Predicting multiple stressor effect on zooplankton abundance, biomass and community composition in two large eutrophic lakes

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„The freshwater zooplankters occupy an important and strategic position within the trophic web of a lake ecosystem and are sensitive to anthropogenic impacts“ (Caroni & Irvine 2010)

Zooplankton are sensitive to environmental stressors:

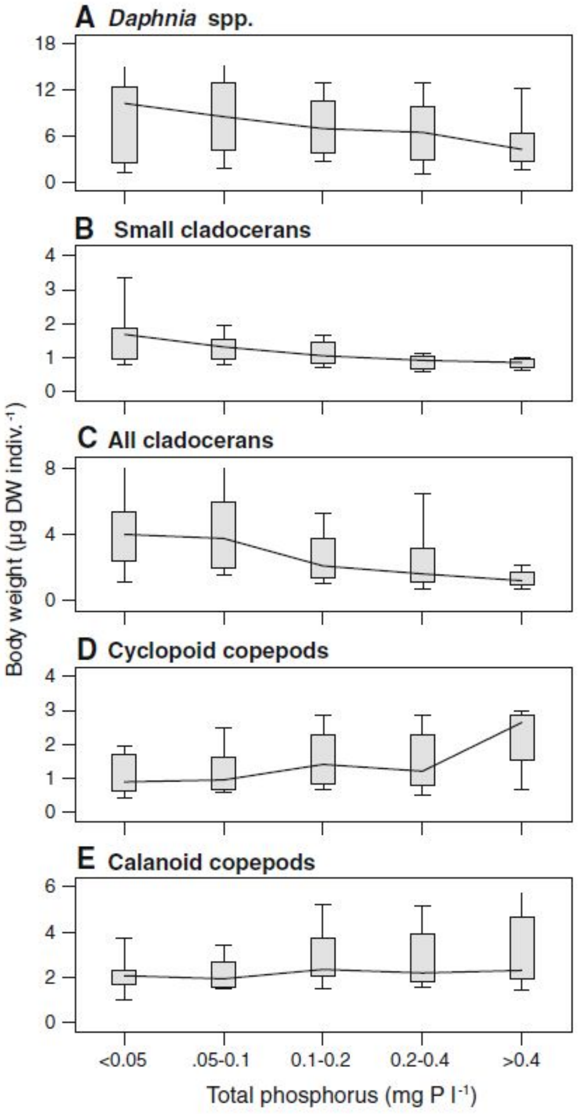
-nutrient loading and eutrophication (Jeppesen et al., 2011; Yang et al., 2017),

-warming (Rasconi et al., 2015),

-pH (Shurin et al., 2010),

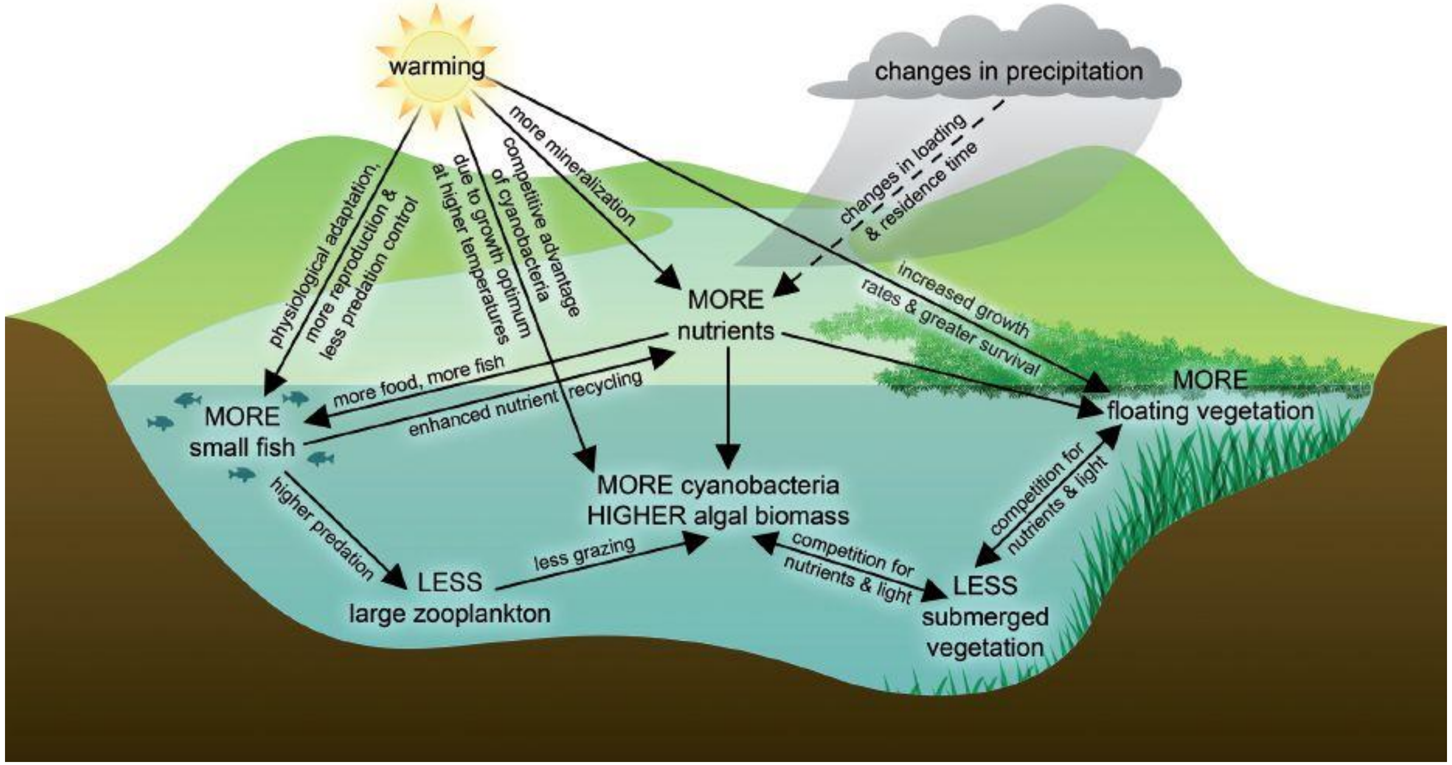
-water transparency (Estlander et al., 2009),

-phytoplankton composition (Cremona et al., 2020).



(Jeppesen et al., 2000, 2011)

Additionally, stressors can carry synergistic effects („allied attack“ Moss et al. 2011).



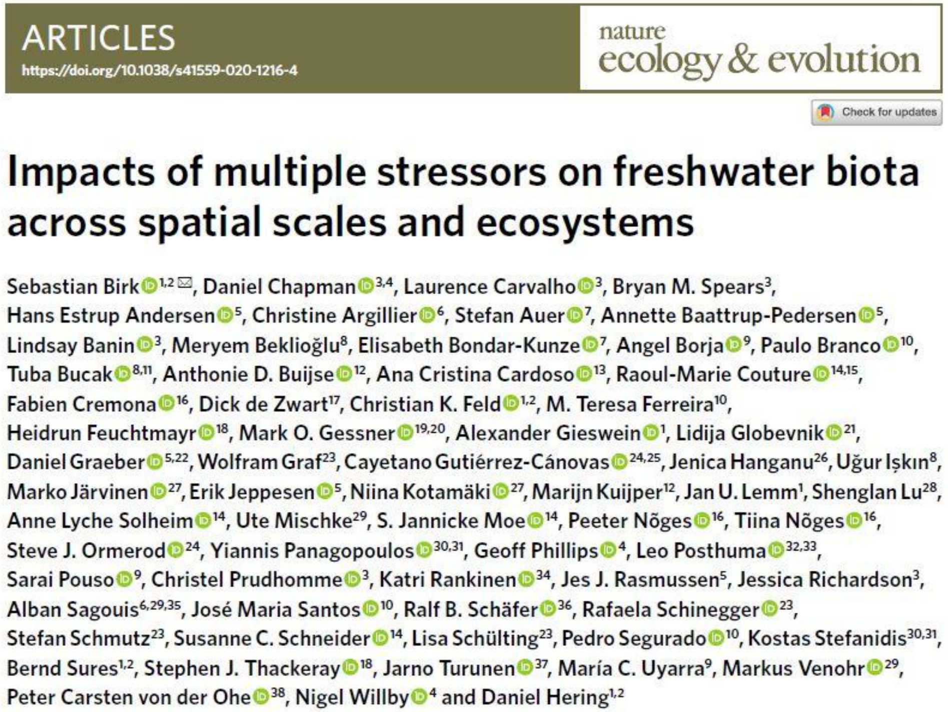
Warming + Cyanobacteria

Warming + eutrophication

Cyanobacteria + turbidity

Etc.

