Benthic diatom index for water quality biomonitoring of Danish running waters

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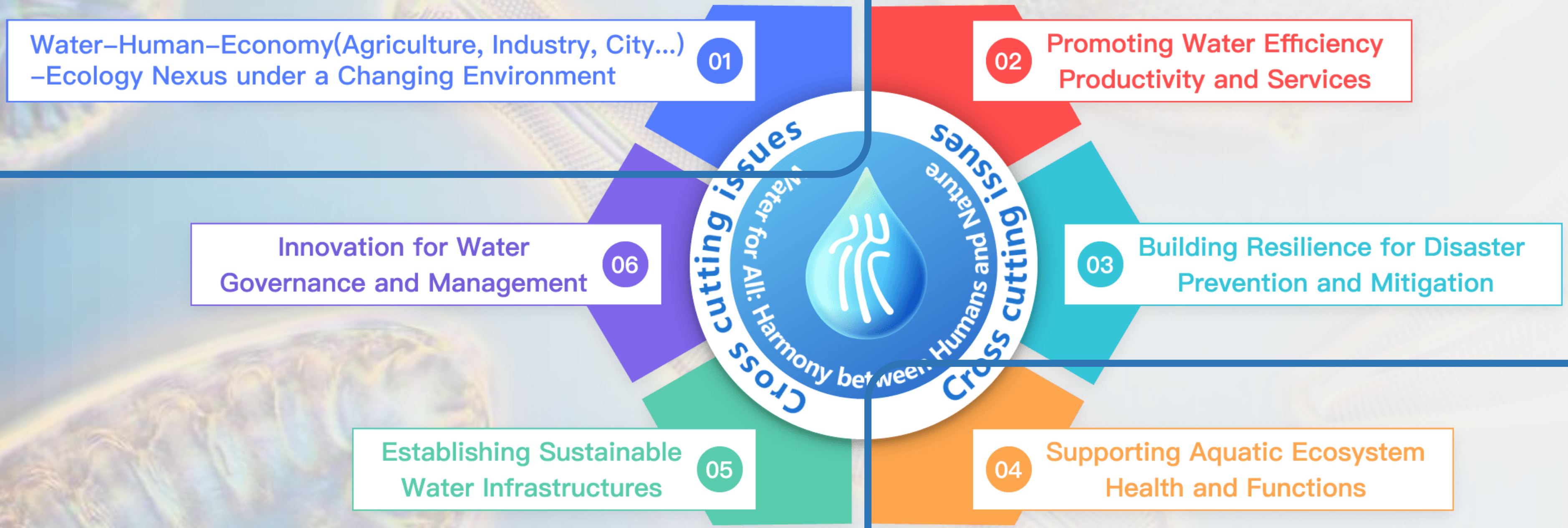
AARHUS UNIVERSITY

XVIII
World Water Congress
International Water Resources Association(IWRA)
Beijing, China | September 11-15, 2023

Biomonitoring of freshwaters



Biomonitoring

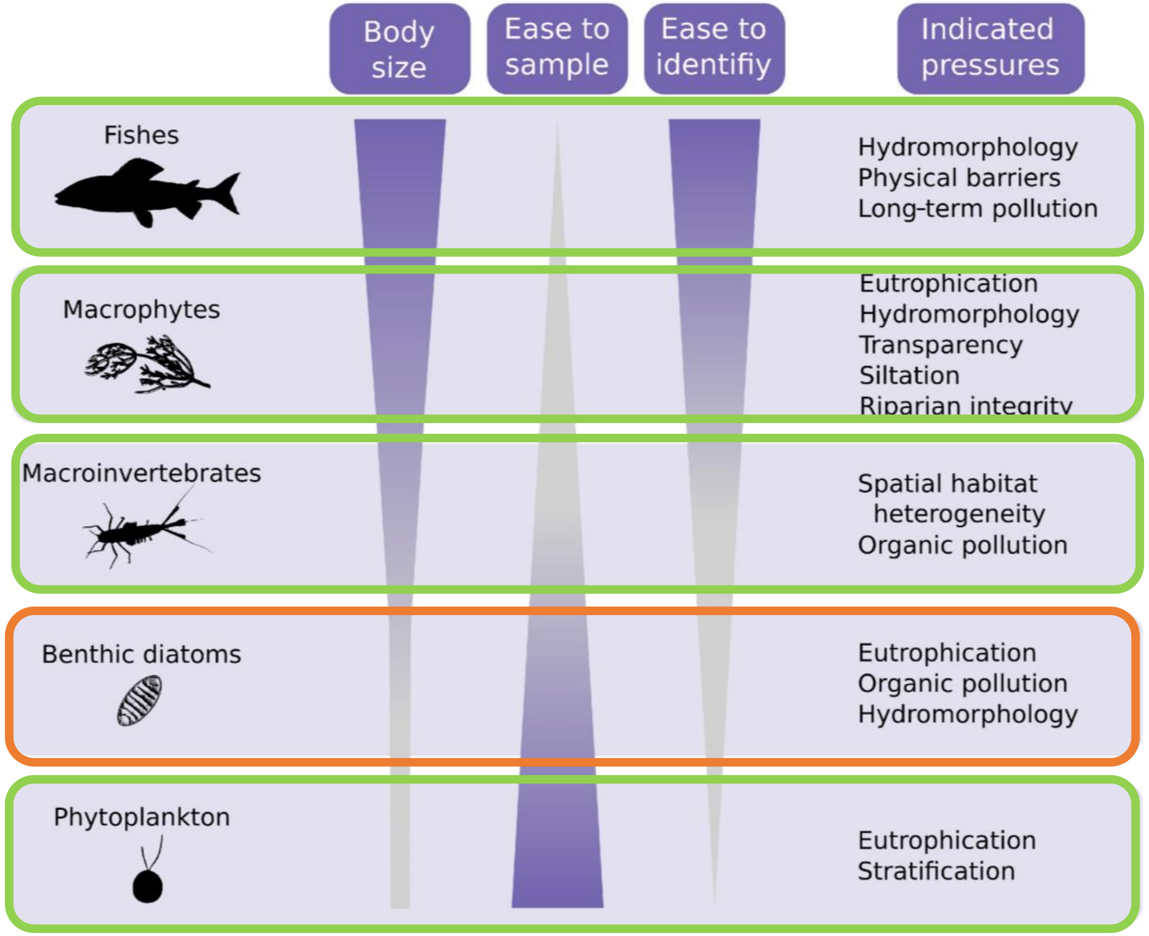
Integrate spatial + temporal alterations of water quality

Ecological responses to environmental impacts (structural + functional)

EU Water Framework Directive - Denmark

Fauna: Fish
Macroinvertebrates

Flora: Macrophytes
Phytoplankton (lakes)
Benthic algae



SID_TID benthic algal index (**Andersen *et al.*, 2018**)

To assess **ecological status** in Danish running waters

(eutrophication, e.g., orthophosphate - PO_4-P)

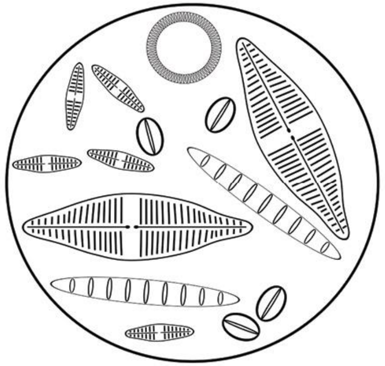
2013 - 2016

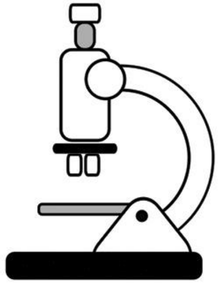
524 monitoring stations in streams - 100m reaches

Other physical-chemical monitoring measures

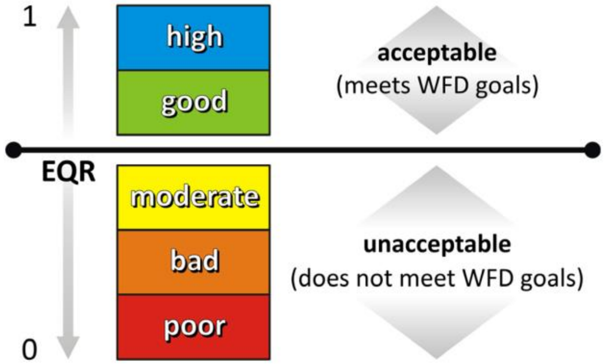
1 taxonomic group: **Diatoms** (Bacillariophyceae) to **species** level

Environmental variables to **Diatom** composition





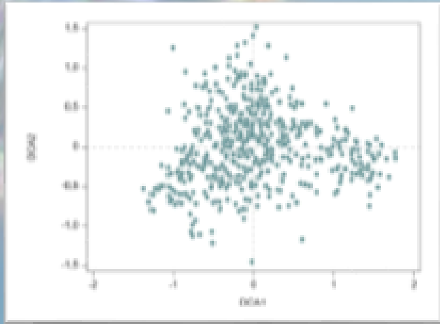
	Taxa	%
	sp. 1	28.6
	sp. 2	35.6
	sp. 3	14.3
	sp. 4	7.2
	sp. 5	14.3



Diatom composition responses to environment

Main environmental gradients (DCA analysis)

PO_4-P + alkalinity + organic matter



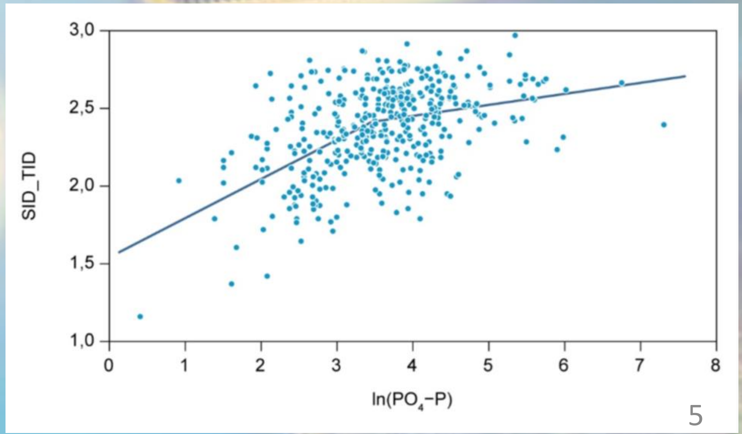
https://omnidia.fr

Ecological Indices + Statistics for Diatoms

18 Diatom **Indices** tested

species sensitivity to eutrophication

Correlation of indices to environmental gradients



Saprobic **D**iatom **I**ndex + **T**rophic **D**iatom **I**ndex: **SID_TID** explained highest variance (26%) of PO_4-P concentration

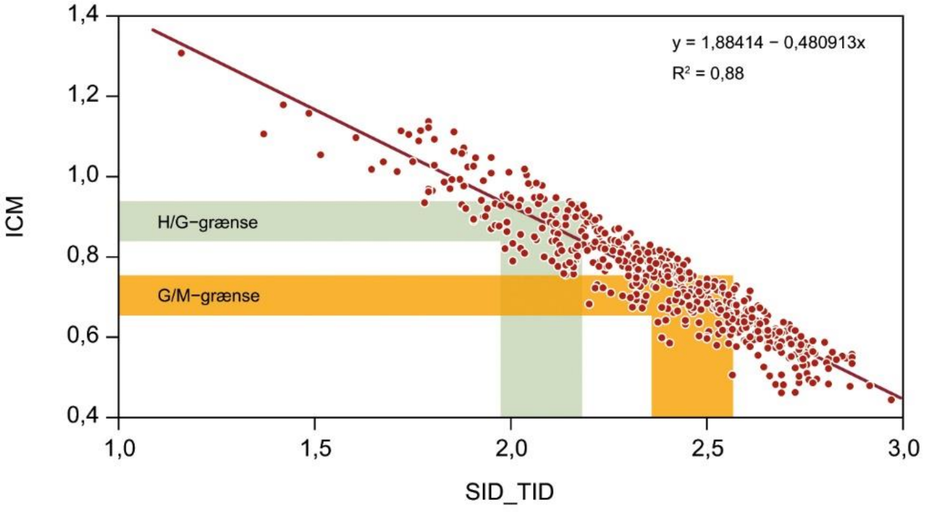
Indices used (alone or combined) in several EU countries

