one boxplot per month. The green line in the Chl-a panels marks a threshold of 30 µg/l for phytoplankton blooms (Dodds et al., 1998).

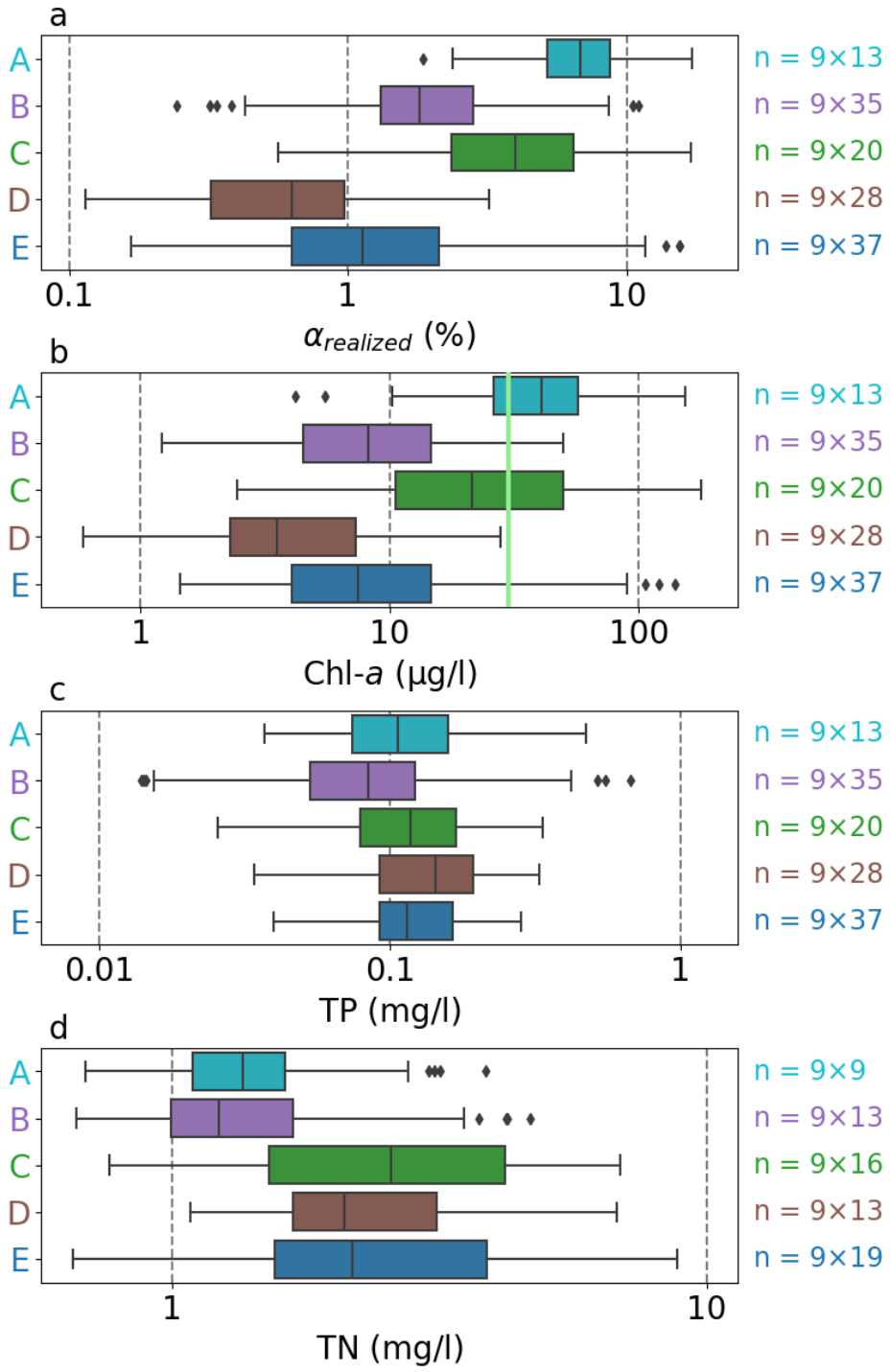

Figure S5. From top row to bottom row: Cluster-wise boxplots of $\alpha_{realized}$ and the concentrations of Chl-a, TP, and TN across all months. The green line in the Chl-a panels marks a threshold of 30 µg/l for phytoplankton blooms (Dodds et al., 1998).