(Moss et al., 2011)



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Impacts of multiple stressors on freshwater biota across spatial scales and ecosystems

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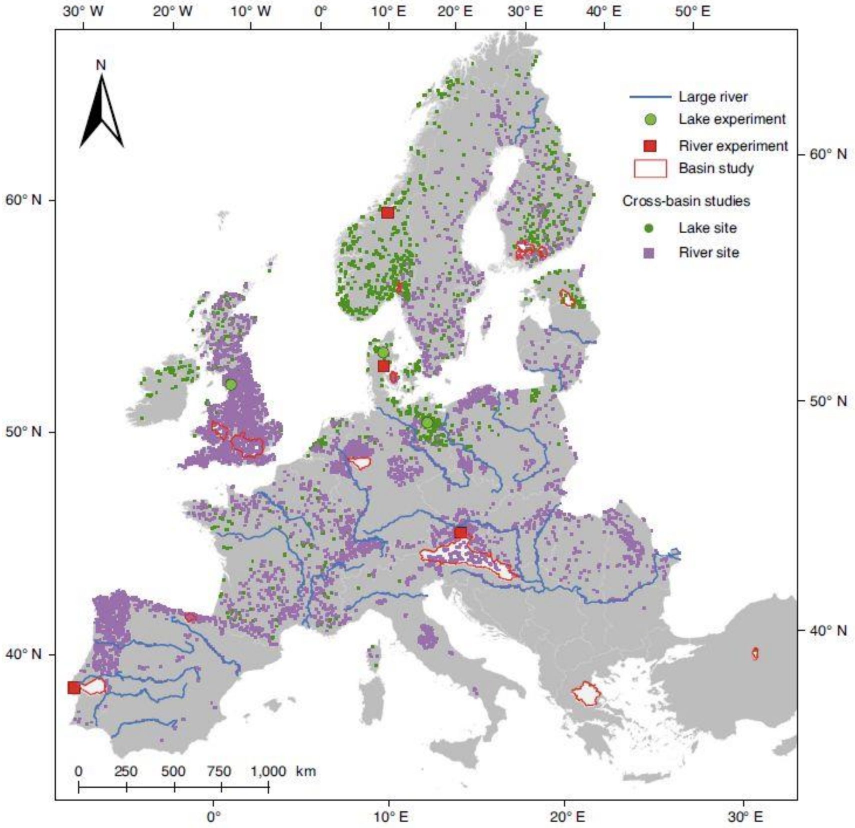


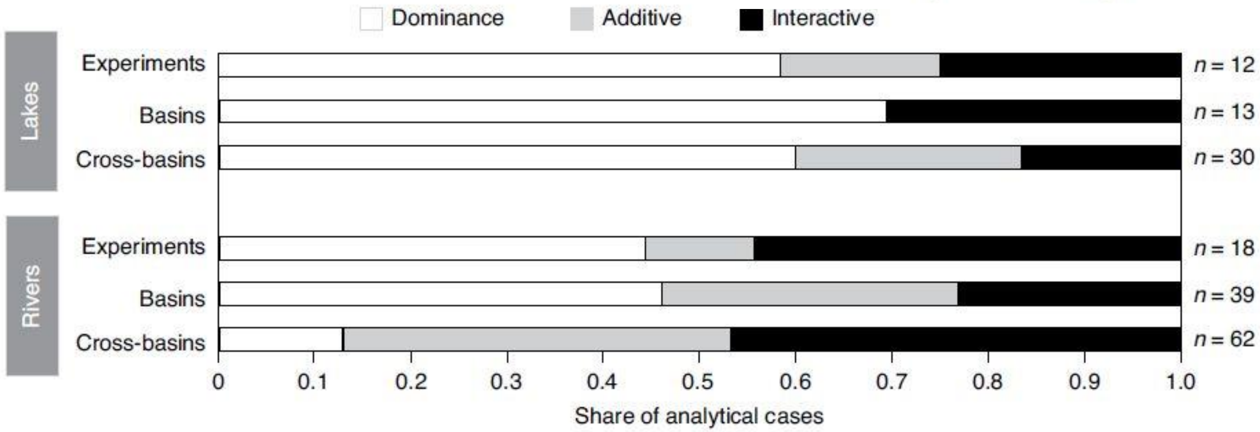
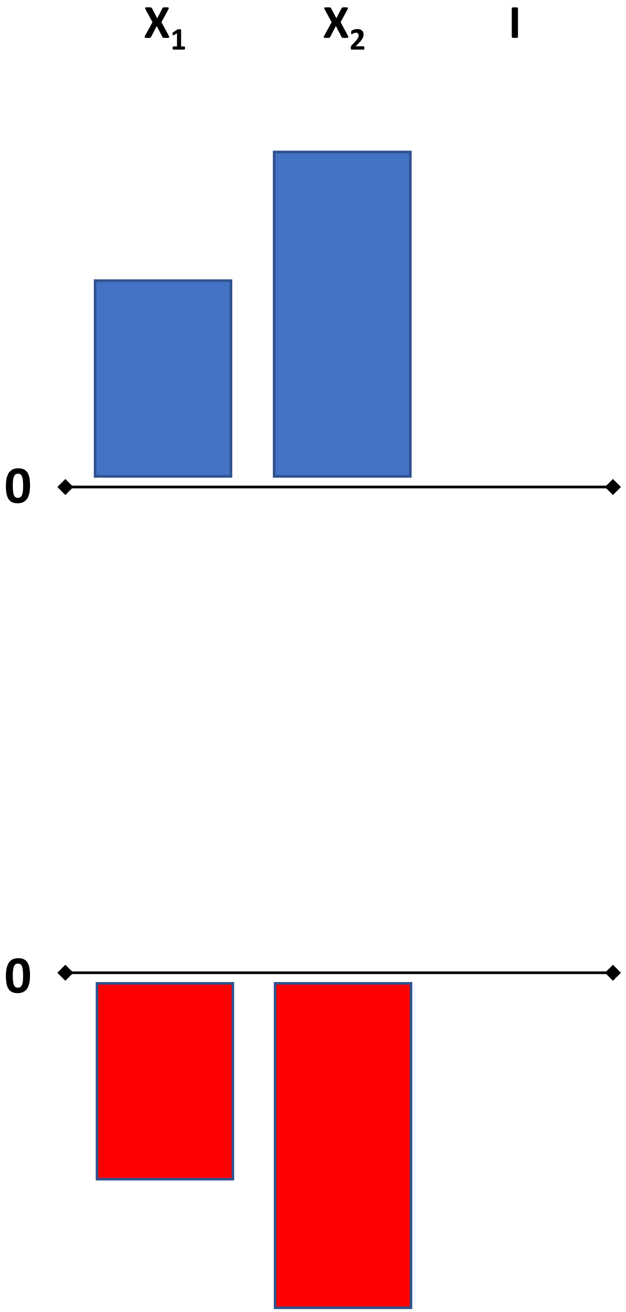


Fig. 2 | Stressor effect types in lakes and rivers. Share of analytical cases across experiments, basin studies and cross-basin studies from lakes ($n = 55$) and rivers ($n = 119$), for which only a single stressor (dominance), both stressors (additive) or their interaction significantly contributed to the variability of the biological response.

-Stressor dominance in lakes but with up to 30% of interactive effects

-Stressor multiple effect on zooplankton studied in mesocosms but harder to quantify in natural ecosystems

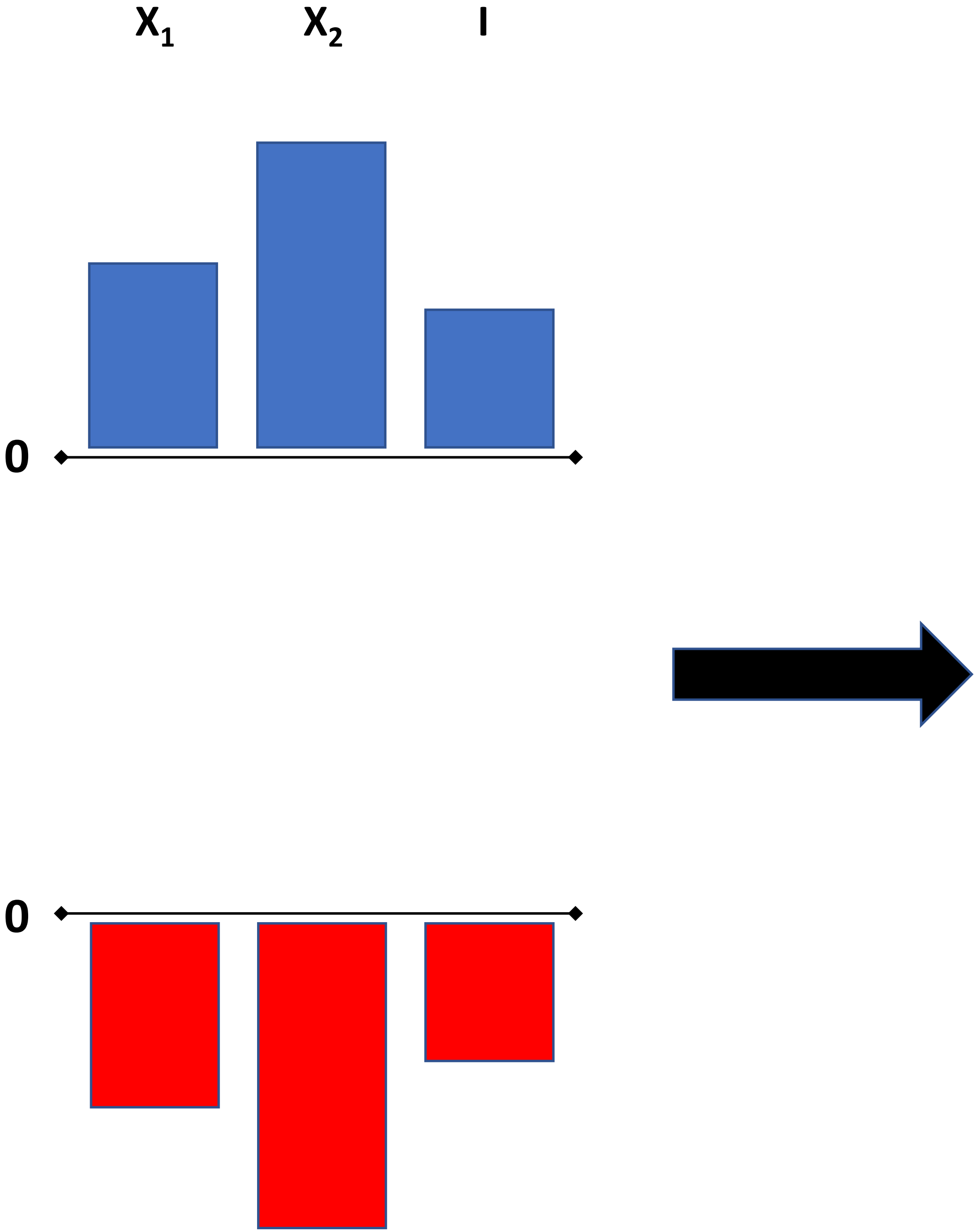
-Shallow lakes : high surface area relative to their volume -> early responders and amplifiers for a variety of environmental stressors