(**Andersen** *et al.*, 2018)

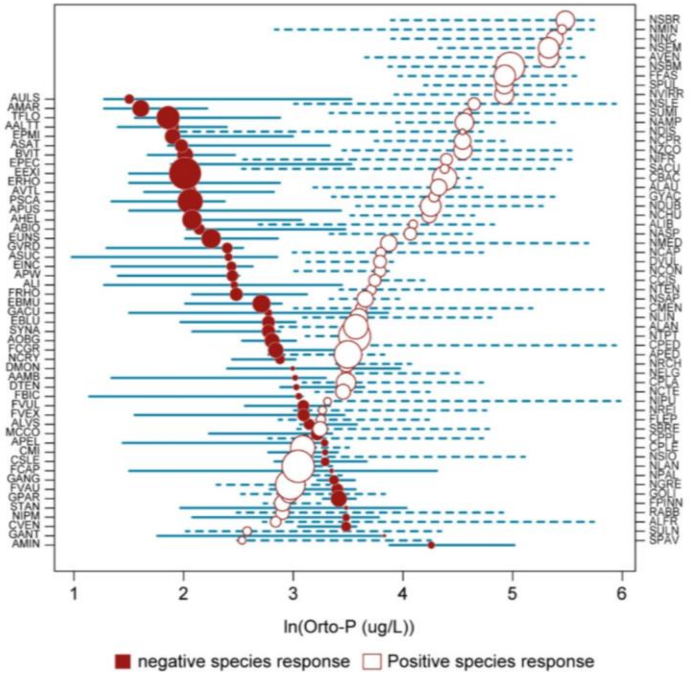
Intercalibration with other indices for EU-WFD countries

Consistency on ecological status evaluation

Intercalibration Common Metric (ICM)
by ranges of water quality



Diatom Species Responses to PO_4-P
Thresholds of compositional changes (TITAN)



(Lecointe *et al.*, 1993; Kelly *et al.*, 2009; Kalyoncu & Serbetci 2013; Andersen *et al.*, 2018)

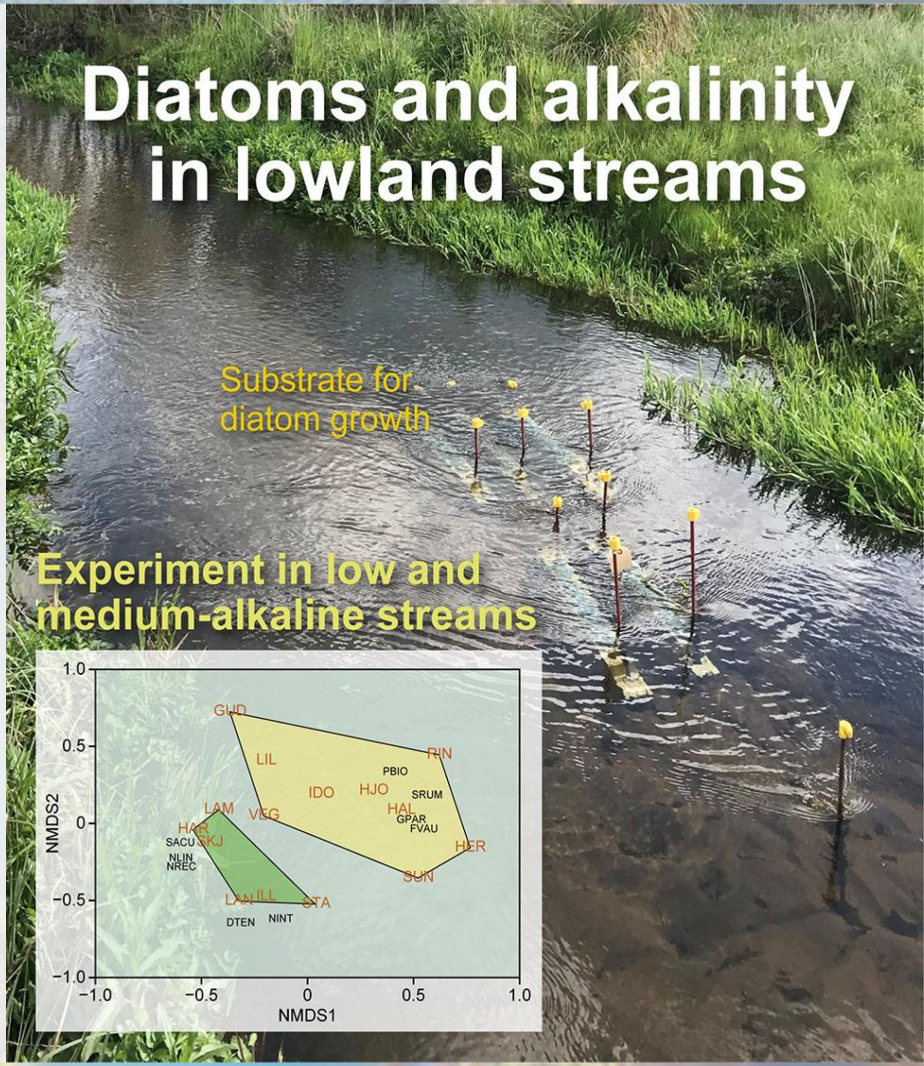
Diatom species composition >> **SID_TID benthic algal index** is influenced both by

PO_4-P + **Alkalinity**

> **fail** to achieve good ecological **status** due to high **alkalinity** (regardless of PO_4-P)

Difficult to disentangle effects of **natural-influenced alkalinity** from **human-driven eutrophication**.

Field survey + experiments: **diatom species** ⊕ to **Alk** and ⊖ to **PO_4-P**



(Baattrup-Pedersen, *et al.,* 2021; Baattrup-Pedersen, *et al.,* 2022)

Purpose:

To disentangle the role of **alkalinity** from **PO_4-P** on the probability of **achieving good ecological status** (SID_TID) on Danish watercourses

To evaluate the ability of **target diatom species** to separate the influence of **alkalinity** from **PO_4-P** on SID_TID assessments

Technical implementation:

1. Literature **review** on the co-variation of **alkalinity** and **PO_4-P** in freshwaters (ISI-web of knowledge + Google)

2. Physicochemical + diatom **data compilation** 2013 - 2020 Danish streams
   Overfladevandsdatabasen (ODA) + Miljøstyrelsen – OMNIDIA

3. **SID_TID** index along gradients of **alkalinity** and **PO_4-P**

4. Target **diatom species** (high alkalinity + low PO_4 from previous studies)
   to alkalinity + PO_4-P gradients (larger dataset)

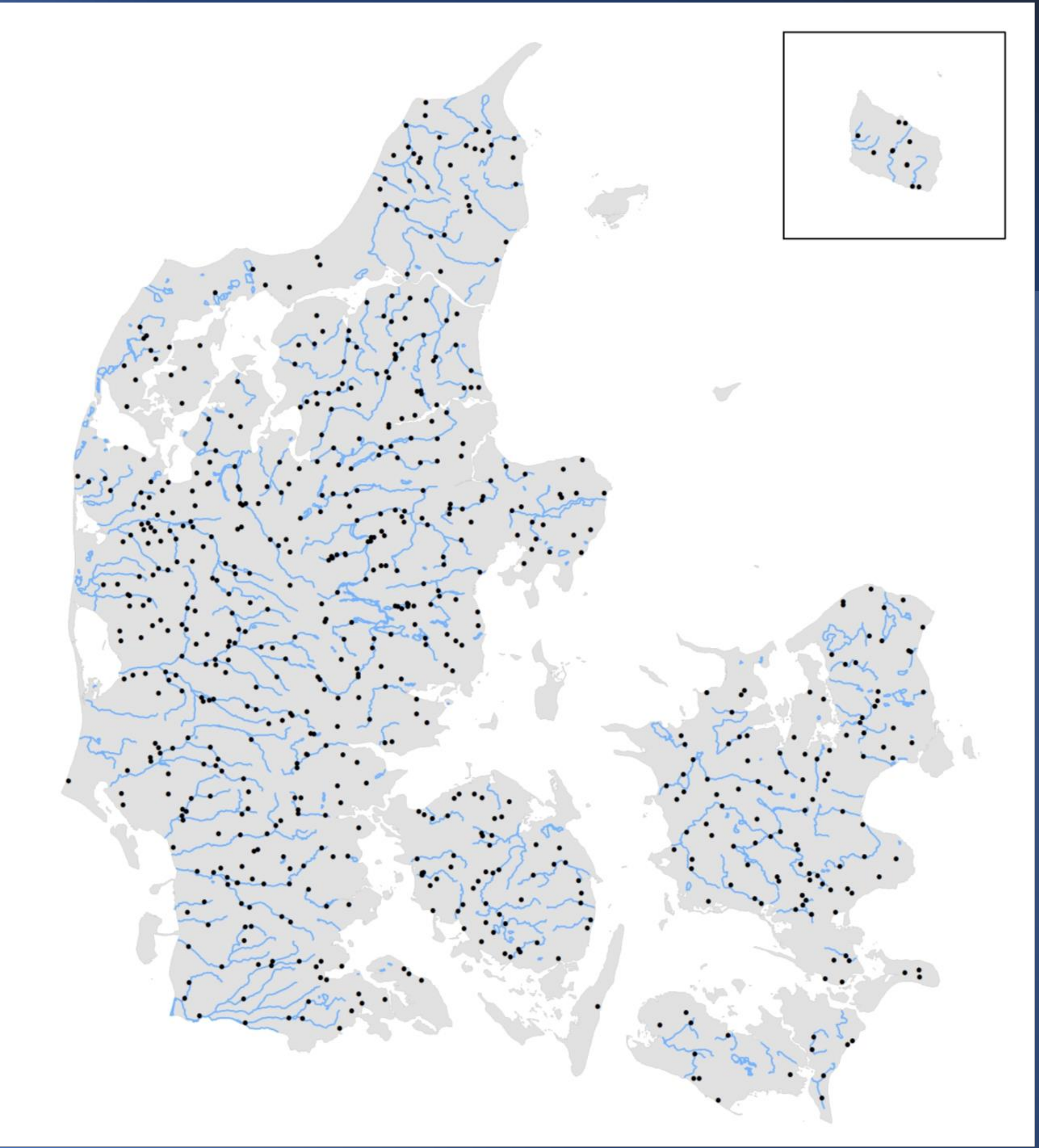
5. Empirical relationship between **SID_TID to alkalinity** >
   developed **probability models** of achieving **good ecological status** /
   critical alkalinity levels – interference to assess eutrophication

(https://omnidia.fr/en/; Pacheco et al., 2023)

Total n= **1036** sample sites / times

2013 - 2020

Physicochemical (Alkalinity + PO_4-P)
+
Benthic algae data (species + SID_TID)



Review:

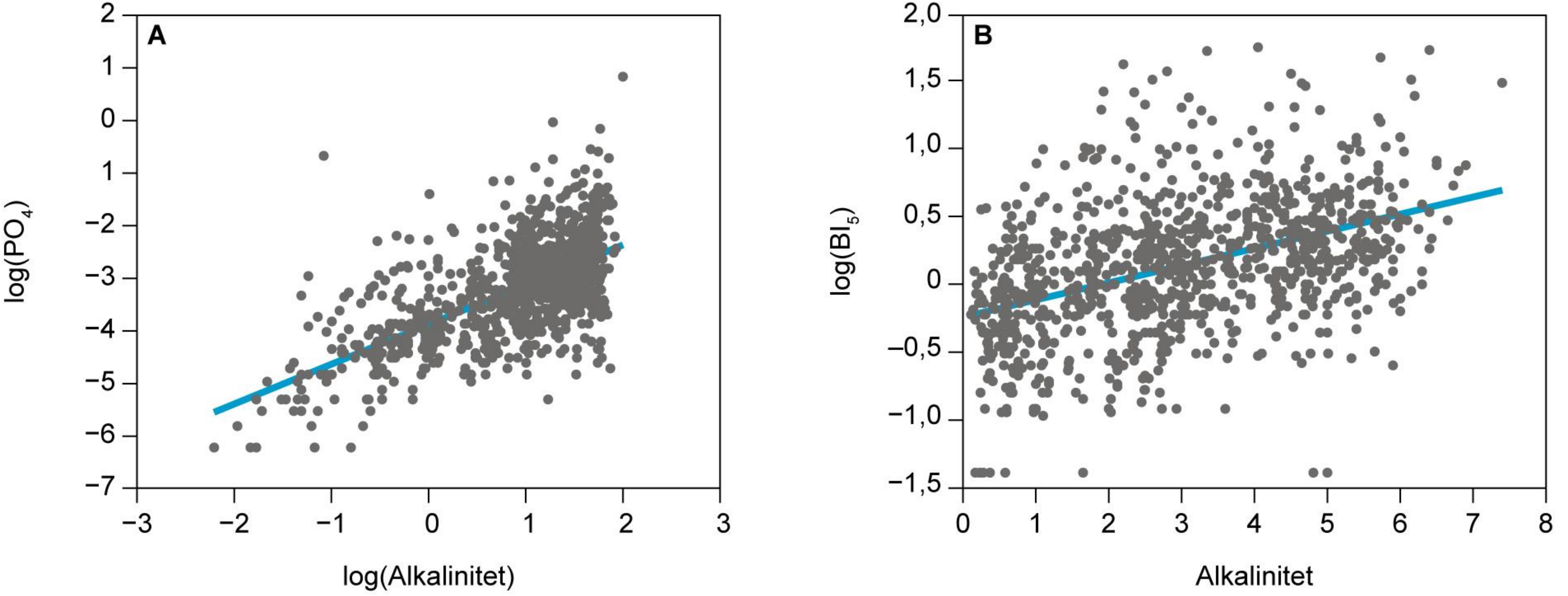
Diatom **species** were associated to **high alkalinity** (alkaphilic species) regardless PO_4-P or negatively associated > supporting previous findings

Frequent association of **PO_4** and **alkalinity**

Some associations with **eutrophication - salinization – alkalinization** processes > worldwide pattern

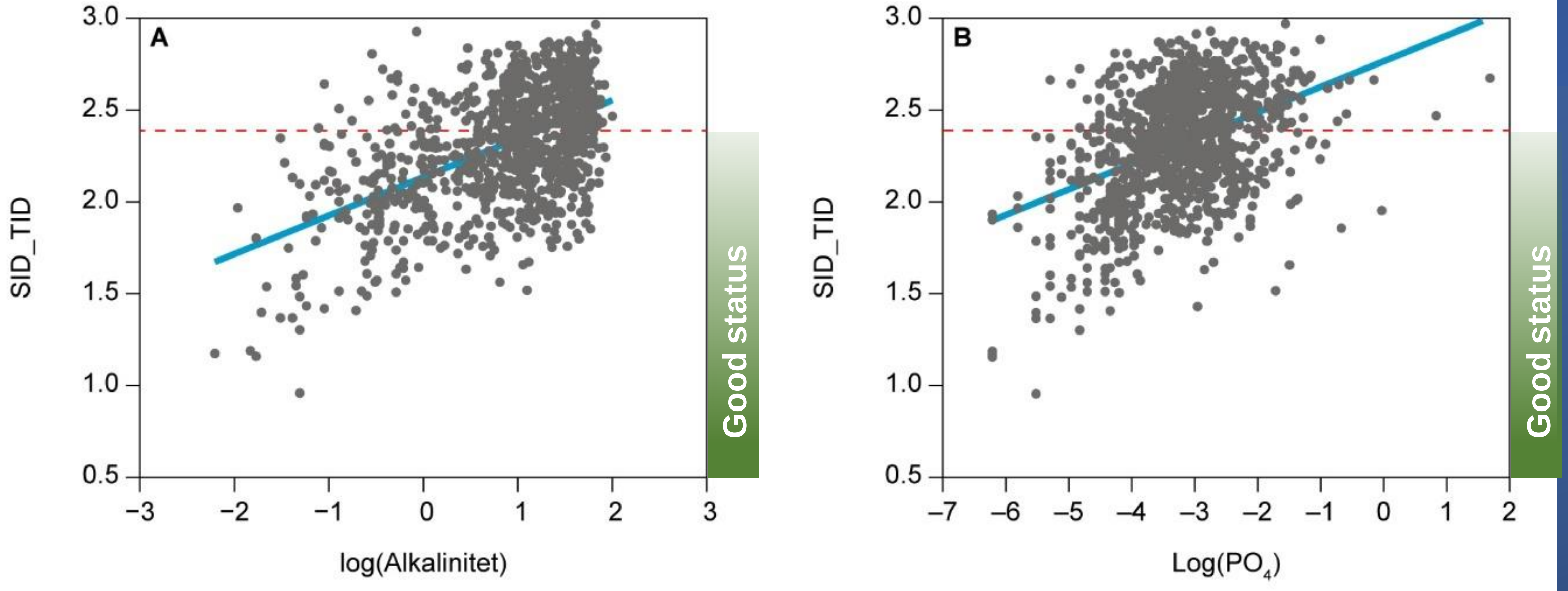
Natural causes + human influence.
E.g., weathering of sedimentary rocks influenced by land use / fertilizers

Alkalinity PO4-P BI5



Equation	Formula	Adjusted R^2	F	p	DF
lm (LogPO4 ~ Log Alk)	LogPO4= -3.876+0.756*LogAlkalinitet	0.41	696.5	<0.001	1016
lm (log BI5 ~ Alk)	LogBI5= -0.242+0.126*Alkalinitet	0.19	230.7	<0.001	999

SID_TID **Alkalinity** **PO_4-P**

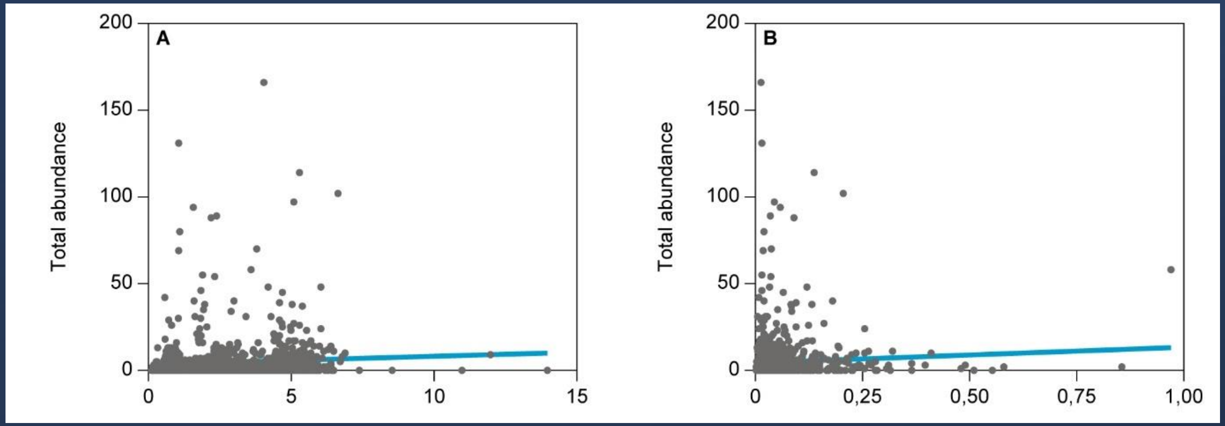


Equation	Formula	Adjusted R^2	F	p	DF
lm (SID_TID ~ Log Alk)	SID_TID= 2.138 +0.480*LogAlkalinitet	0.28	394.9	<0.001	1016
lm (SID_TID ~ Log PO_4)	SID_TID= 2.775 +0.142*LogPO_4	0.18	223.4	<0.001	1016

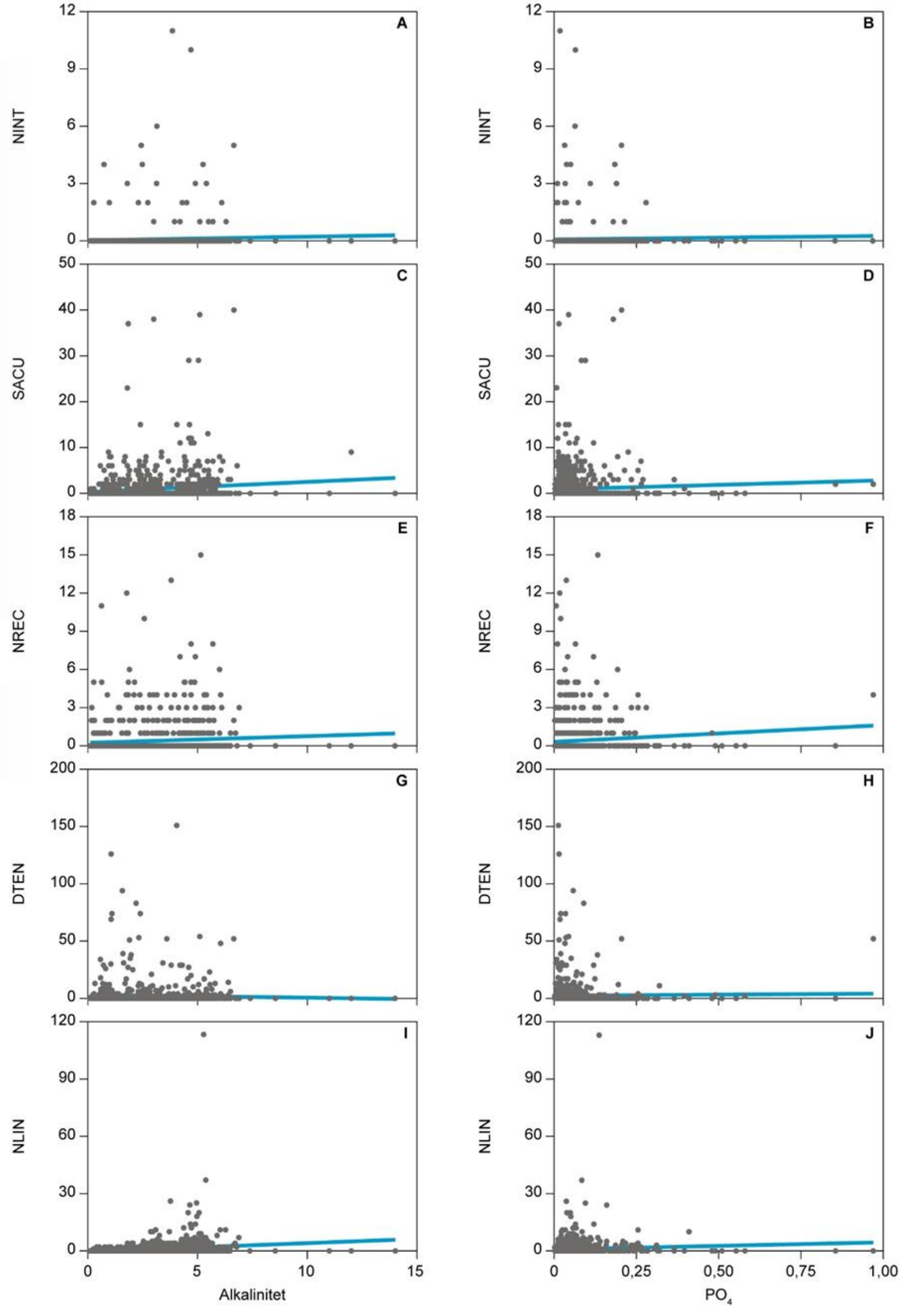
Species abbreviation	Species name	Indicator value for alkalinity	Regression slope	F-value
NINT	*Nitzschia intermedia*	0,512*	0,808	7,56**
SACU	*Synedra acus*	0,486*	1,236	16,12**
NREC	*Nitzschia recta*	0,476*	1,273	6,91*
DTEN	*Diatoma tenue*	0,438*	0,754	41,83***
NLIN	*Nitzschia linearis*	0,41**	1,199	41,79***