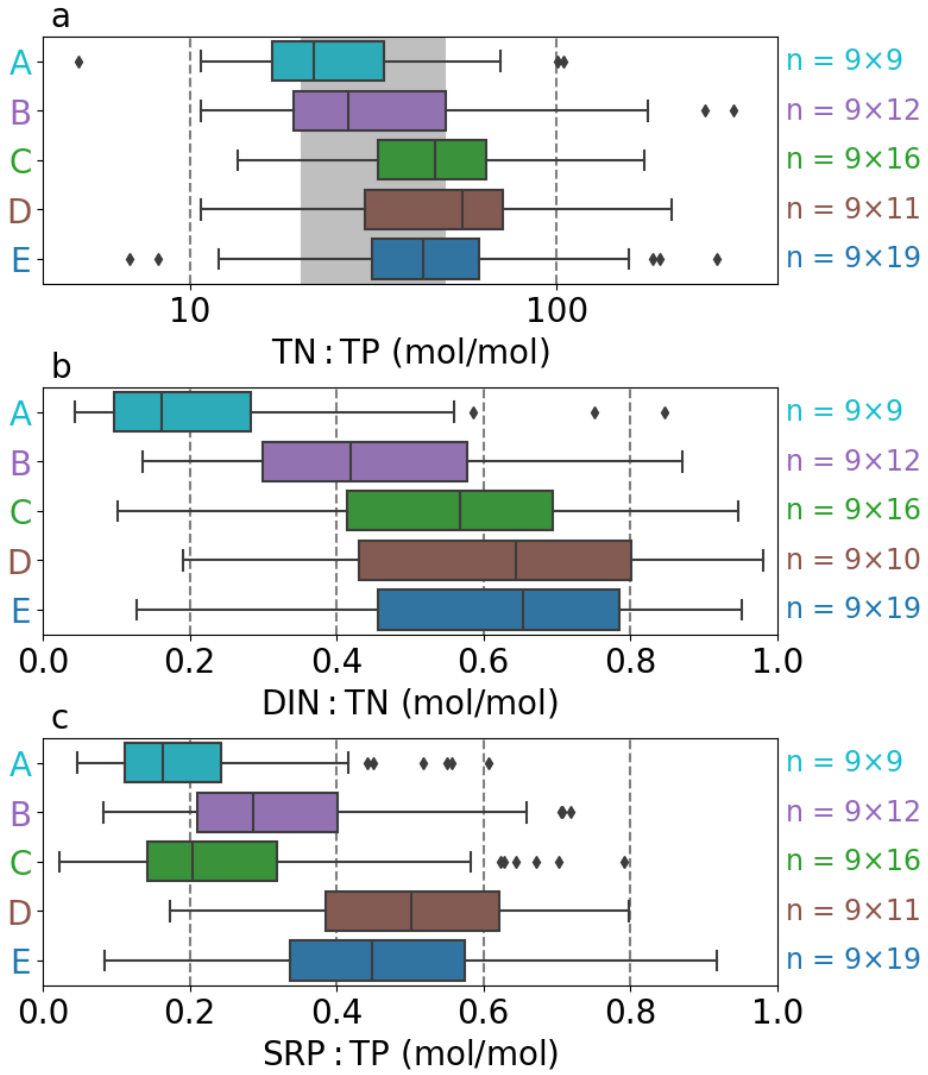

Figure S6. From top row to bottom row: Cluster-wise boxplots of the ratios TN:TP, DIN:TN, and SRP:TP across all months. In the top row, the gray area marks the range $20 \leq$ TN:TP ≤ 50 indicating N and P co-deficiency while TN:TP < 20 indicates N deficiency only and TN:TP > 50 indicates P deficiency only (Guildford and Hecky, 2000; Graeber et al., 2024).