Additive

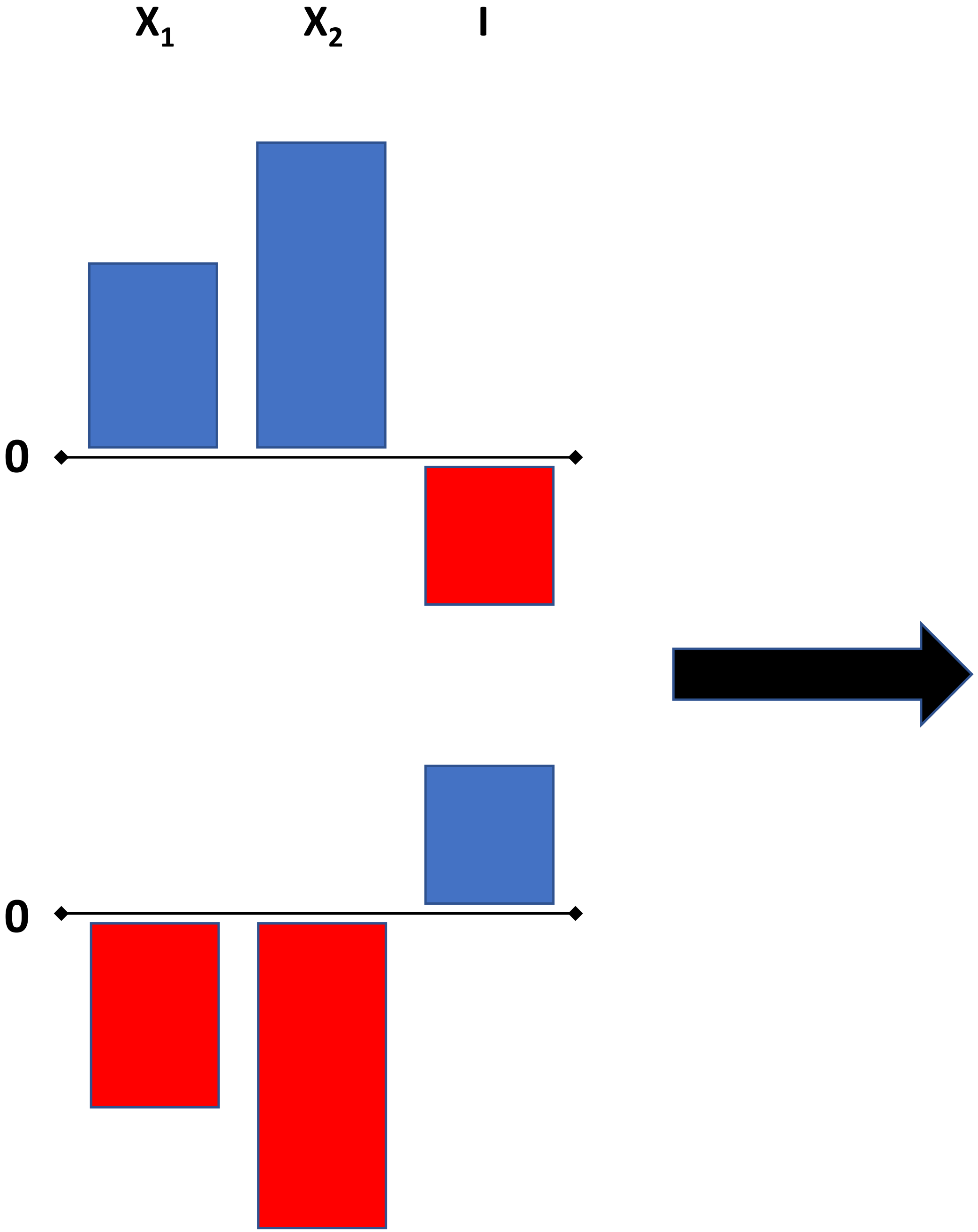
(no interaction)

(Feld et al. 2016)



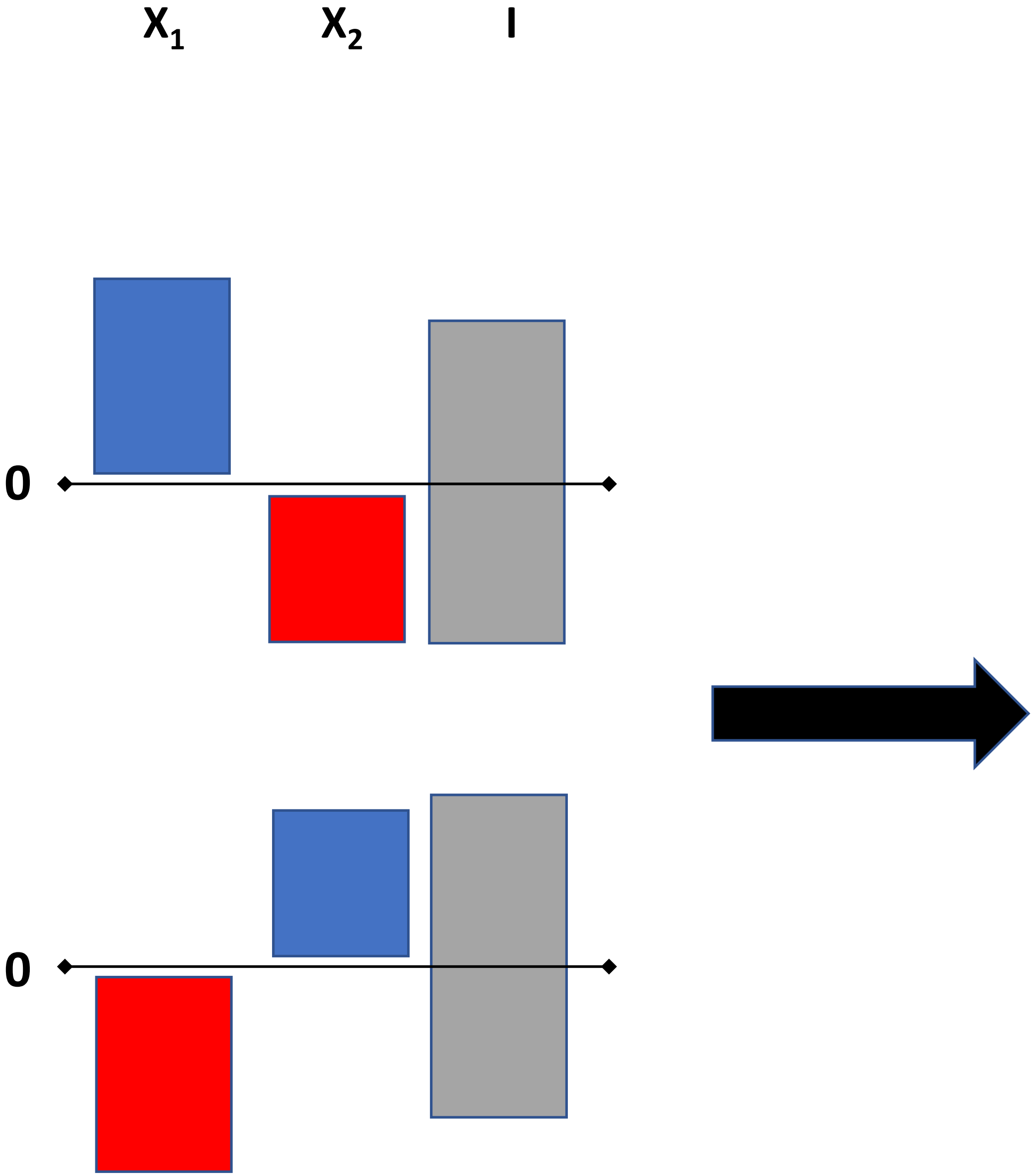
Synergistic

(Feld et al. 2016)



Antagonistic

(Feld et al. 2016)



Opposing

(Feld et al. 2016)

Võrtsjärv

A = 270 km^2

z = 2.8 m

z_{max} = 6 m

TP = 48 µg L^{-1}

TN = 0.91 mg L^{-1}

Dominant phytoplankton: *Limnothrix planktonica, L. redekei*

Dominant zooplankton (biomass): *Bosmina longirostris, Chydorus sphaericus, Mesocyclops, Thermocyclops*