(Baattrup-Pedersen, et al., 2021; Baattrup-Pedersen, et al., 2022)

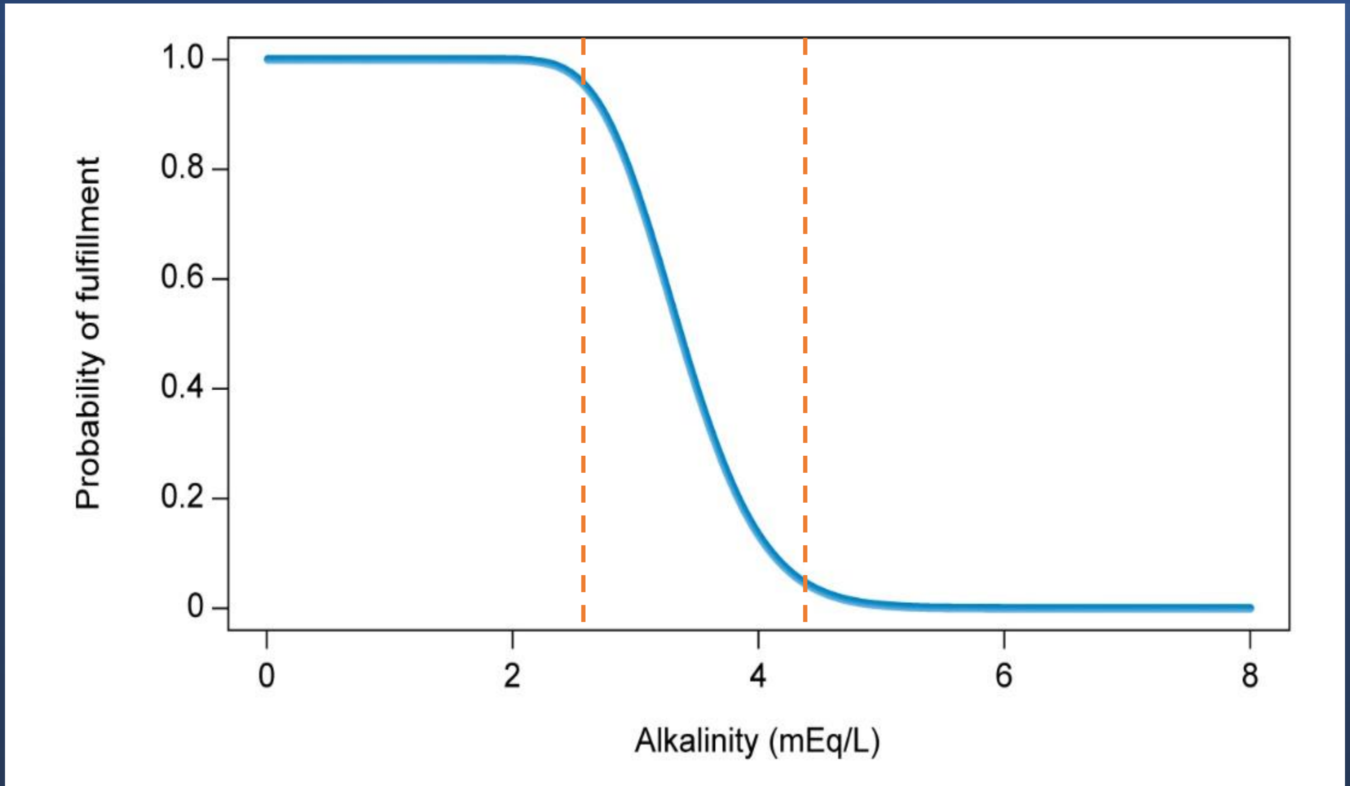
Only poor related or no significant responses



Alkalinity **PO_4-P**



Probability model > Alkalinity



Probability of target fulfillment	Alkalinity (mEq/L)
< 5%	4.352
25%	3.737
50%	3.362
75%	3.024
> 95%	2.597

Expected Quality Reference for SID_TID index (SID_TID < 2.39)

Model: $R2 = 0.28$, $F= 400.92$, p-value < 0.001, $DF= 1022$

Main messages:

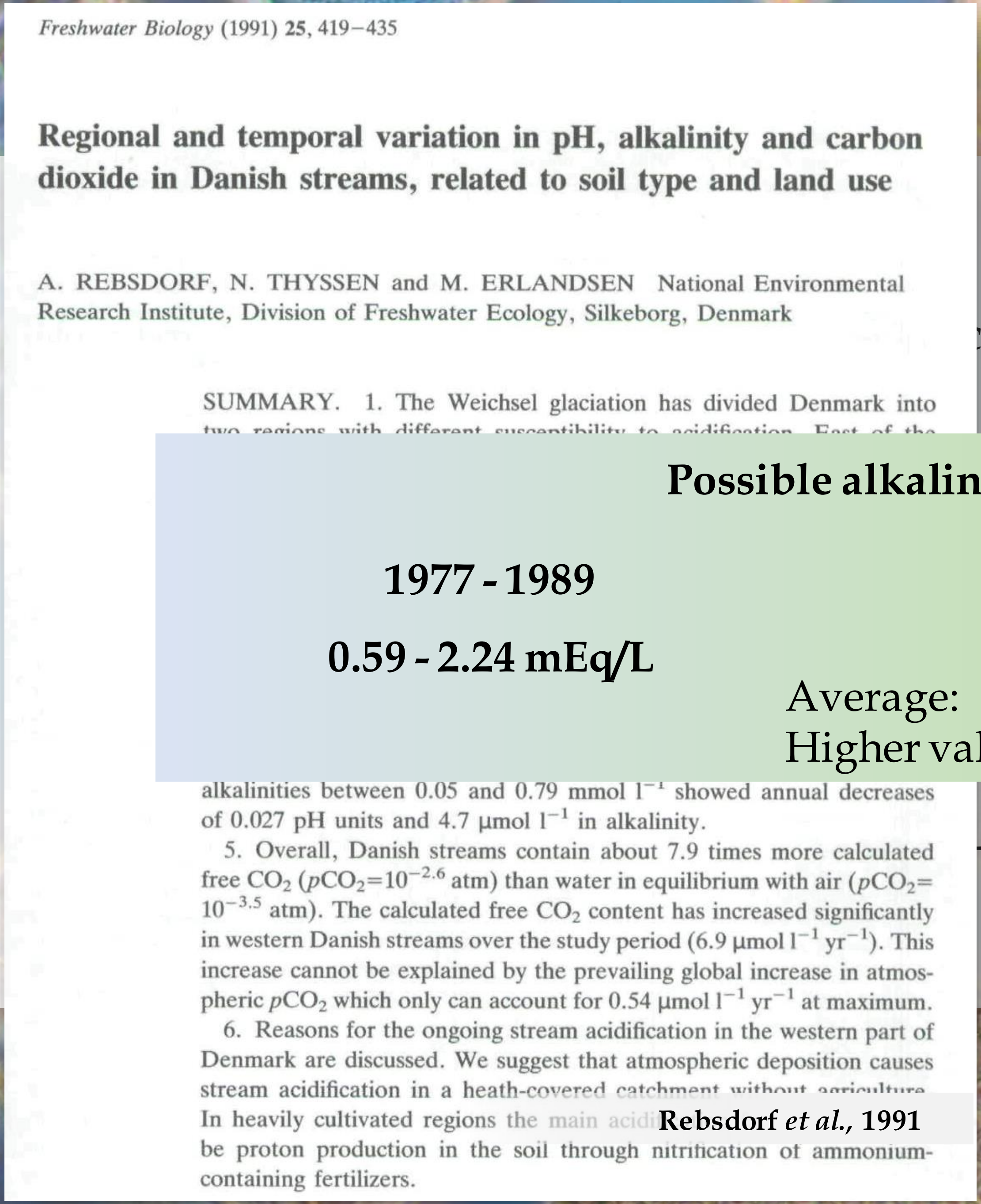
SID_TID is a useful index to evaluate ecological conditions on running waters (*e.g.* eutrophication)

However, it can be **drastically influenced by alkalinity** (confounding factor)

Frequent association of **PO_4-P** and **alkalinity** – affects biomonitoring capacities

Association: **eutrophication + salinization + alkalinization**
Natural causes (lithology) + human influence: agriculture, fertilizers, etc.

Emergent environmental process worldwide - not sufficiently studied in Denmark


Freshwater Biology (1991) **25**, 419–435

Regional and temporal variation in pH, alkalinity and carbon dioxide in Danish streams, related to soil type and land use

A. REBSDORF, N. THYSSEN and M. ERLANDSEN National Environmental Research Institute, Division of Freshwater Ecology, Silkeborg, Denmark

SUMMARY. 1. The Weichsel glaciation has divided Denmark into two regions with different susceptibility to acidification. East of the …

alkalinities between 0.05 and 0.79 mmol l^{-1} showed annual decreases of 0.027 pH units and 4.7 µmol l^{-1} in alkalinity.

5. Overall, Danish streams contain about 7.9 times more calculated free CO_2 ($pCO_2=10^{-2.6}$ atm) than water in equilibrium with air ($pCO_2=10^{-3.5}$ atm). The calculated free CO_2 content has increased significantly in western Danish streams over the study period (6.9 µmol l^{-1} yr^{-1}). This increase cannot be explained by the prevailing global increase in atmospheric pCO_2 which only can account for 0.54 µmol l^{-1} yr^{-1} at maximum.

6. Reasons for the ongoing stream acidification in the western part of Denmark are discussed. We suggest that atmospheric deposition causes stream acidification in a heath-covered catchment without agriculture. In heavily cultivated regions the main acidi… be proton production in the soil through nitrification of ammonium-containing fertilizers.