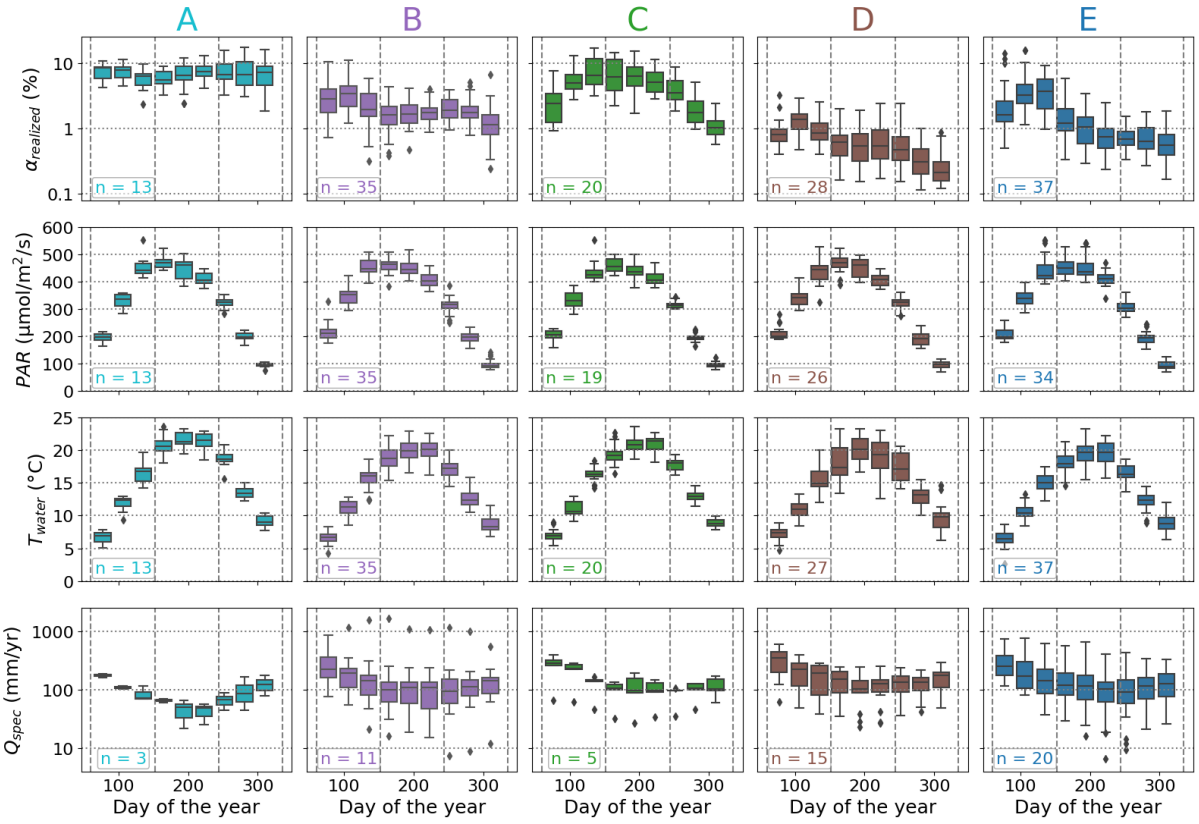

Figure S7. From top row to bottom row: Cluster-wise boxplots of the degree of realized eutrophication $\alpha_{realized}$, photosynthetically active radiation PAR, water temperature T_{water}, and specific discharge Q_{spec} with one boxplot per month. For comparability between stations, discharge Q was converted into specific discharge Q_{spec} via $Q_{spec} = Q/A$. The catchment area A was obtained from HydroRIVERS (Lehner and Grill, 2013) for the nearest reach to each station. The number of included stations are indicated for each panel.