Strong presence of ciliates

Peipsi

A = 3555 km^2

z = 7.1 m

z_{max} = 15.3 m

TP = 49 µg L^{-1}

TN = 0.72 mg L^{-1}

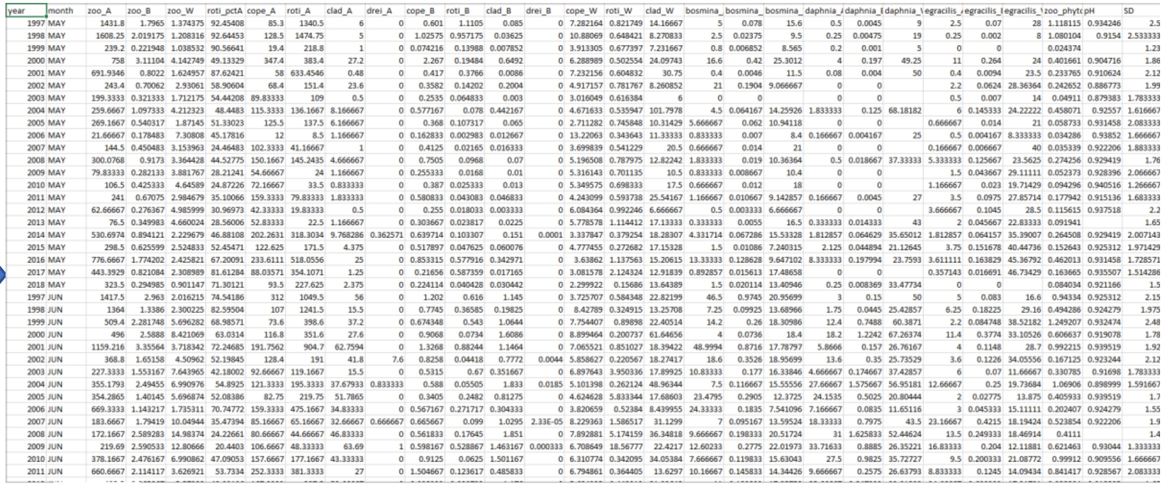
Dominant phytoplankton: *Gloeotrichia echinulata, Aphanizomenon flos-aquae*

Dominant zooplankton (biomass): *Daphnia spp., Bosmina spp., Eudiaptomus gracilis*

From plankton to equations

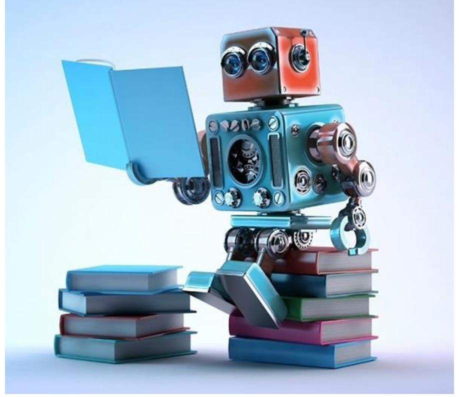
B_{meta}, A_{meta}, B_{clad}, A_{clad},
B_{cope}, A_{cope}, B_{cili}, A_{cili}

TN, TP, NO_3, B_{cyan},
chla, T, SD, pH

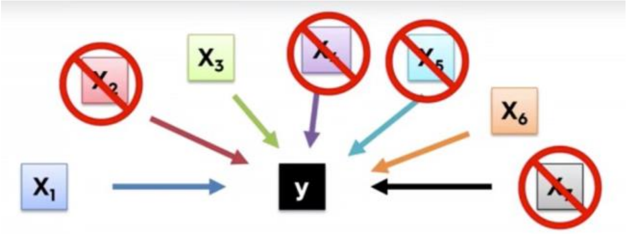


year	month	zoo_A	zoo_B	zoo_W	roti_pctA	cope_A	roti_A	clad_A	drei_A	cope_B	roti_B	clad_B	drei_B
1997	MAY	1431.8	1.7965	1.374375	92.45408	85.3	1340.5	6	0	0.601	1.1105	0.085	0
1998	MAY	1608.25	2.019175	1.208316	92.64453	128.5	1474.75	5	0	1.02575	0.957175	0.03625	0
1999	MAY	239.2	0.221948	1.038532	90.56641	19.4	218.8	1	0	0.074216	0.13988	0.007852	0
2000	MAY	758	3.11104	4.142749	49.13329	347.4	383.4	27.2	0	2.267	0.19484	0.6492	0
2001	MAY	691.9346	0.8022	1.624957	87.62421	58	633.4546	0.48	0	0.417	0.3766	0.0086	0
2002	MAY	243.4	0.70062	2.93061	58.90604	68.4	151.4	23.6	0	0.3582	0.14202	0.2004	0
2003	MAY	199.3333	0.321333	1.712175	54.44208	89.83333	109	0.5	0	0.2535	0.064833	0.003	0
2004	MAY	259.6667	1.097333	4.212323	48.4483	115.3333	136.1667	8.166667	0	0.577167	0.078	0.442167	0
2005	MAY	269.1667	0.540317	1.87145	51.33023	125.5	137.5	6.166667	0	0.368	0.107317	0.065	0
2006	MAY	21.66667	0.178483	7.30808	45.17816	12	8.5	1.166667	0	0.162833	0.002983	0.012667	0
2007	MAY	144.5	0.450483	3.153963	24.46483	102.3333	41.16667	1	0	0.4125	0.02165	0.016333	0
2008	MAY	300.0768	0.9173	3.364428	44.52775	150.1667	145.2435	4.666667	0	0.7505	0.0968	0.07	0
2009	MAY	79.83333	0.282133	3.881767	28.21241	54.66667	24	1.166667	0	0.255333	0.0168	0.01	0
2010	MAY	106.5	0.425333	4.64589	24.87226	72.16667	33.5	0.833333	0	0.387	0.025333	0.013	0
2011	MAY	241	0.67075	2.984679	35.10066	159.3333	79.83333	1.833333	0	0.580833	0.043083	0.046833	0
2012	MAY	62.66667	0.276367	4.985999	30.96973	42.33333	19.83333	0.5	0	0.255	0.018033	0.003333	0
2013	MAY	76.5	0.349983	4.660024	28.56006	52.83333	22.5	1.166667	0	0.303667	0.023817	0.0225	0
2014	MAY	530.6974	0.894121	2.229679	46.88108	202.2631	318.3034	9.768286	0.362571	0.639714	0.103307	0.151	0.0001
2015	MAY	298.5	0.625599	2.524833	52.45471	122.625	171.5	4.375	0	0.517897	0.047625	0.060076	0
2016	MAY	776.6667	1.774202	2.425821	67.20091	233.6111	518.0556	25	0	0.853315	0.577916	0.342971	0
2017	MAY	443.3929	0.821084	2.308989	81.61284	88.03571	354.1071	1.25	0	0.21656	0.587359	0.017165	0
2018	MAY	323.5	0.294985	0.901147	71.30121	93.5	227.625	2.375	0	0.224114	0.040428	0.030442	0
1997	JUN	1417.5	2.963	2.016215	74.54186	312	1049.5	56	0	1.202	0.616	1.145	0
1998	JUN	1364	1.3386	2.300225	82.59504	107	1241.5	15.5	0	0.7745	0.36585	0.19825	0
1999	JUN	509.4	2.281748	5.696282	68.98571	73.6	398.6	37.2	0	0.674348	0.543	1.0644	0
2000	JUN	496	2.5888	8.421069	63.0314	116.8	351.6	27.6	0	0.9068	0.0734	1.6086	0
2001	JUN	1159.216	3.35564	3.718342	72.24685	191.7562	904.7	62.7594	0	1.3268	0.88244	1.1464	0
2002	JUN	368.8	1.65158	4.50962	52.19845	128.4	191	41.8	7.6	0.8258	0.04418	0.7772	0.0044
2003	JUN	227.3333	1.553167	7.643965	42.18002	92.66667	119.1667	15.5	0	0.5315	0.67	0.351667	0
2004	JUN	355.1793	2.49455	6.990976	54.8925	121.3333	195.3333	37.67933	0.833333	0.588	0.05505	1.833	0.0185
2005	JUN	354.2865	1.40145	5.696874	52.08386	82.75	219.75	51.7865	0	0.3405	0.2482	0.81275	0
2006	JUN	669.3333	1.143217	1.735311	70.74772	159.3333	475.1667	34.83333	0	0.567167	0.271717	0.304333	0
2007	JUN	183.6667	1.79419	10.04944	35.47394	85.16667	65.16667	32.66667	0.666667	0.665667	0.099	1.0295	2.33E-05
2008	JUN	172.1667	2.589283	14.98374	24.22661	80.66667	44.66667	46.83333	0	0.561833	0.17645	1.851	0
2009	JUN	219.69	2.590533	12.80666	20.4403	106.6667	48.33333	63.69	1	0.598167	0.528867	1.463167	0.000333
2010	JUN	378.1667	2.476167	6.990862	47.09053	157.6667	177.1667	43.33333	0	0.9125	0.0625	1.501167	0
2011	JUN	660.6667	2.114117	3.626921	53.7334	252.3333	381.3333	27	0	1.504667	0.123617	0.485833	0