Rebsdorf *et al.*, 1991

Possible alkalinization of Danish streams

1977 - 1989	2013 - 2020
0.59 - 2.24 mEq/L	**3.07 - 14 mEq/L**

Average: 300 %

Higher values: 700 %

Pacheco *et al.*, 2023

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Benthic diatom index for water quality biomonitoring of Danish running waters

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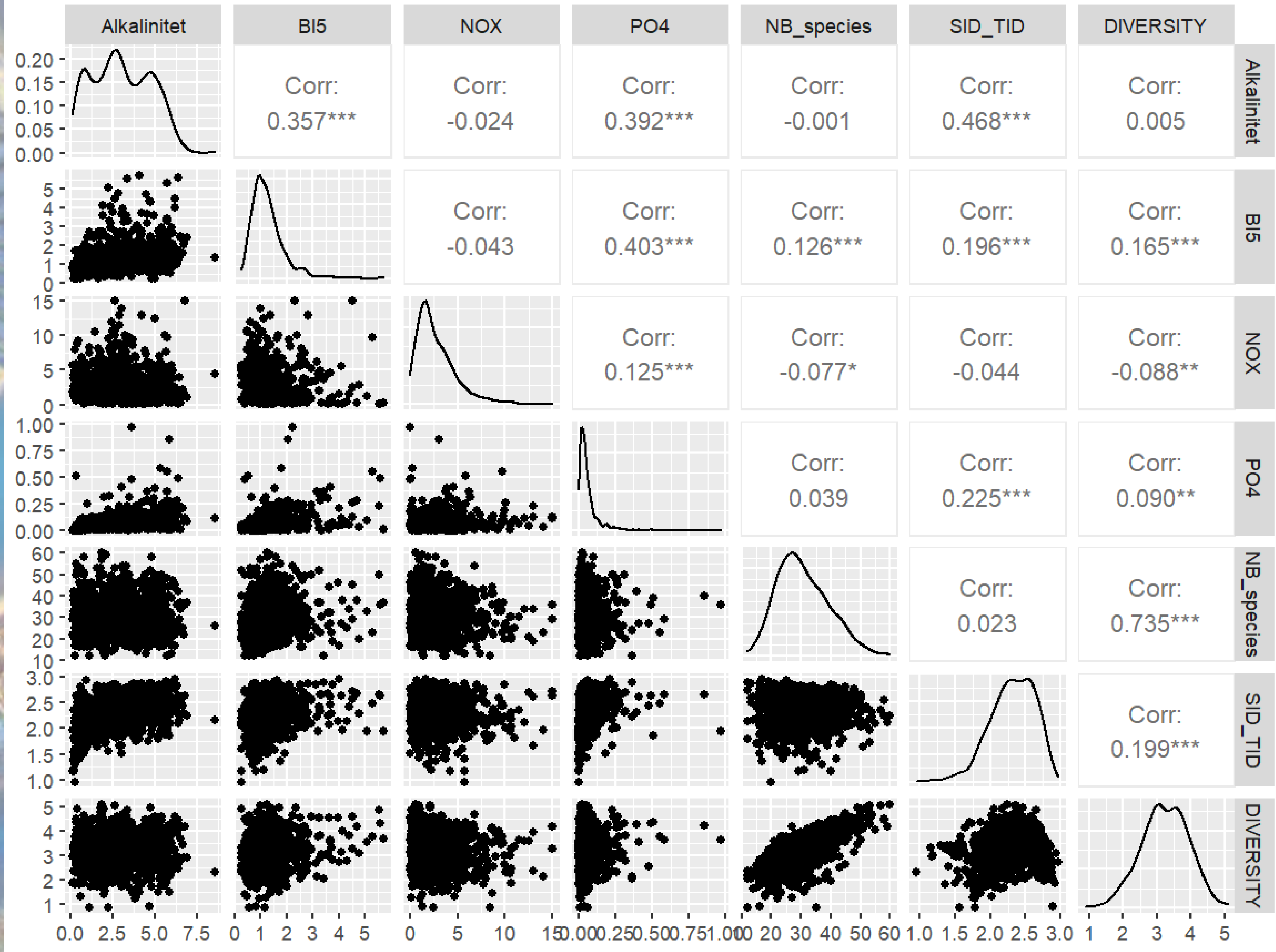
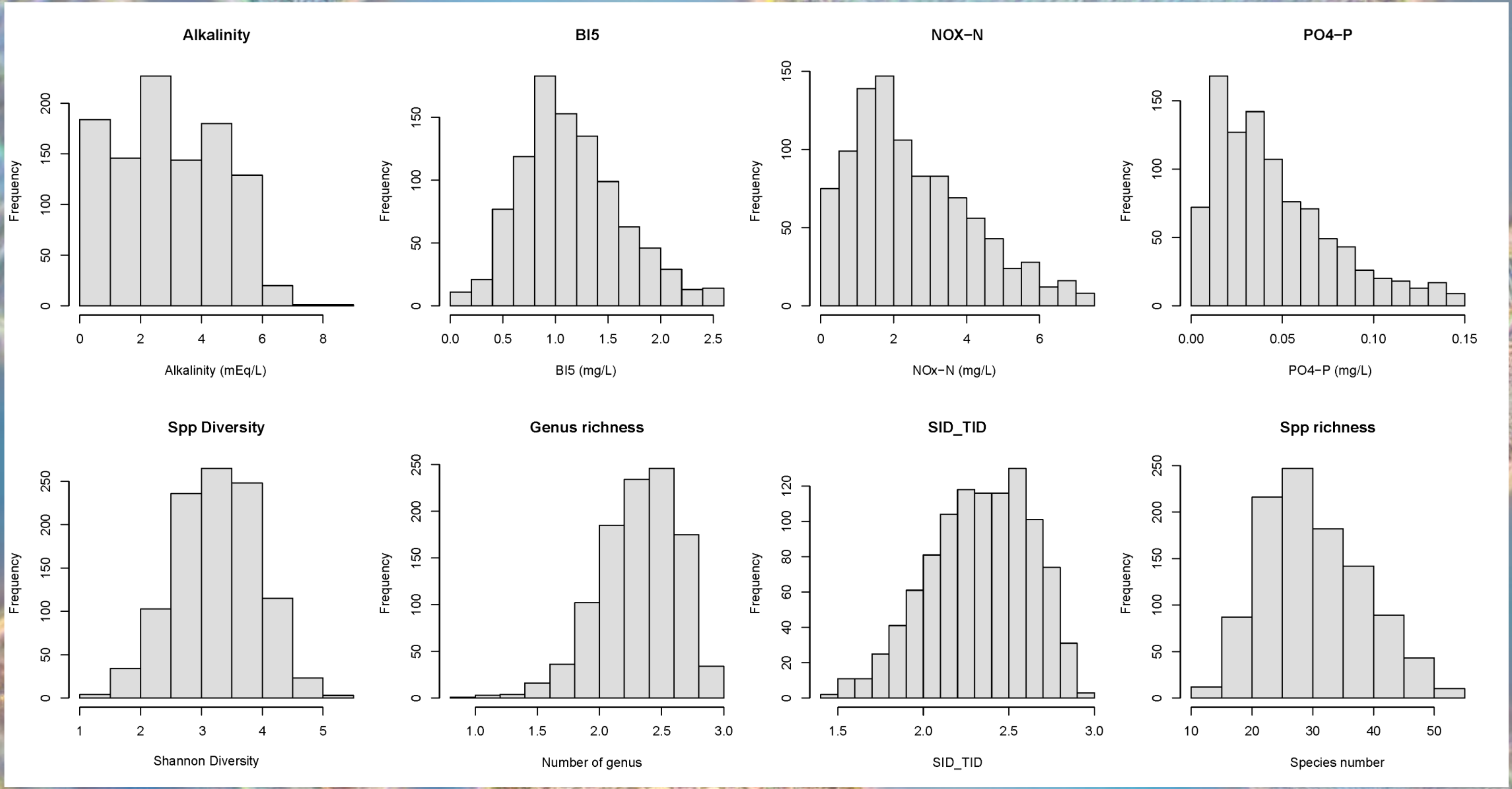
Pearson´s correlogram




Alkalinity
Frequency
Alkalinity (mEq/L)
BI5
Frequency
BI5 (mg/L)
NOX−N
Frequency
NOx−N (mg/L)
PO4−P
Frequency
PO4−P (mg/L)
Spp Diversity
Frequency
Shannon Diversity
Genus richness
Frequency
Number of genus
SID_TID
Frequency
SID_TID
Spp richness
Frequency
Species number

Physicochemical variables

	Alkalinity	Ammonia + ammonium	Nitrite + Nitrate	Total Nitrogen	Ortho-phosphate	Total Phosphorus	BI5	Catchment area
		NH_4^+ + NH_3	NO_2- + NO_3-	TN	PO_4^{3-}	TP		
	(mEq/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(km^2)
Average	3.04	0.117	2.858	3.214	0.063	0.123	1.30	64.12
Median	2.90	0.054	2.241	2.630	0.041	0.093	1.15	18.63

Biological variables

	SID_TID	Species number	Shannon´s Diversity	Evenness	NINT	SACU	NREC	DTEN	NLIN	Total abundance
Average	2.32	31	3.24	0.66	0.08	0.97	0.40	2.46	1.00	5.2
Median	2.34	30	3.24	0.68	0	0	0	0	0	2.0

Equation	Formula	Adjusted R^2	F	p	DF
lm (NINT ~ Alk)	NINT= 0.024 + 0.0190 * Alkalinitet	0.002	2.80	0.09	1020
lm (SACU ~ Alk)	SACU= 0.301 + 0.219 * Alkalinitet	0.012	13.87	<0.001	1020
lm (NREC ~ Alk)	NREC= 0.238 + 0.052 * Alkalinitet	0.004	5.02	0.022	1020
lm (DTEN ~ Alk)	DTEN= 3.267 - 0.267 * Alkalinitet	0.001	2.28	0.131	1020
lm (NLIN ~ Alk)	NLIN= -0.34 + 0.439 * Alkalinitet	0.030	32.84	<0.001	1020
lm (Total ~ Alk)	Total= 3.490 + 0.461 * Alkalinitet	0.003	4.33	0.038	1020
lm (NINT ~ PO4)	NINT= 0.070 + 0.185 * PO4	-0.001	0.48	0.488	1020
lm (SACU ~ PO4)	SACU= 0.847 + 1.987 * PO4	0.001	2.03	0.155	1020
lm (NREC ~ PO4)	NREC= 0.317 + 1.311 * PO4	0.005	5.88	0.015	1020
lm (DTEN ~ PO4)	DTEN= 2.347 + 1.801 * PO4	0.001	0.19	0.667	1020
lm (NLIN ~ PO4)	NLIN= 0.767 + 3.721 * PO4	0.003	4.12	0.043	1020
lm (Total ~ PO4)	Total= 4.348 + 9.006 * PO4	0.002	2.96	0.086	1020

Tabel 4.2. PO_4-P koncentrationer i vandløbene (µgL^{-1}). Værdierne er baseret på gennemsnit over 5 år på hver enkelt vandløb (n=524). Min angiver minimumskoncentrationen, max angiver maksimumkoncentrationen, 25% angiver den nedre kvartil, 75% angiver den øvre kvartil mens median angiver mediankoncentrationen.