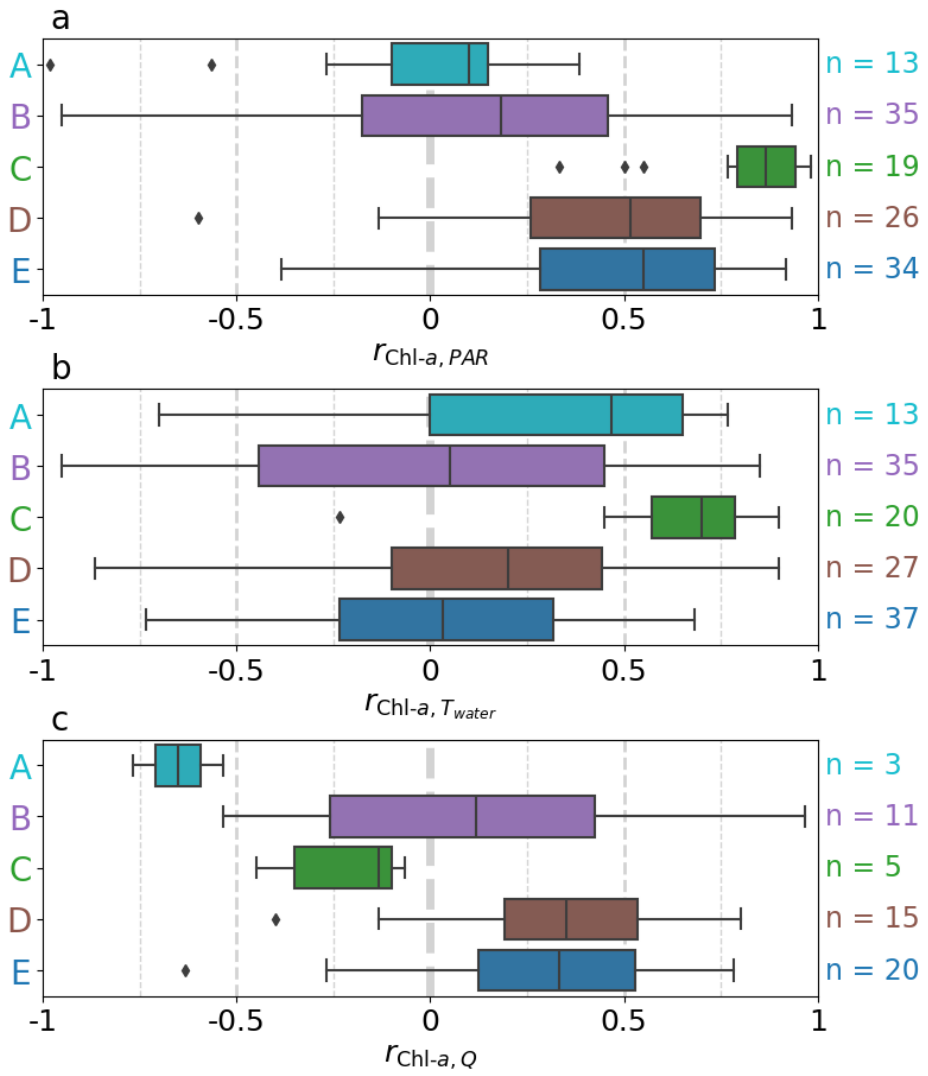

Figure S8. Cluster-wise distribution of the Spearman rank correlation coefficients at single stations: (a) between Chl-a and PAR, (b) between Chl-a and T_{water}, and (c) between Chl-a and Q.