year	month	cope_W	roti_W	clad_W	bosmina_	bosmina_	bosmina_	daphnia_	daphnia_	daphnia_	egracilis_	egracilis_	egracilis_	zoo_phyt	pH	SD
1997	MAY	7.282164	0.821749	14.16667	5	0.078	15.6	0.5	0.0045	9	2.5	0.07	28	1.118115	0.934246	2.5
1998	MAY	10.88069	0.648421	8.270833	2.5	0.02375	9.5	0.25	0.00475	19	0.25	0.002	8	1.080104	0.9154	2.533333
1999	MAY	3.913305	0.677397	7.231667	0.8	0.006852	8.565	0.2	0.001	5	0	0		0.024374		1.23
2000	MAY	6.288989	0.502554	24.09743	16.6	0.42	25.3012	4	0.197	49.25	11	0.264	24	0.401661	0.904716	1.86
2001	MAY	7.232156	0.604832	30.75	0.4	0.0046	11.5	0.08	0.004	50	0.4	0.0094	23.5	0.233765	0.910624	2.12
2002	MAY	4.917157	0.781767	8.260852	21	0.1904	9.066667	0	0		2.2	0.0624	28.36364	0.242652	0.886773	1.99
2003	MAY	3.016049	0.616384	6	0	0		0	0		0.5	0.007	14	0.04911	0.879383	1.783333
2004	MAY	4.671633	0.535947	101.7978	4.5	0.064167	14.25926	1.833333	0.125	68.18182	6	0.145333	24.22222	0.458071	0.92557	1.616667
2005	MAY	2.711282	0.745848	10.31429	5.666667	0.062	10.94118	0	0		0.666667	0.014	21	0.058733	0.931458	2.083333
2006	MAY	13.22063	0.343643	11.33333	0.833333	0.007	8.4	0.166667	0.004167	25	0.5	0.004167	8.333333	0.034286	0.93852	1.666667
2007	MAY	3.699839	0.541229	20.5	0.666667	0.014	21	0	0		0.166667	0.006667	40	0.035339	0.922206	1.883333
2008	MAY	5.196508	0.787975	12.82242	1.833333	0.019	10.36364	0.5	0.018667	37.33333	5.333333	0.125667	23.5625	0.274256	0.929419	1.76
2009	MAY	5.316143	0.701135	10.5	0.833333	0.008667	10.4	0	0		1.5	0.043667	29.11111	0.052373	0.928396	2.066667
2010	MAY	5.349575	0.698333	17.5	0.666667	0.012	18	0	0		1.166667	0.023	19.71429	0.094296	0.940516	1.266667
2011	MAY	4.243099	0.593738	25.54167	1.166667	0.010667	9.142857	0.166667	0.0045	27	3.5	0.0975	27.85714	0.177942	0.915136	1.683333
2012	MAY	6.084364	0.992246	6.666667	0.5	0.003333	6.666667	0	0		3.666667	0.1045	28.5	0.115615	0.937518	2.2
2013	MAY	5.778578	1.114412	17.13333	0.333333	0.0055	16.5	0.333333	0.014333	43	2	0.045667	22.83333	0.091941		1.65
2014	MAY	3.337847	0.379254	18.28307	4.331714	0.067286	15.53328	1.812857	0.064629	35.65012	1.812857	0.064157	35.39007	0.264508	0.929419	2.007143
2015	MAY	4.777455	0.272682	17.15328	1.5	0.01086	7.240315	2.125	0.044894	21.12645	3.75	0.151678	40.44736	0.152643	0.925312	1.971429
2016	MAY	3.63862	1.137563	15.20615	13.33333	0.128628	9.647102	8.333333	0.197994	23.7593	3.611111	0.163829	45.36792	0.462013	0.931458	1.728571
2017	MAY	3.081578	2.124324	12.91839	0.892857	0.015613	17.48658	0	0		0.357143	0.016691	46.73429	0.163665	0.935507	1.514286
2018	MAY	2.299922	0.15686	13.64389	1.5	0.020114	13.40946	0.25	0.008369	33.47734	0	0		0.084034	0.921166	1.5
1997	JUN	3.725707	0.584348	22.82199	46.5	0.9745	20.95699	3	0.15	50	5	0.083	16.6	0.94334	0.925312	2.15
1998	JUN	8.42789	0.324915	13.25708	7.25	0.09925	13.68966	1.75	0.0445	25.42857	6.25	0.18225	29.16	0.494286	0.924279	1.975
1999	JUN	7.754407	0.89898	22.40514	14.2	0.26	18.30986	12.4	0.7488	60.3871	2.2	0.084748	38.52182	1.249207	0.932474	2.48
2000	JUN	8.899464	0.200737	61.64656	4	0.0736	18.4	18.2	1.2242	67.26374	11.4	0.3774	33.10526	0.606637	0.919078	1.78
2001	JUN	7.065521	0.851027	18.39422	48.9994	0.8716	17.78797	5.8666	0.157	26.76167	4	0.1148	28.7	0.992215	0.939519	1.92
2002	JUN	5.858627	0.220567	18.27417	18.6	0.3526	18.95699	13.6	0.35	25.73529	3.6	0.1226	34.05556	0.167125	0.923244	2.12
2003	JUN	6.897643	3.950336	17.89925	10.83333	0.177	16.33846	4.666667	0.174667	37.42857	6	0.07	11.66667	0.330785	0.91698	1.783333
2004	JUN	5.101398	0.262124	48.96344	7.5	0.116667	15.55556	27.66667	1.575667	56.95181	12.66667	0.25	19.73684	1.06906	0.898999	1.591667
2005	JUN	4.624628	5.833344	17.68603	23.4795	0.2905	12.3725	24.1535	0.5025	20.80444	2	0.02775	13.875	0.405933	0.939519	1.7
2006	JUN	3.820659	0.52384	8.439955	24.33333	0.1835	7.541096	7.166667	0.0835	11.65116	3	0.045333	15.11111	0.202407	0.924279	1.55
2007	JUN	8.229363	1.586517	31.1299	7	0.095167	13.59524	18.33333	0.7975	43.5	23.16667	0.4215	18.19424	0.523854	0.922206	1.9
2008	JUN	7.892881	5.174159	36.34818	9.666667	0.198333	20.51724	31	1.625833	52.44624	13.5	0.249333	18.46914	0.4111		1.4
2009	JUN	6.708649	18.56777	22.4217	12.60233	0.2775	22.01973	33.71633	0.8885	26.35221	16.83333	0.204	12.11881	0.621463	0.93044	1.333333
2010	JUN	6.310774	0.342095	34.05384	7.666667	0.119833	15.63043	27.5	0.9825	35.72727	9.5	0.200333	21.08772	0.99912	0.909556	1.666667
2011	JUN	6.794861	0.364405	13.6297	10.16667	0.145833	14.34426	9.666667	0.2575	26.63793	8.833333	0.1245	14.09434	0.841417	0.928567	2.083333

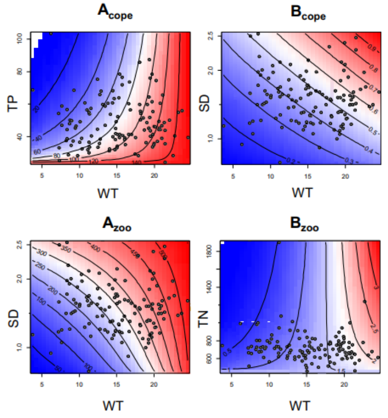


Machine Learning Algorithms
(boosted regression trees,
random forests)