	Min	**25 %**	**median**	**75 %**	**max**
PO_4-P-koncentration	1,50	20,00	36,6	62,3	1.490,0

The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: eqr_r_sid_tid

Number of Observations Read	1023
Number of Observations Used	1023

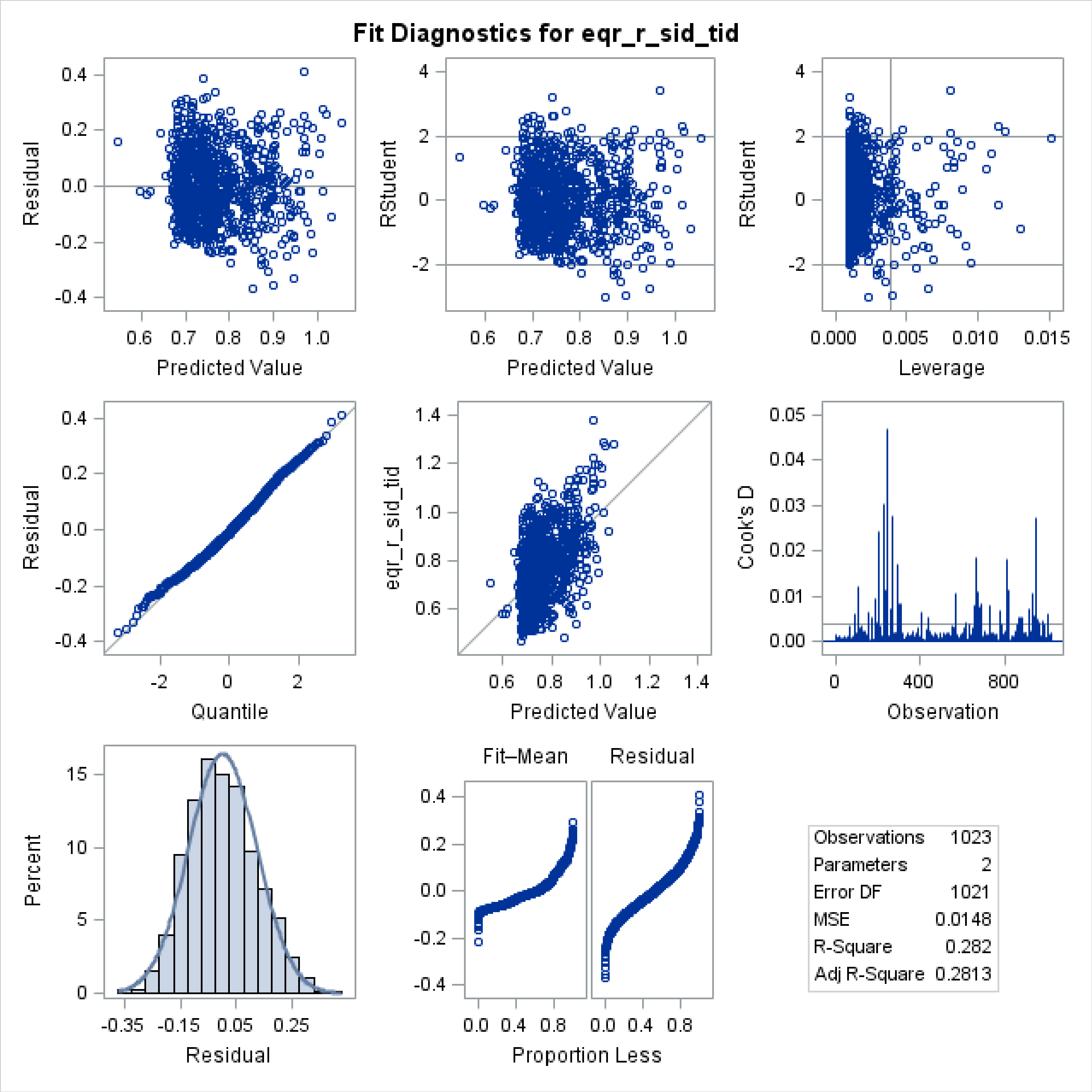
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	5.93392	5.93392	400.92	<.0001
Error	1021	15.11167	0.01480		
Corrected Total	1022	21.04559			

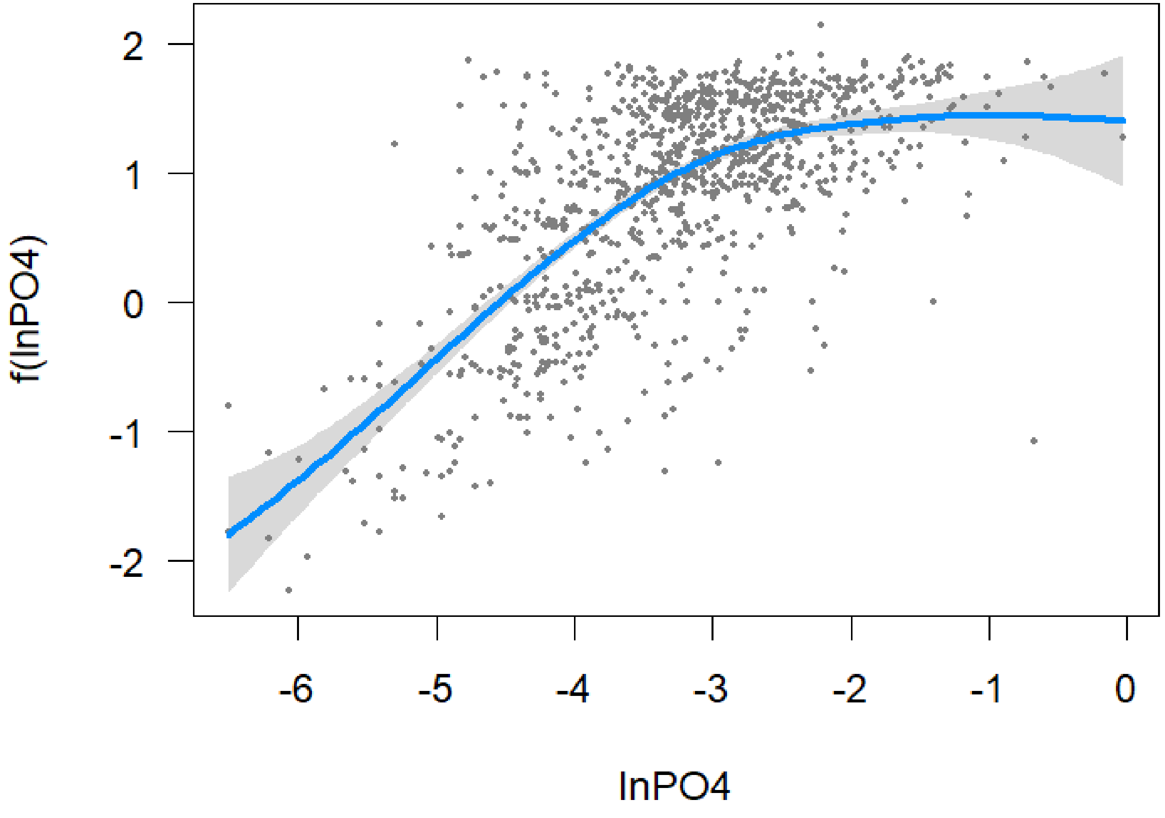
Root MSE	0.12166	R-Square	0.2820
Dependent Mean	0.76343	Adj R-Sq	0.2813
Coeff Var	15.93574		

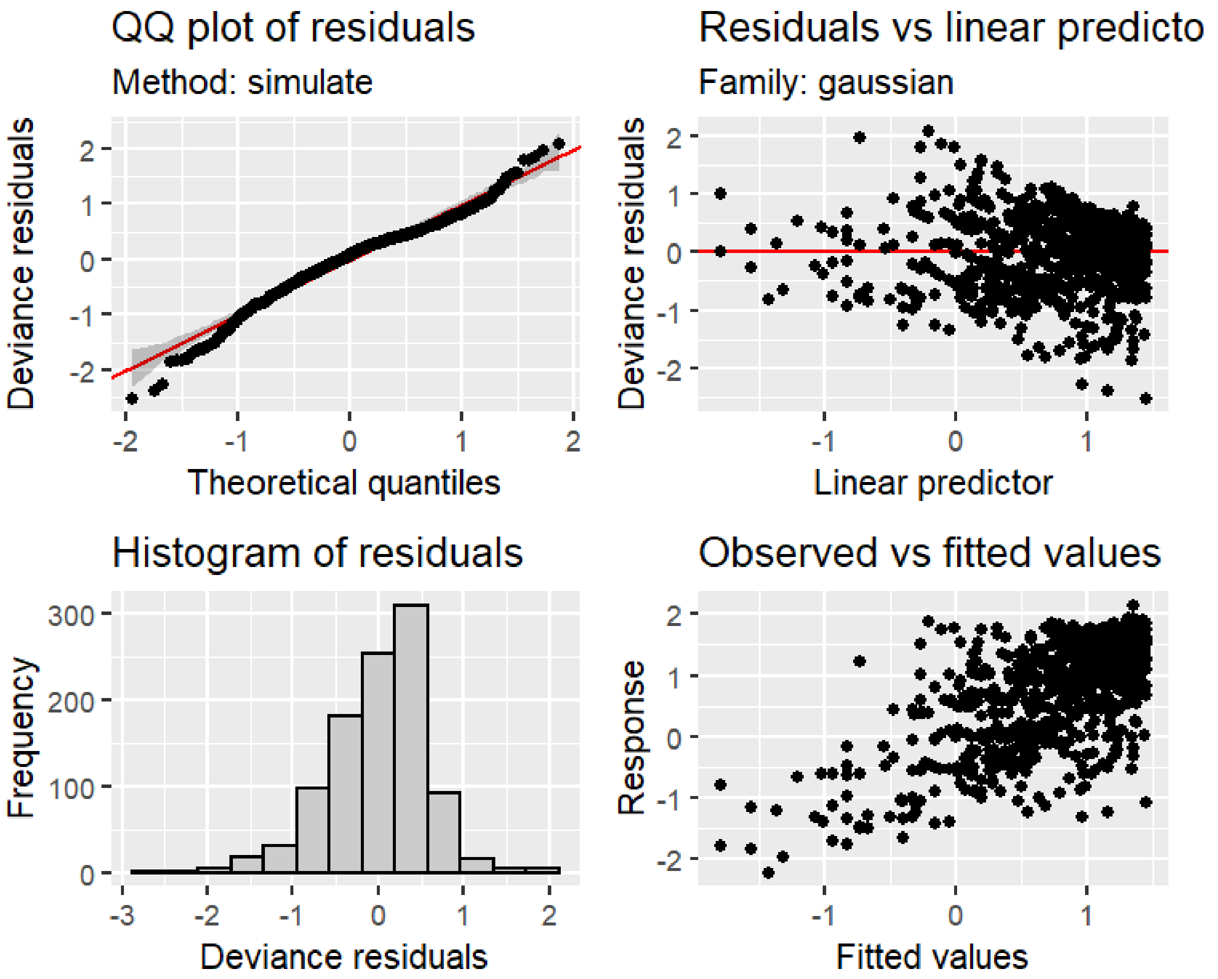
Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	0.84555	0.00559	151.17	<.0001
l_alk	1	-0.09430	0.00471	-20.02	<.0001



gam (Ln Alk ~ Ln PO4) Residuals OK, Very strongly correlation





Approximate significance of smooth terms:

	edf	Ref.df	F	p-value	
s(lnPO4)	4.435	5.319	170.6	<2e-16	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) = **0.471** Deviance explained = **47.4%**
-REML = 901.89 Scale est. = 0.33962 n = 1018

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Alkalinity and diatom assemblages in lowland streams: How to separate alkalinity from inorganic phosphorus in ecological assessments?

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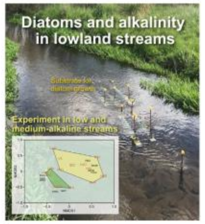
HIGHLIGHTS

- Alkalinity is important for diatom communities in lowland streams.
- Different species of diatoms were associated with different levels of alkalinity.
- Good ecological status may fail in alkaline streams despite low phosphate.
- Specific diatom species can disentangle the influence of alkalinity from phosphate.

GRAPHICAL ABSTRACT



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ABSTRACT

Benthic algae are widely used as ecological indicators of the ecological status of streams because they are widely distributed, they show high species diversity and they respond rapidly to human pressures in particular eutrophication and organic pollution. Recent findings have highlighted that in addition to human pressures, alkalinity may also play a role for community composition as bicarbonate becomes an increasingly important carbon source for photosynthesis when alkalinity increases. With this study, we aimed to elucidate how alkalinity influences the distribution of diatoms in Danish lowland streams, and to explore ifdiatom assemblage patterns can be affected by alkalinity in a way that interferes with the ecological assessment using diatom-based indices. We found that alkalinity affect the benthic algae community in lowland streams and that different species of diatoms were associated with different levels of alkalinity, a finding that might indicate dissimilarities in the efficiency of their HCO_3^- use. *Nitzschia intermedia*, *Synedra acus*, *Nitzschia recta*, *Diatoma tenue*, and *Nitzschia linearis* were associated with high alkalinity, whereas *Synedra rumpens*, *Fragilaria vaucheriae*, *Psammothidium bioretii*, and *Gomphonema parvulum* were associated with low alkalinity in streams with very low levels of phosphate. We also found that the Danish indicator for ecological status in streams (a combination of two Austrian indices, the Saprobic Index (SID) and the Trophic Index (TID) may exceed levels acceptable for good ecological status in moderate to high alkaline streams despite low phosphate levels. These findings highlight the need for the development of a diagnostic method to disentangle the effects of alkalinity from eutrophication and, additionally, that we need more insight into the autecology of species to interpret ecological assessments to be able to guide management efforts.