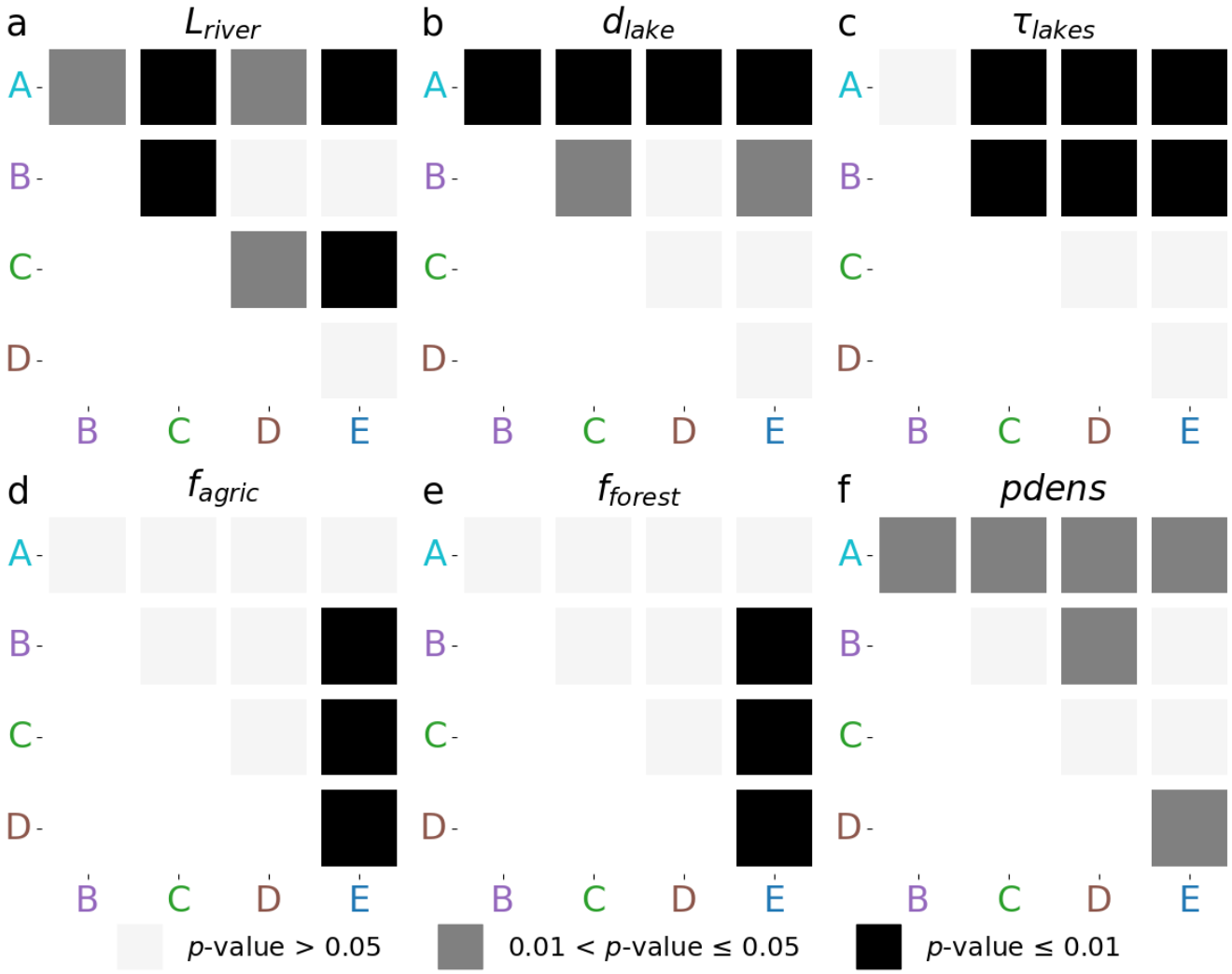

Figure S9. Cluster comparison of the river network properties L_{river}, d_{lake}, and τ_{lakes} and catchment characteristics f_{forest}, f_{agric}, and $pdens$. Grey and black squares indicate significant differences in the cluster-wise distributions of the parameters (Figure 7) assessed by Mann-Whitney U tests (gray: 0.01 $\leq$ p-value $<$ 0.05; black: p-value $<$ 0.01).

Table S1. Cluster-wise and monthly fractions of stations in the P deficiency range (TN:TP $>$ 50), the N and P co-deficiency range (20 $\leq$ TN:TP $\leq$ 50), or the N deficiency range (TN:TP $<$ 20).