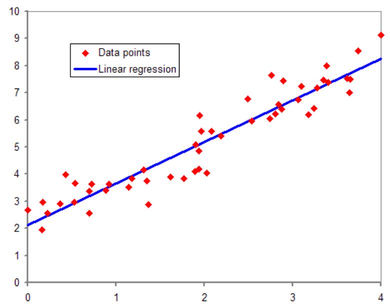


Most important predictors

Interaction assessment

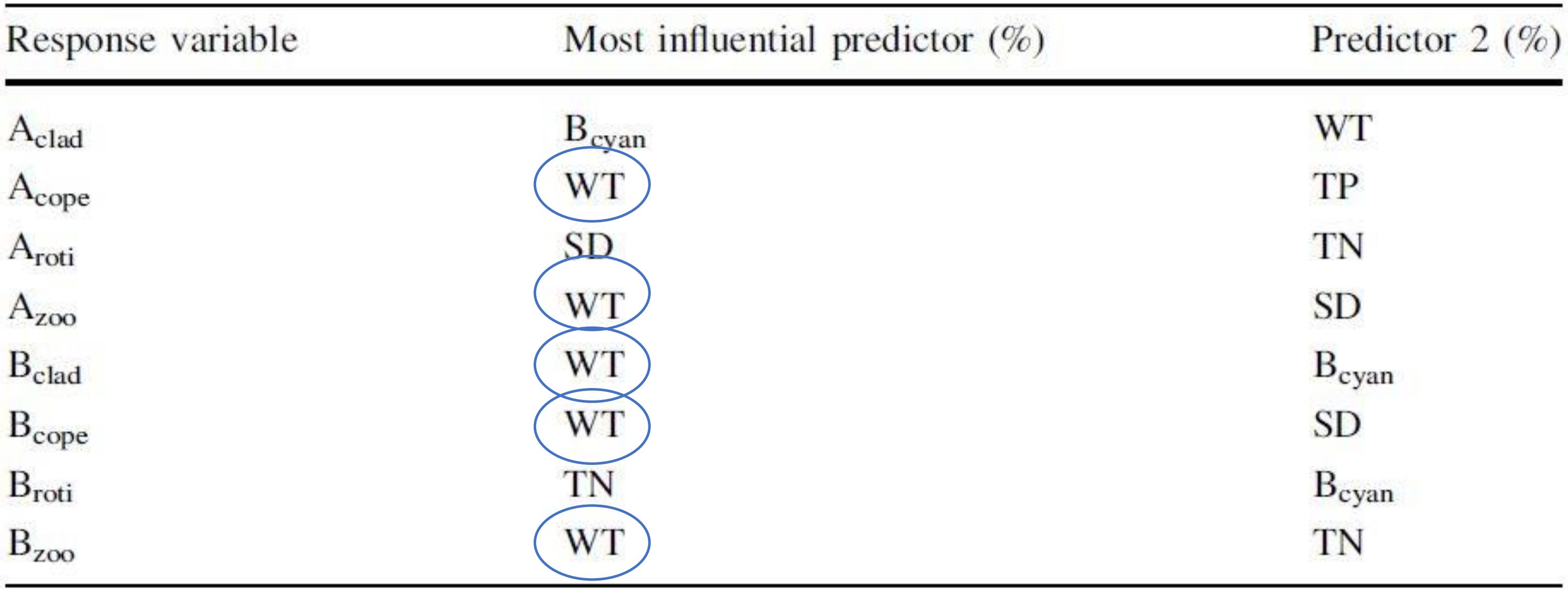


Multivariate linear regression



Peipsi

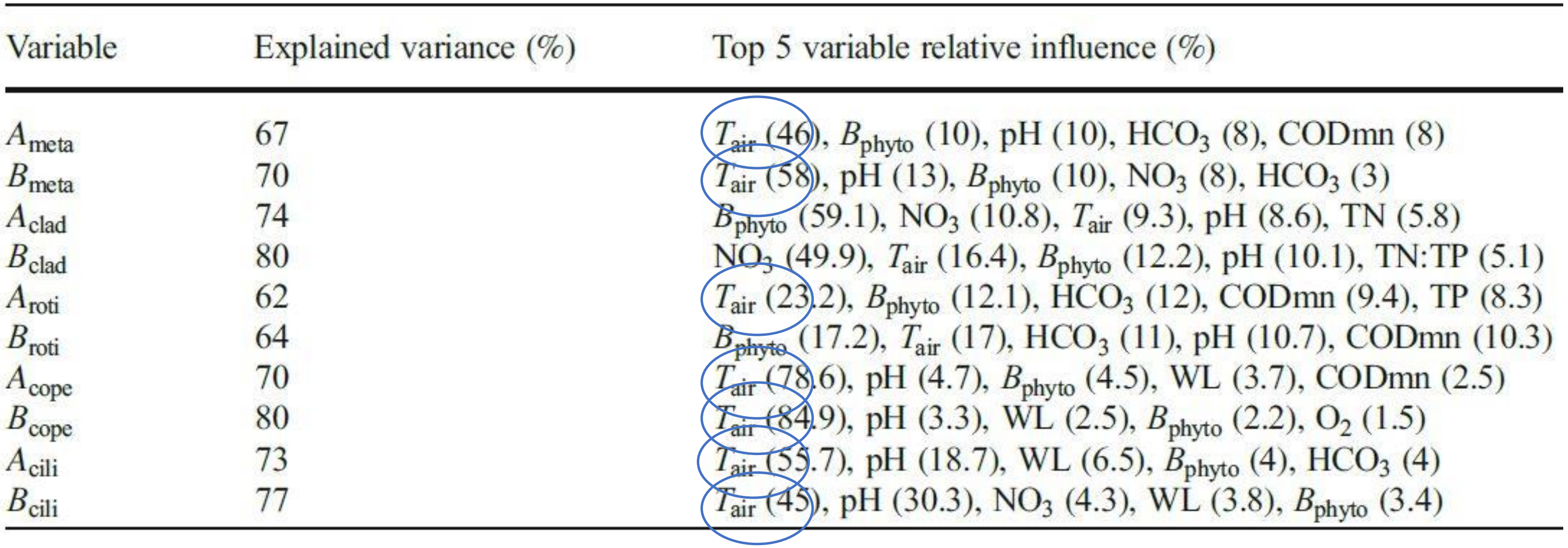
Water temperature is the dominant stressor, followed by the **biomass of cyanobacteria** and **Secchi depth**.



Response variable	Most influential predictor (%)	Predictor 2 (%)
A_{clad}	B_{cyan}	WT
A_{cope}	WT	TP
A_{roti}	SD	TN
A_{zoo}	WT	SD
B_{clad}	WT	B_{cyan}
B_{cope}	WT	SD
B_{roti}	TN	B_{cyan}
B_{zoo}	WT	TN

Võrtsjärv

Air temperature is the dominant stressor, followed by **pH** and the biomass of phytoplankton.



Variable	Explained variance (%)	Top 5 variable relative influence (%)
A_{meta}	67	T_{air} (46), B_{phyto} (10), pH (10), HCO_3 (8), CODmn (8)
B_{meta}	70	T_{air} (58), pH (13), B_{phyto} (10), NO_3 (8), HCO_3 (3)
A_{clad}	74	B_{phyto} (59.1), NO_3 (10.8), T_{air} (9.3), pH (8.6), TN (5.8)
B_{clad}	80	NO_3 (49.9), T_{air} (16.4), B_{phyto} (12.2), pH (10.1), TN:TP (5.1)
A_{roti}	62	T_{air} (23.2), B_{phyto} (12.1), HCO_3 (12), CODmn (9.4), TP (8.3)
B_{roti}	64	B_{phyto} (17.2), T_{air} (17), HCO_3 (11), pH (10.7), CODmn (10.3)
A_{cope}	70	T_{air} (78.6), pH (4.7), B_{phyto} (4.5), WL (3.7), CODmn (2.5)
B_{cope}	80	T_{air} (84.9), pH (3.3), WL (2.5), B_{phyto} (2.2), O_2 (1.5)
A_{cili}	73	T_{air} (55.7), pH (18.7), WL (6.5), B_{phyto} (4), HCO_3 (4)
B_{cili}	77	T_{air} (45), pH (30.3), NO_3 (4.3), WL (3.8), B_{phyto} (3.4)

Cremona et al. 2020 (*Climatic Change*)
Cremona et al. 2021 (*Hydrobiologia*)

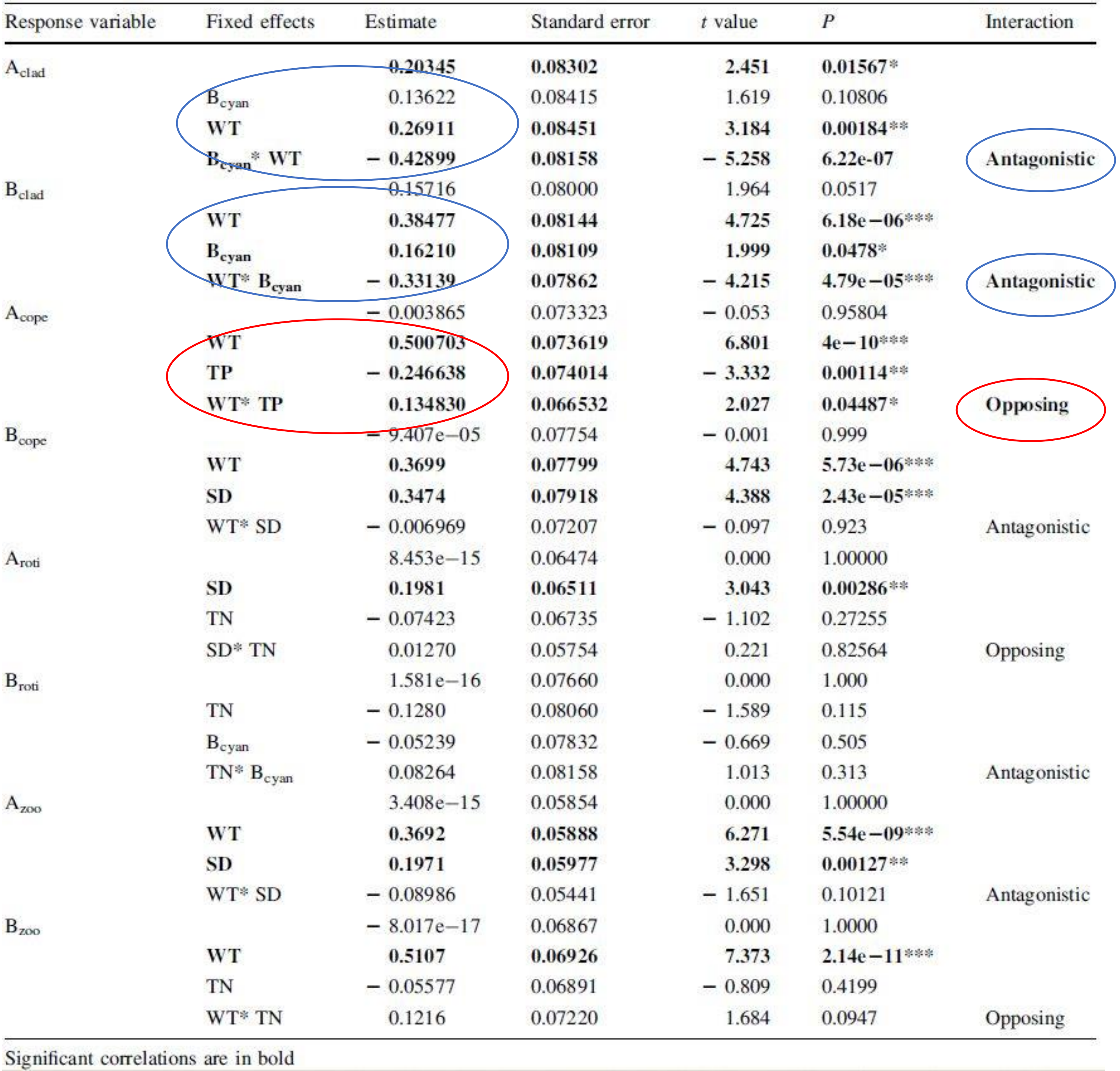
Peipsi

Antagonistic interactions:

Temperature and cyanobacteria have **individual positive effect** on zooplankton, but **negative effect together**

Opposing interaction:

Temperature and phosphorus counteract each other



Response variable	Fixed effects	Estimate	Standard error	*t* value	*P*	Interaction
A_{clad}		**0.20345**	**0.08302**	**2.451**	**0.01567***	
	B_{cyan}	0.13622	0.08415	1.619	0.10806	
	WT	**0.26911**	**0.08451**	**3.184**	**0.00184****	
	B_{cyan}* WT	**− 0.42899**	**0.08158**	**− 5.258**	**6.22e-07**	**Antagonistic**
B_{clad}		0.15716	0.08000	1.964	0.0517	
	WT	**0.38477**	**0.08144**	**4.725**	**6.18e−06*****	
	B_{cyan}	**0.16210**	**0.08109**	**1.999**	**0.0478***	
	WT* B_{cyan}	**− 0.33139**	**0.07862**	**− 4.215**	**4.79e−05*****	**Antagonistic**
A_{cope}		− 0.003865	0.073323	− 0.053	0.95804	
	WT	**0.500703**	**0.073619**	**6.801**	**4e−10*****	
	TP	**− 0.246638**	**0.074014**	**− 3.332**	**0.00114****	
	WT* TP	**0.134830**	**0.066532**	**2.027**	**0.04487***	**Opposing**
B_{cope}		− 9.407e−05	0.07754	− 0.001	0.999	
	WT	**0.3699**	**0.07799**	**4.743**	**5.73e−06*****	
	SD	**0.3474**	**0.07918**	**4.388**	**2.43e−05*****	
	WT* SD	− 0.006969	0.07207	− 0.097	0.923	Antagonistic
A_{roti}		8.453e−15	0.06474	0.000	1.00000	
	SD	**0.1981**	**0.06511**	**3.043**	**0.00286****	
	TN	− 0.07423	0.06735	− 1.102	0.27255	
	SD* TN	0.01270	0.05754	0.221	0.82564	Opposing
B_{roti}		1.581e−16	0.07660	0.000	1.000	
	TN	− 0.1280	0.08060	− 1.589	0.115	
	B_{cyan}	− 0.05239	0.07832	− 0.669	0.505	
	TN* B_{cyan}	0.08264	0.08158	1.013	0.313	Antagonistic
A_{zoo}		3.408e−15	0.05854	0.000	1.00000	
	WT	**0.3692**	**0.05888**	**6.271**	**5.54e−09*****	
	SD	**0.1971**	**0.05977**	**3.298**	**0.00127****	
	WT* SD	− 0.08986	0.05441	− 1.651	0.10121	Antagonistic
B_{zoo}		− 8.017e−17	0.06867	0.000	1.0000	
	WT	**0.5107**	**0.06926**	**7.373**	**2.14e−11*****	
	TN	− 0.05577	0.06891	− 0.809	0.4199	
	WT* TN	0.1216	0.07220	1.684	0.0947	Opposing

Significant correlations are in bold

Cremona et al. 2021 (*Hydrobiologia*)

Võrtsjärv

Antagonistic interactions:

Temperature and cyanobacteria have **individual positive effect** on the abundance of Cladocerans, but **negative effect together**

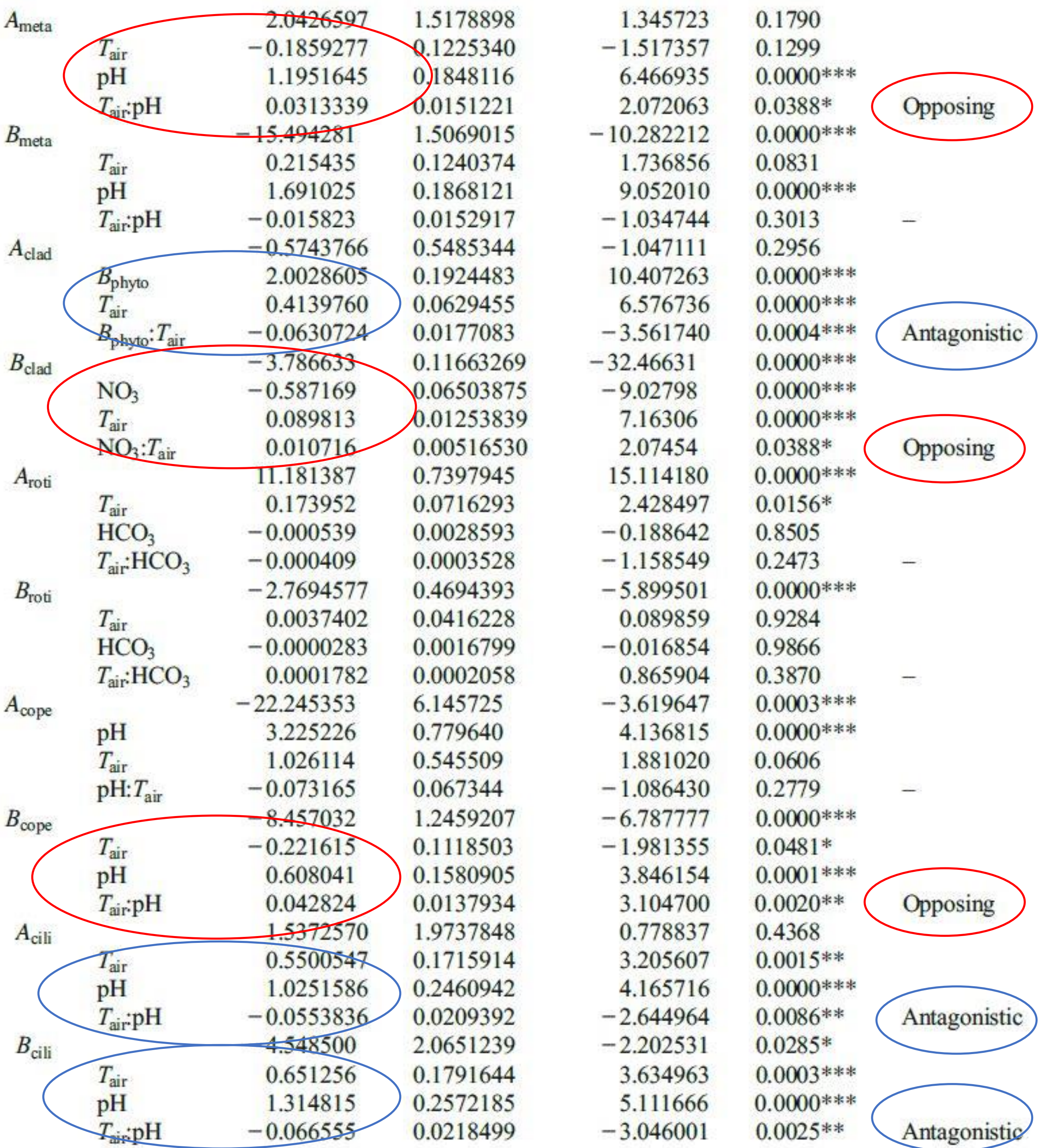
Same for Temperature and pH for ciliates

Opposing interaction:

Temperature and nitrates counteract each other for the biomass of Cladocerans

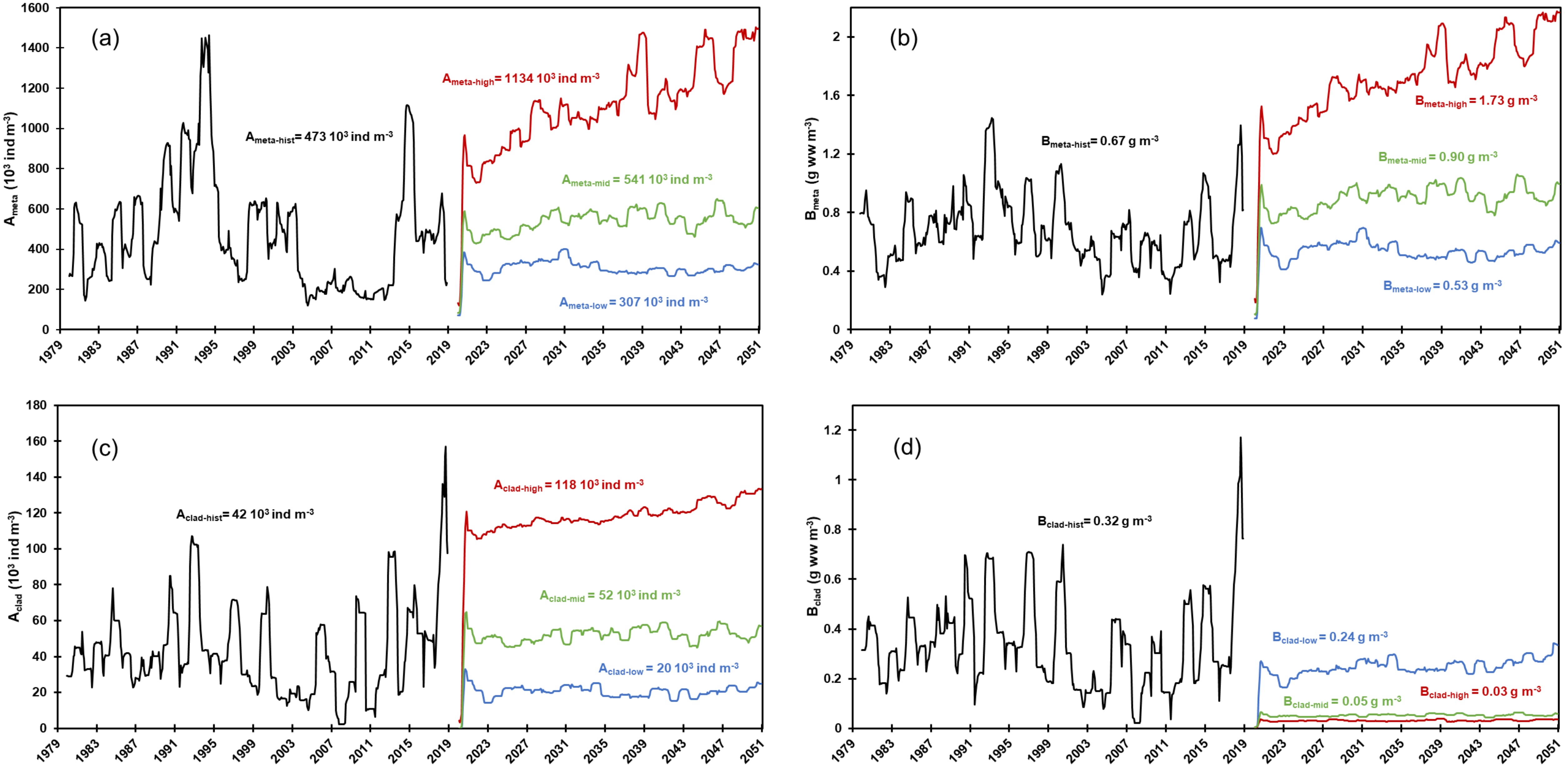
Same for temperature and pH for the abundance of metazooplankton