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E-mail address: abp@ecos.au.dk (A. Baattrup-Pedersen).

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Tabel 4.2. De 25 mest almindelige arter af bentiske alger i danske vandløb.

Art	% af alle registreringer	Forekomst i andel vandløb (%)
Achnanthes minutissima	23,8	99,4
Navicula lanceolata	10,4	89,3
Navicula gregaria	6,54	93,5
Gomphonema parvulum	6,51	85,5
Amphora pediculus	4,04	69,1
Gomphonema angustatum	4,01	79,8
Achnanthes lanceolata	3,22	71,0
Gomphonema olivaceum	3,10	57,4
Fragilaria vaucheriae	2,90	79,2
Achnanthes lanceolata frequentissima	2,54	43,3
Fragilaria capucina var. gracilis	2,43	63,2
Meridion circulare	2,06	66,8
Nitzschia dissipata	1,78	75,6
Fragilaria pinnata	1,43	55,5
Navicula minima	1,22	59,4
Synedra ulna	1,13	59,0
Rhoicosphenia abbreviata	1,04	43,5
Cocconeis placentula var. euglypta	0,93	46,8
Nitzschia palea	0,90	63,4
Navicula tripunctata	0,89	51,1
Diatoma tenuis	0,77	30,9
Reimeria sinuata	0,71	39,1
Cymbella silesiaca	0,69	38,5
Nitzschia paleacea	0,64	38,7
Fragilaria construens var. venter	0,63	36,1

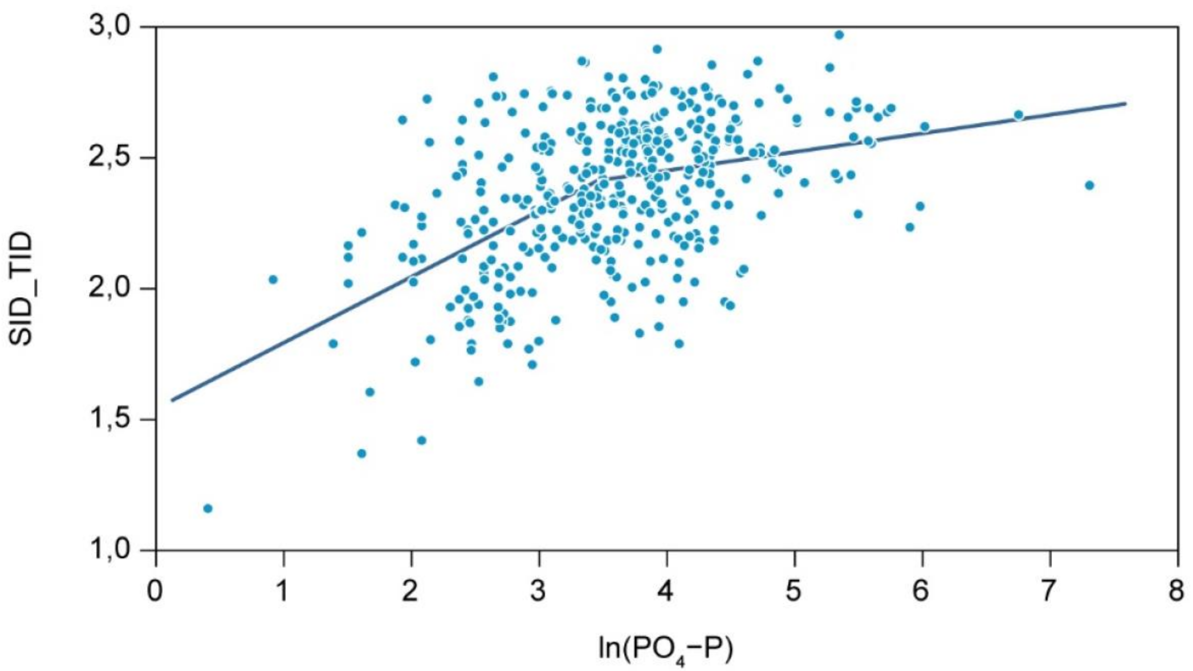
ICM = (EQR_IPS + EQR_TID) / 2

EQR (index) = observed index value/reference value for index

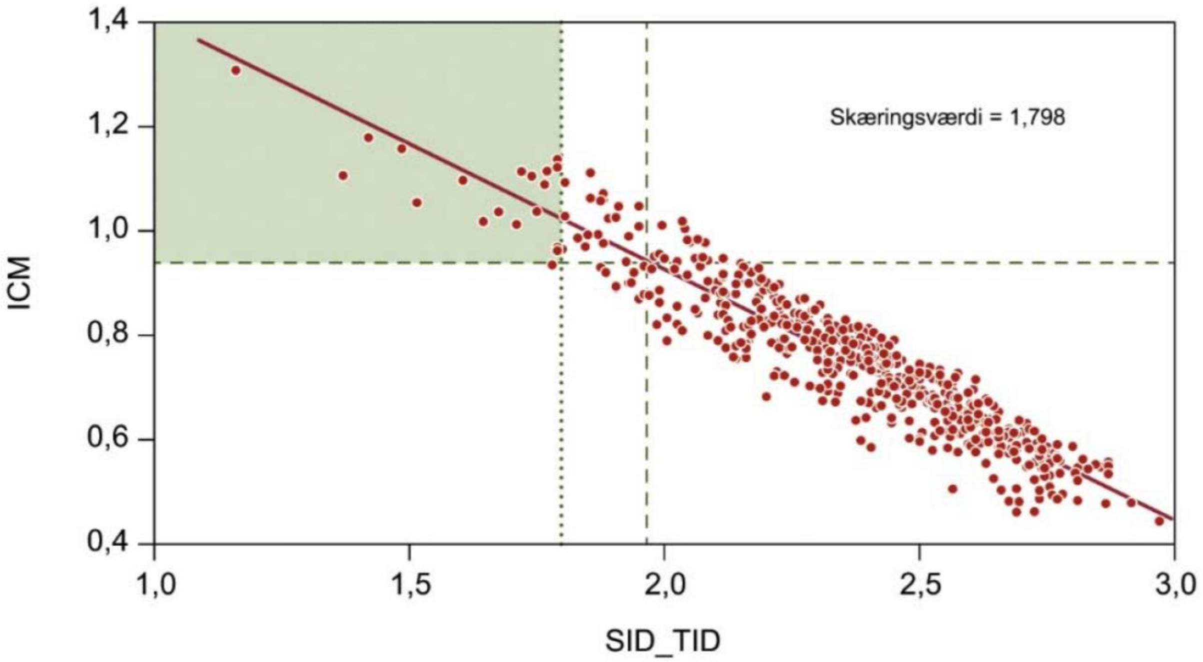
IPS (Specific Pollution Sensitivity Index; Coste in Cemagref, 1982)

TID (Trophic Index, Rott et al. 1999)

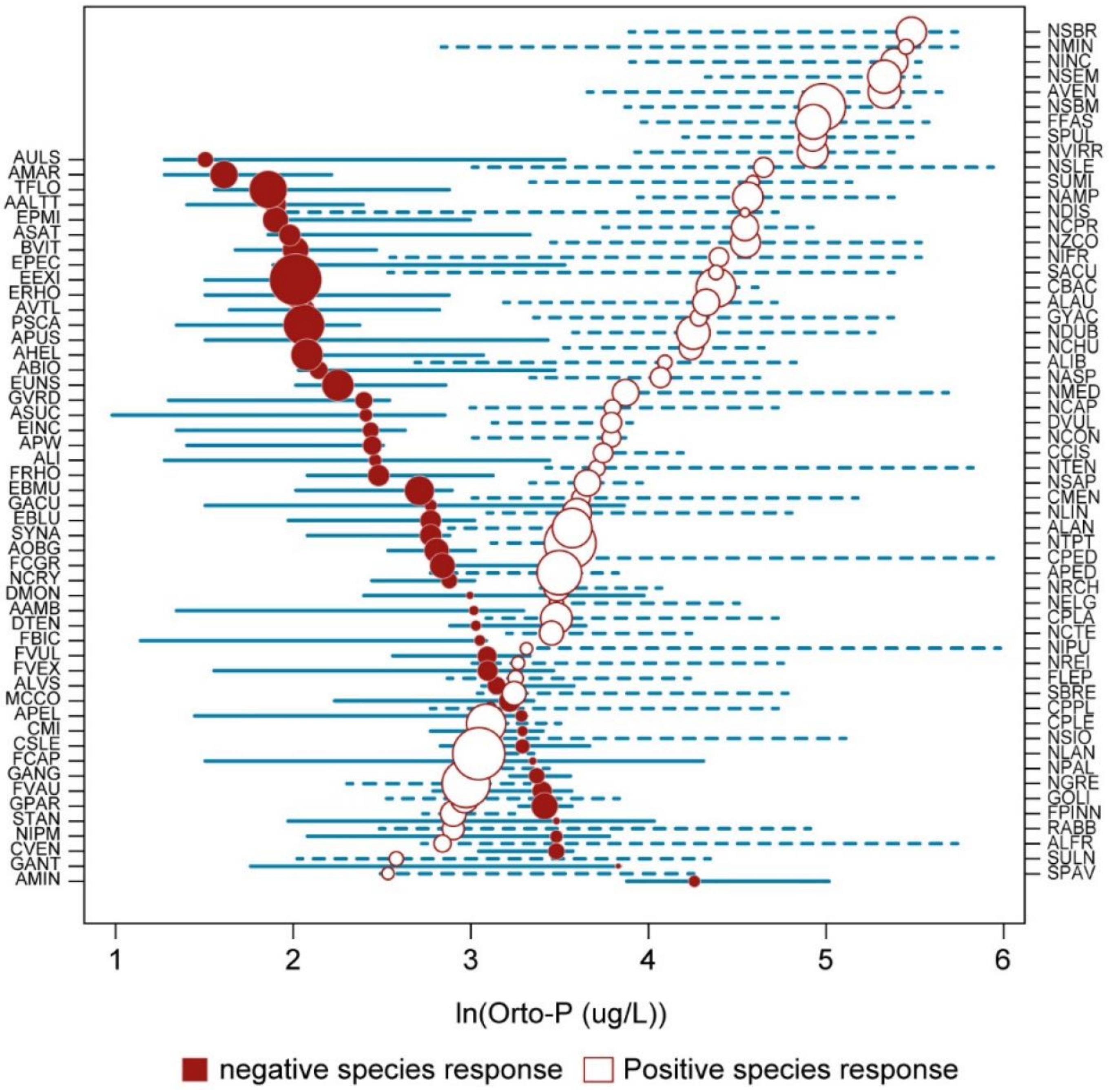
Figur 4.4. Den todelte, lineære sammenhæng mellem SID_TID og koncentrationen af PO_4-P i vandløbsvand. PO_4-P-koncentrationen er ln-transformeret. Change point (*k*) er ved ln(PO_4-P) = -3,45; svarende til en PO_4-P-koncentration på 32 $\mu g L^{-1}$.