Cluster	Deficiency	All-year	March	April	May	June	July	August	September	October	November
All	P	35.6%	80.0%	72.9%	44.3%	20.0%	11.4%	8.6%	12.9%	32.9%	37.1%
	N + P	45.7%	18.6%	25.7%	52.9%	62.9%	58.6%	51.4%	50.0%	40.0%	51.4%
	N	18.7%	1.4%	1.4%	2.9%	17.1%	30.0%	40.0%	37.1%	27.1%	11.4%
A	P	7.4%	33.3%	33.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	N + P	46.9%	55.6%	55.6%	77.8%	55.6%	33.3%	22.2%	33.3%	44.4%	44.4%
	N	45.7%	11.1%	11.1%	22.2%	44.4%	66.7%	77.8%	66.7%	55.6%	55.6%
B	P	24.8%	61.5%	38.5%	30.8%	23.1%	15.4%	7.7 %	7.7%	23.1%	15.4%
	N + P	44.4%	38.5%	61.5%	69.2%	46.2%	38.5%	23.1%	30.8%	23.1%	69.2%
	N	30.8%	0.0%	0.0%	0.0%	30.8%	46.2%	69.2%	61.5%	53.8%	15.4%
C	P	44.4%	100%	93.8%	56.2%	18.8%	6.2%	12.5%	12.5%	37.5%	62.5%
	N + P	43.1%	0.0%	6.2%	43.8%	75.0%	56.2%	50.0%	68.8%	50.0%	37.5%
	N	12.5%	0.0%	0.0%	0.0%	6.2%	37.5%	37.5%	18.8%	12.5%	0.0%
D	P	50.4%	100.0%	100.0%	61.5%	38.5%	23.1%	15.4%	23.1%	46.2%	46.2%
	N + P	37.6%	0.0%	0.0%	38.5%	61.5%	69.2%	61.5%	30.8%	23.1%	53.8%
	N	12.0%	0.0%	0.0%	0.0%	0.0%	7.7%	23.1%	46.2%	30.8%	0.0%
E	P	38.6%	84.2%	78.9%	52.6%	15.8%	10.5%	5.3%	15.8%	42.1%	42.1%
	N + P	53.8%	15.8%	21.1%	47.4%	68.4%	78.9%	78.9%	68.4%	52.6%	52.6%
	N	7.6%	0.0%	0.0%	0.0%	15.8%	10.5%	15.8%	15.8%	5.3%	5.3%

Table S2. Overview of correlation coefficients of Chl-a and the nutrients TN and TP.

Parameter	Cluster	Min.	25-p	Median	75-p	Max.	Fraction of significant correlations ($n_{sign.}/n_{total}$)
$r_{\text{Chl-}a,\text{TP}}$	A	-0.18	0.60	0.70	0.83	0.87	61.5% (8/13)
	B	-0.72	-0.20	0.33	0.67	0.80	34.3% (12/35)
	C	-0.02	0.33	0.57	0.74	0.88	40.0% (8/20)
	D	-0.83	-0.40	-0.09	0.19	0.52	7.1% (2/28)
	E	-0.73	-0.43	0.00	0.42	0.78	10.8% (4/37)
$r_{\text{Chl-}a,\text{TN}}$	A	-0.16	0.45	0.68	0.82	0.87	55.6% (5/9)
	B	-0.80	-0.08	0.12	0.42	0.63	7.7% (1/13)
	C	-0.82	-0.47	-0.15	-0.02	0.32	18.8% (3/16)
	D	-0.88	-0.35	-0.15	0.42	0.70	38.5% (5/13)
	E	-0.42	-0.05	0.51	0.69	0.87	35.0% (7/20)

Table S3. Overview of correlation coefficients of $\alpha_{realized}$ and the physical parameters PAR, T_{water}, and Q.

Parameter	Cluster	Min.	25-p	Median	75-p	Max.	Fraction of significant correlations ($n_{sign.}/n_{total}$)
$r_{\alpha_{realized},PAR}$	A	-0.97	-0.42	0.02	0.13	0.77	15.4% (2/13)
	B	-0.80	-0.21	0.02	0.47	0.80	20.0% (7/35)
	C	0.38	0.76	0.85	0.93	0.98	89.5% (17/19)
	D	-0.70	0.27	0.48	0.55	0.95	19.2% (5/26)
	E	-0.28	0.18	0.41	0.61	0.85	14.7% (5/34)
$r_{\alpha_{realized},T_{water}}$	A	-0.62	-0.23	0.00	0.18	0.73	7.7% (1/13)
	B	-0.88	-0.39	-0.22	0.13	0.68	14.3% (5/35)
	C	-0.53	0.43	0.58	0.67	0.87	30.0% (6/20)
	D	-0.90	-0.16	0.00	0.35	0.83	18.5% (5/27)
	E	-0.73	-0.38	-0.08	0.05	0.52	10.8% (4/37)
$r_{\alpha_{realized},Q}$	A	-0.63	-0.38	-0.13	0.18	0.48	0.0% (0/3)
	B	-0.43	-0.10	0.22	0.53	0.97	9.1% (1/11)
	C	-0.65	-0.05	-0.03	-0.02	0.00	0.0% (0/5)
	D	-0.43	0.29	0.40	0.61	0.72	20.0% (3/15)
	E	-0.62	-0.02	0.61	0.67	0.93	35.0% (7/20)