Cremona et al. 2020 (*Climatic Change*)

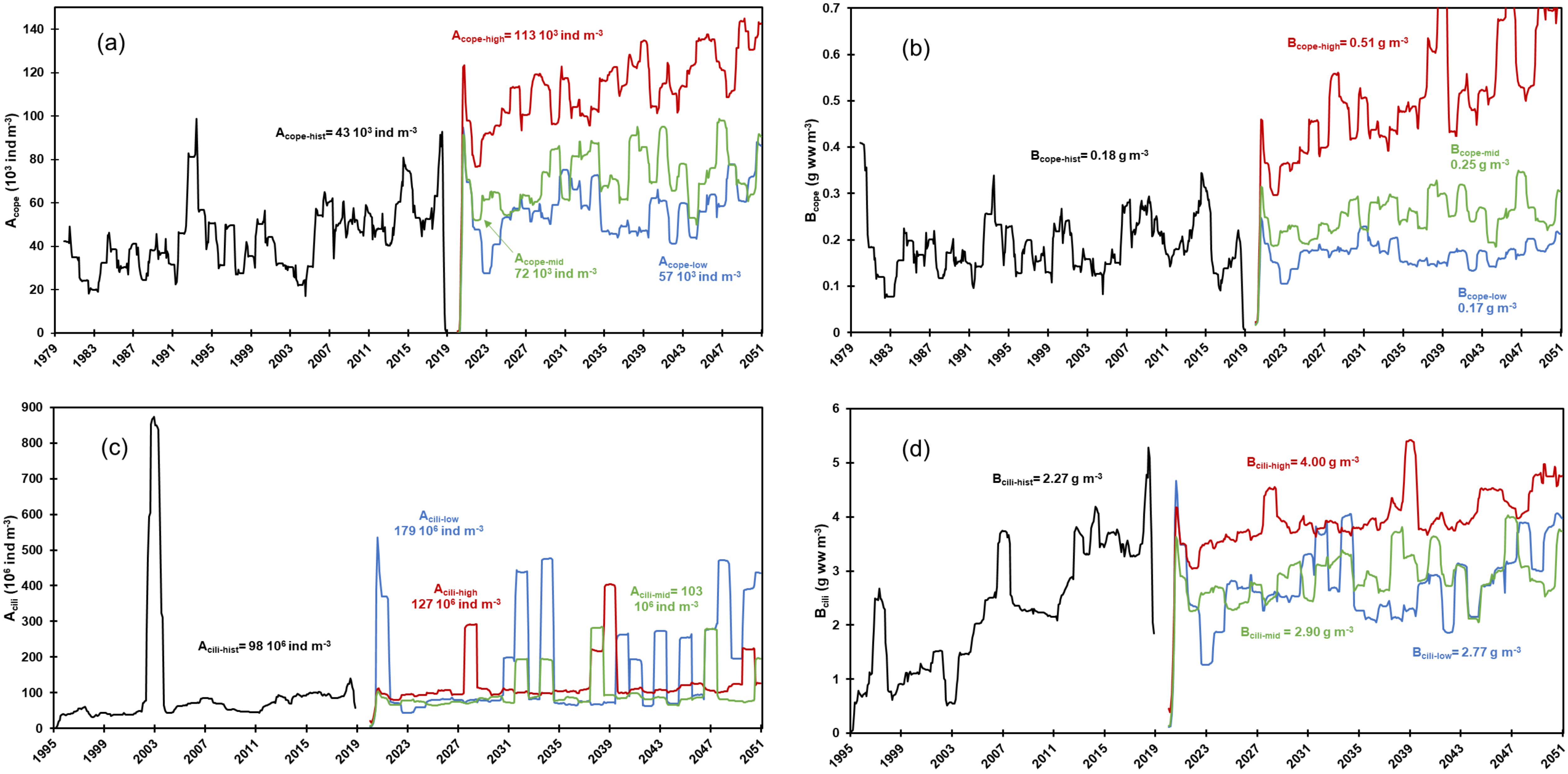


A_{meta}		2.0426597	1.5178898	1.345723	0.1790	
	T_{air}	−0.1859277	0.1225340	−1.517357	0.1299	
	pH	1.1951645	0.1848116	6.466935	0.0000***	
	T_{air}:pH	0.0313339	0.0151221	2.072063	0.0388*	Opposing
B_{meta}		−15.494281	1.5069015	−10.282212	0.0000***	
	T_{air}	0.215435	0.1240374	1.736856	0.0831	
	pH	1.691025	0.1868121	9.052010	0.0000***	
	T_{air}:pH	−0.015823	0.0152917	−1.034744	0.3013	–
A_{clad}		−0.5743766	0.5485344	−1.047111	0.2956	
	B_{phyto}	2.0028605	0.1924483	10.407263	0.0000***	
	T_{air}	0.4139760	0.0629455	6.576736	0.0000***	
	B_{phyto}:T_{air}	−0.0630724	0.0177083	−3.561740	0.0004***	Antagonistic
B_{clad}		−3.786633	0.11663269	−32.46631	0.0000***	
	NO_3	−0.587169	0.06503875	−9.02798	0.0000***	
	T_{air}	0.089813	0.01253839	7.16306	0.0000***	
	NO_3:T_{air}	0.010716	0.00516530	2.07454	0.0388*	Opposing
A_{roti}		11.181387	0.7397945	15.114180	0.0000***	
	T_{air}	0.173952	0.0716293	2.428497	0.0156*	
	HCO_3	−0.000539	0.0028593	−0.188642	0.8505	
	T_{air}:HCO_3	−0.000409	0.0003528	−1.158549	0.2473	–
B_{roti}		−2.7694577	0.4694393	−5.899501	0.0000***	
	T_{air}	0.0037402	0.0416228	0.089859	0.9284	
	HCO_3	−0.0000283	0.0016799	−0.016854	0.9866	
	T_{air}:HCO_3	0.0001782	0.0002058	0.865904	0.3870	–
A_{cope}		−22.245353	6.145725	−3.619647	0.0003***	
	pH	3.225226	0.779640	4.136815	0.0000***	
	T_{air}	1.026114	0.545509	1.881020	0.0606	
	pH:T_{air}	−0.073165	0.067344	−1.086430	0.2779	–
B_{cope}		−8.457032	1.2459207	−6.787777	0.0000***	
	T_{air}	−0.221615	0.1118503	−1.981355	0.0481*	
	pH	0.608041	0.1580905	3.846154	0.0001***	
	T_{air}:pH	0.042824	0.0137934	3.104700	0.0020**	Opposing
A_{cili}		1.5372570	1.9737848	0.778837	0.4368	
	T_{air}	0.5500547	0.1715914	3.205607	0.0015**	
	pH	1.0251586	0.2460942	4.165716	0.0000***	
	T_{air}:pH	−0.0553836	0.0209392	−2.644964	0.0086**	Antagonistic
B_{cili}		−4.548500	2.0651239	−2.202531	0.0285*	
	T_{air}	0.651256	0.1791644	3.634963	0.0003***	
	pH	1.314815	0.2572185	5.111666	0.0000***	
	T_{air}:pH	−0.066555	0.0218499	−3.046001	0.0025**	Antagonistic

Simulation of future conditions in Võrtsjärv : **rise** of total zooplankton biomass, but **decrease** of Cladocerans (large)



Simulation of future conditions in Võrtsjärv : **rise** of Copepods, no change for ciliates



Take home messages

-> temperature is the strongest stressor affecting zooplankton

-> multiple stressors affect zooplankton in both lakes

-> most interactions are opposing or antagonistic

-> global warming would favor smaller zooplankters (Copepods) at the expense of larger ones (Cladocerans)

Thank you for your attention !

☺

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