Figur 7.1 Sammenhængen mellem Intercalibration Common Metric (ICM) og SID_TID for alle vandløb. Den vandrette, stiplede linje viser den øvre værdi for det acceptable interval for skæringsværdi mellem høj/god tilstandsklasse (0,939). Den lodrette, stiplede linje viser den tilsvarende indeksværdi. Det grønne rektangel indeholder registreringer, der ligger i referenceområdet, idet disse er afskåret som gennemsnittet for de værdier, der ligger over ICM-grænseværdien.



Figur 7.3. Resultater fra TITAN-analysen. Forekomsten af de individuelle arter i forhold til koncentrationen af PO_4-P-koncentrationen (ln transformeret) i vandløbsvandet (fuldtoptrukne og stiplede, vandrette linjer) og deres identificerede change points. De fyldte cirkler markerer change points for arter, der responderer negativt på øget PO_4-P-koncentration; åbne cirkler markerer change points for arter, der responderer positivt på øget PO_4-P-koncentration. De lodrette, grå linjer markerer, hvor de to overordnede identificerede change points for de samlede algesamfund ligger. En oversigt over artsnavne og deres forkortelser findes i appendiks 2.



Tabel 9. Sammenhæng (lineær regression) mellem de væsentlige arters hyppighed og alkalinitet. * angiver statistisk signifikans α=0,05.

	Alkalinitet		
Art	**Hældning**	**F**	**p**
ALFR	0,330	97,84	<0,01*
APED	0,914	68,18	<0,01*
ASAT	-2,665	110,42	<0,01*
CSLE	-0,035	58,51	<0,01*
DTEN	1,151	73,42	<0,01*
EBLU	-0,734	11,91	<0,01*
EEXI	-2,55	9,55	<0,01*
EUNS	-0,905	4,87	0,03*
FCGR	-0,391	556,58	<0,01*
FPIN	0,416	228,66	<0,01*
FVAU	-0,863	165,69	<0,01*
GANG	-1,272	7,18	0,01*
GOLI	0,624	12,78	<0,01*
GPAR	-1,089	668,22	<0,01*
MCCO	-3,251	91,14	<0,01*
NDIS	0,214	14,26	<0,01*
NGRE	0,517	372,50	<0,01*
NLAN	0,271	73,59	<0,01*
NLIN	1,326	129,48	<0,01*
NPAL	-0,081	20,17	<0,01*
SACU	1,152	39,47	<0,01*
SULN	0,389	88,49	<0,01*
TFLO	-0,966	166,02	<0,01*

					P-respons		
Art	**Artsnavn**	**Saprob-tal**	**Trofisk tal**	**Alk-respons**	**a**	**b**	**c**
ALFR	*Achnanthes lanceolata ssp. frequentissima*	2,5	2,8	+	+	+	*God *Moderat
APED	*Amphora pediculus*	2,1	2,8	+	+	- / +	*Ringe/Dårlig
ASAT	*Achnanthes subatomoides*	1,1	2,1	-	-	0	*Høj
CSLE	*Cymbella silesiaca*	2,0	2,0	-	-	-	*God
DTEN	*Diatoma tenue*	1,3	1,4	+	-	-	*Høj
EBLU	*Eunotia bilunaris*	1,7	0,7	-	-	-	*Høj
EEXI	*Eunotia exigua*	1,1	1,9	-	-	-	*God
EUNS	*Eunotia sp.*	NA	NA	-	-	- / 0 / +	*Høj
FCGR	*Fragilaria capucina var. gracilis*	1,3	1,1	-	-	NA	NA
FPIN	*Fragilaria pinnata*	1,4	2,2	+	+	0	*Moderat *Ringe/Dårlig
FVAU	*Fragilaria vaucheriae*	2,5	1,8	-	-	- / 0 / +	*Høj
GANG	*Gomphonema angustatum*	1	NA	-	-	- / 0 / +	Moderat
GOLI	*Gomphonema olivaceum*	2,1	2,9	+	+	+ / -	Ringe/Dårlig
GPAR	*Gomphonema parvulum*	2,6	3,6	-	-	+	*God
MCCO	*Meridion circulare var. constrictum*	1,2	1,2	-	-	-	*Høj
NDIS	*Nitzschia dissipata*	2,0	2,4	+	+	- / +	God
NGRE	*Navicula gregaria*	2,5	3,5	+	+	+	*Moderat *God
NLAN	*Navicula lanceolata*	2,3	3,5	+	+	0	*Moderat
NLIN	*Nitzschia linearis*	1,9	3,4	+	+	0	*Moderat *Ringe/Dårlig
NPAL	*Nitzschia palea*	2,8	3,3	-	+	+	*Moderat
SACU	*Synedra acus*	NA	1,8	+	+	0	Moderat
SULN	*Synedra ulna*	2,7	3,5	+	+	- / 0 / +	*Høj
TFLO	*Tabellaria flocculosa*	1,1	0,8	-	-	-	*Høj

+ og - angiver hhv. positiv og negativ respons på øget P-koncentration. I tilfælde, hvor der er angivet både + og –, er det første tegn et udtryk for, hvilken respons der er registreret flest gange i den internationale litteratur. 0 angiver neutral respons.

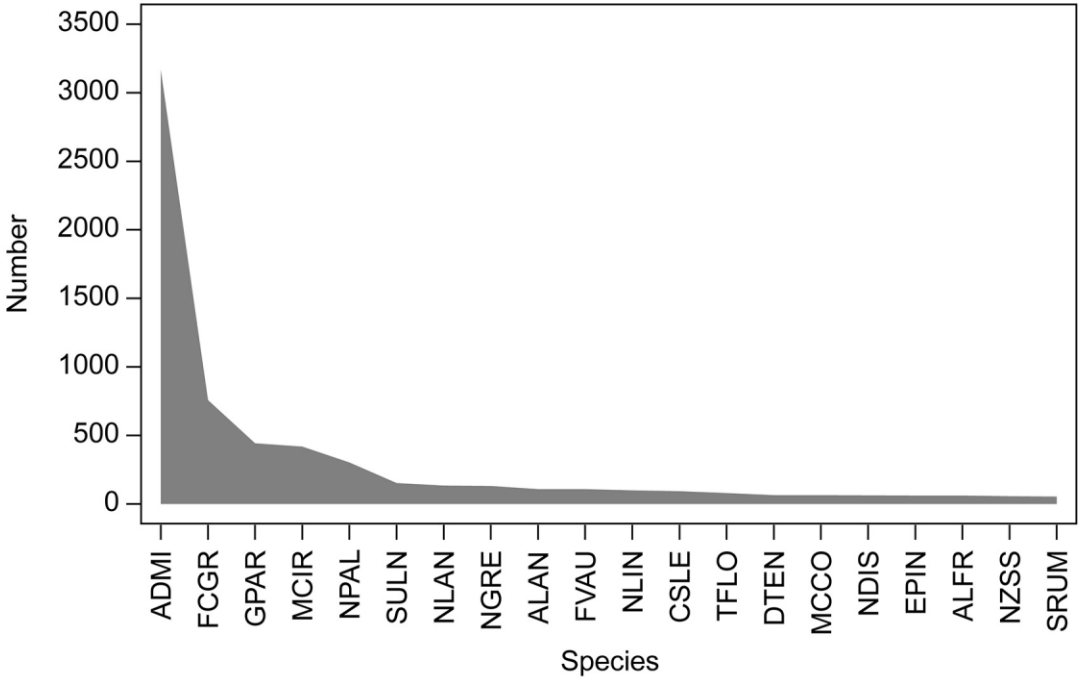


Table 3

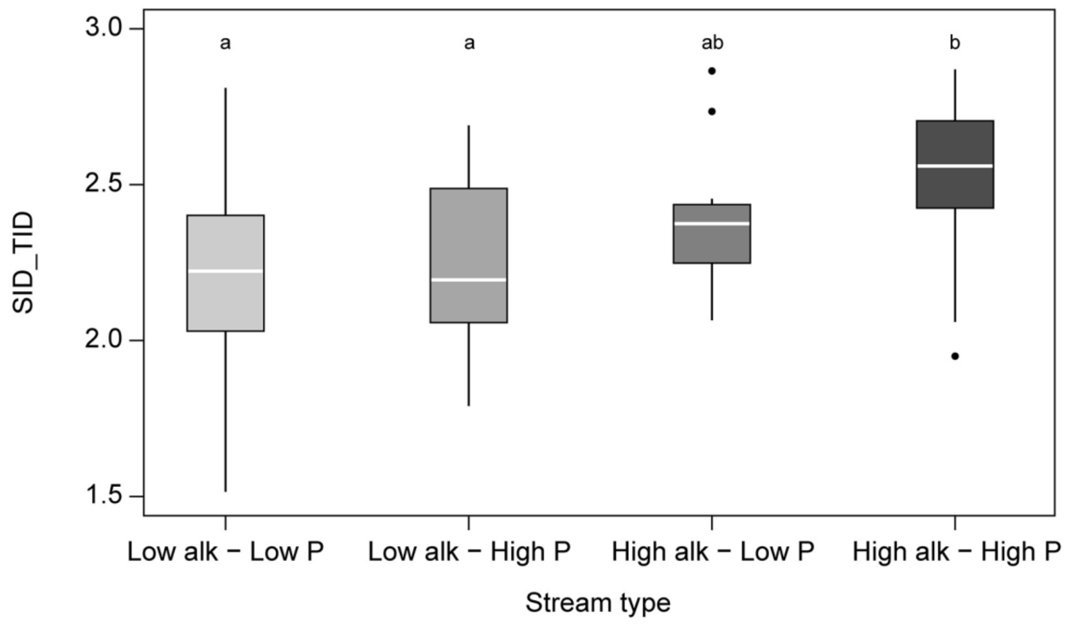
Identified indicator species and their indicator values for low (N = 9) and high (N = 6) alkalinity sites together with their response to alkalinity. Significance levels are $^*P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

Alkalinity group	Indicator species	Indicator value	Alkalinity response, slope	F
High	*Nitzschia intermedia*	0.51*	0.808	7.56***
	Synedra acus	0.49*	1.236	16.12**
	Nitzschia recta	0.48*	1.273	6.91*
	Diatoma tenue	0.44*	0.754	41.83***
	Nitzschia linearis	0.41**	1.199	41.79***
Low	*Synedra rumpens*	0.63*	−1.476	13.52**
	Fragilaria vaucheriae	0.56*	−0.616	37.18***
	Psammothidiun bioretii	0.46*	−1.496	5.76*
	Gomphonema parvulum	0.40*	−0.888	143.21***

Table 4

Saprobe and trophic values for the identified indicator species as given in the algae database OMNIDIA and a summary of their response to alkalinity (from Table 3) and inorganic phosphorus based on the international literature (further detailed in appendix a). Additionally, the ecological status class characteristic for the species is given according to Kelly et al. (2008). * indicates that the species is especially characteristic of the particular ecological status class. NA = missing value.

Species name	In short	Saprobic value	Trophic value	Alkalinity response	PO_4-P response according to the literature	Characteristic ecological status class according to Kelly et al. (2008)
Diatoma tenue	DTEN	1.3	1.4	+	−	*High
Fragilaria vaucheriae	FVAU	2.5	1.8	−	−	*High
Gomphonema parvulum	GPAR	2.6	3.6	−	+	*Good
Nitzschia recta	NREC	1.5	3.0	+	0	*Poor/Bad
Nitzschia linearis	NLIN	1.9	3.4	+	0	*Moderate *Poor/Bad
Nitzschia intermedia	NINT	NA	2.9	+	+	NA
Psammothidium bioretii	PBIO	1.2	1.8	−	−	NA
Synedra acus	SACU	NA	1.8	+	0	Moderate
Synedra rumpens	SRUM	1.6	1.0	−	0	High


3.0
2.5
2.0
1.5
SID_TID
a
a
ab
b
Low alk − Low P
Low alk − High P
High alk − Low P
High alk − High P
Stream type