Table S4. Overview of correlation coefficients of Chl-a and the physical parameters PAR, T_{water}, and Q.

Parameter	Cluster	Min.	25-p	Median	75-p	Max.	Fraction of significant correlations ($n_{sign.}/n_{total}$)
$r_{\text{Chl-}a,PAR}$	A	-0.98	-0.10	0.10	0.15	0.38	7.7% (1/13)
	B	-0.95	-0.18	0.18	0.46	0.93	25.7% (9/35)
	C	0.33	0.79	0.87	0.94	0.98	84.2% (16/19)
	D	-0.60	0.26	0.52	0.70	0.93	34.6% (9/26)
	E	-0.38	0.28	0.55	0.73	0.92	38.2% (13/34)
$r_{\text{Chl-}a,T_{water}}$	A	-0.70	0.00	0.47	0.65	0.77	23.1% (3/13)
	B	-0.95	-0.44	0.05	0.45	0.85	28.6% (10/35)
	C	-0.23	0.57	0.70	0.79	0.90	55.0% (11/20)
	D	-0.87	-0.10	0.20	0.44	0.90	25.9% (7/27)
	E	-0.73	-0.23	0.03	0.32	0.68	13.5% (5/37)
$r_{\text{Chl-}a,Q}$	A	-0.77	-0.71	-0.65	-0.59	-0.53	33.3% (1/3)
	B	-0.53	-0.26	0.12	0.42	0.97	9.1% (1/11)
	C	-0.45	-0.35	-0.13	-0.10	-0.07	0.0% (0/5)
	D	-0.40	0.19	0.35	0.53	0.80	6.7% (1/15)
	E	-0.63	0.12	0.33	0.53	0.78	15.0% (3/20)

Table S5. Summary statistics of river network properties and catchment characteristics differentiated by the five clusters.

Cluster		L_{river} (km)	d_{lake} (km)	τ_{lakes} (days/km)	f_{agric} (%)	f_{forest} (%)	$pdens$ (inhab./km^2)
A	Min	8	0.00	1.05	45	27	19.3
	25-p	26	0.65	4.72	46	37	39.2
	Median	56	2.07	13.04	48	46	59.1
	75-p	61	3.09	39.16	58	48	59.4
	Max	820	32.15	106.66	69	49	59.7
B	Min	15	0.02	0.00	18	29	31.9
	25-p	54	3.42	4.54	42	39	86.3
	Median	120	11.14	13.47	46	42	109.4
	75-p	219	25.64	17.6	48	46	148.3
	Max	499	70.05	137.26	60	78	301.0
C	Min	5	0.77	0.00	43	32	87.4
	25-p	171	9.74	0.79	45	35	136.0
	Median	295	21.68	2.38	50	39	145.5
	75-p	814	50.78	4.71	56	44	158.7
	Max	1007	64.77	13.47	59	45	173.0
D	Min	5	0.06	0.00	29	11	42.0
	25-p	62	4.46	0.35	42	37	133.1
	Median	141	39.22	2.25	50	39	176.6
	75-p	363	61.90	9.53	54	45	243.6
	Max	669	123.63	16.62	86	64	437.0
E	Min	11	2.40	0.00	46	13	40.8
	25-p	65	13.58	0.58	56	25	94.8
	Median	151	22.93	2.43	61	31	122.9
	75-p	250	31.64	7.23	67	36	160.4
	Max	706	139.49	28.68	82	40	278.5

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