Supplementary Materials for

Quantifying the effects of response diversity dynamics on ecosystem stability

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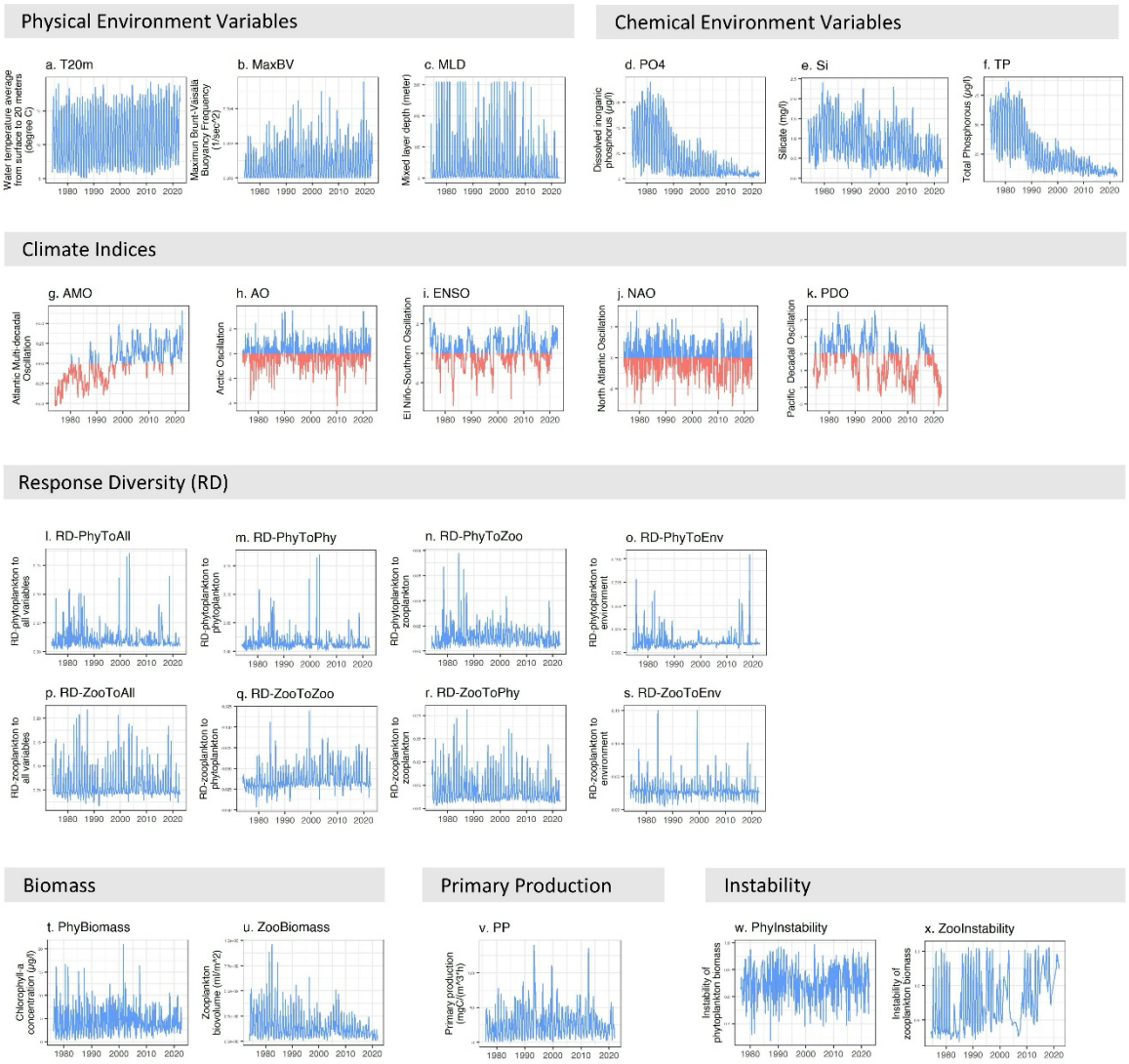
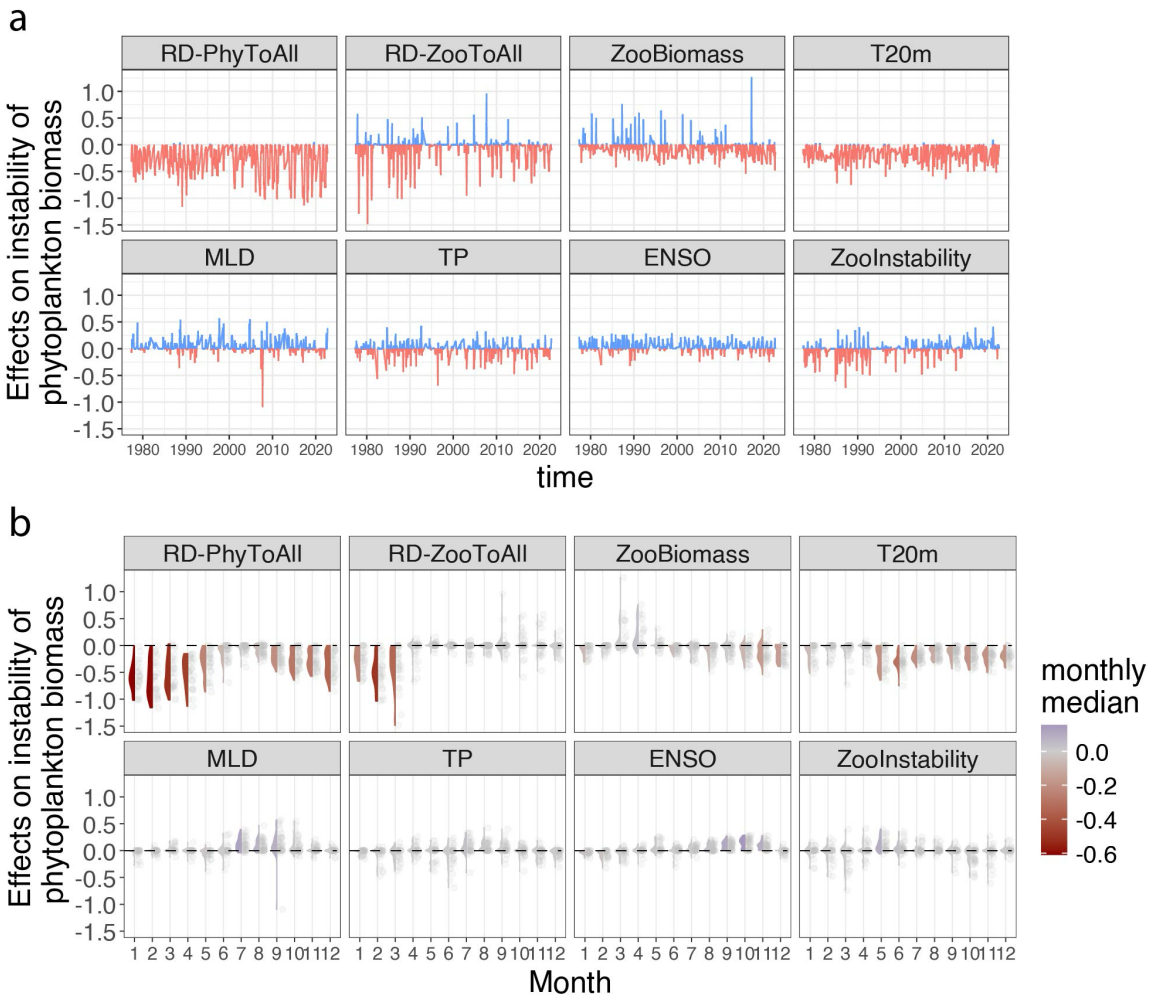
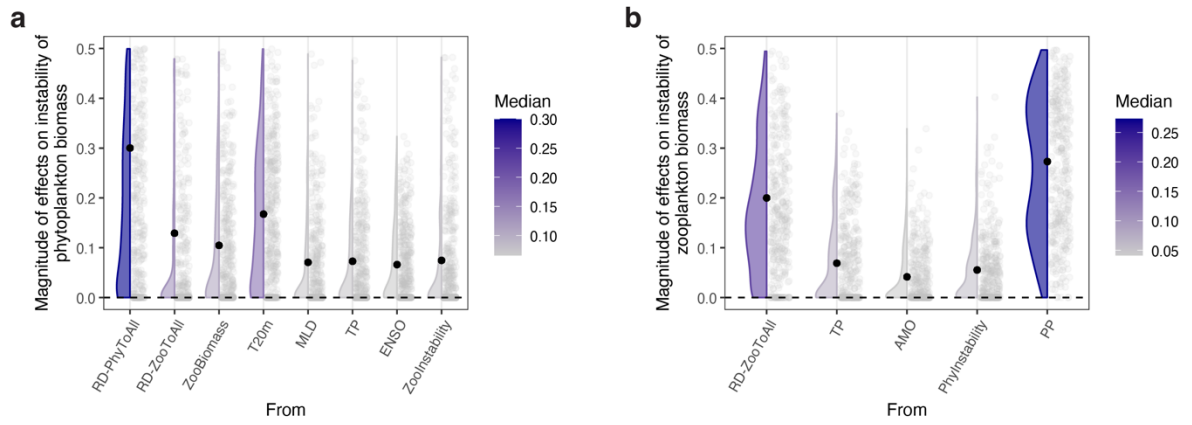
SI Figures



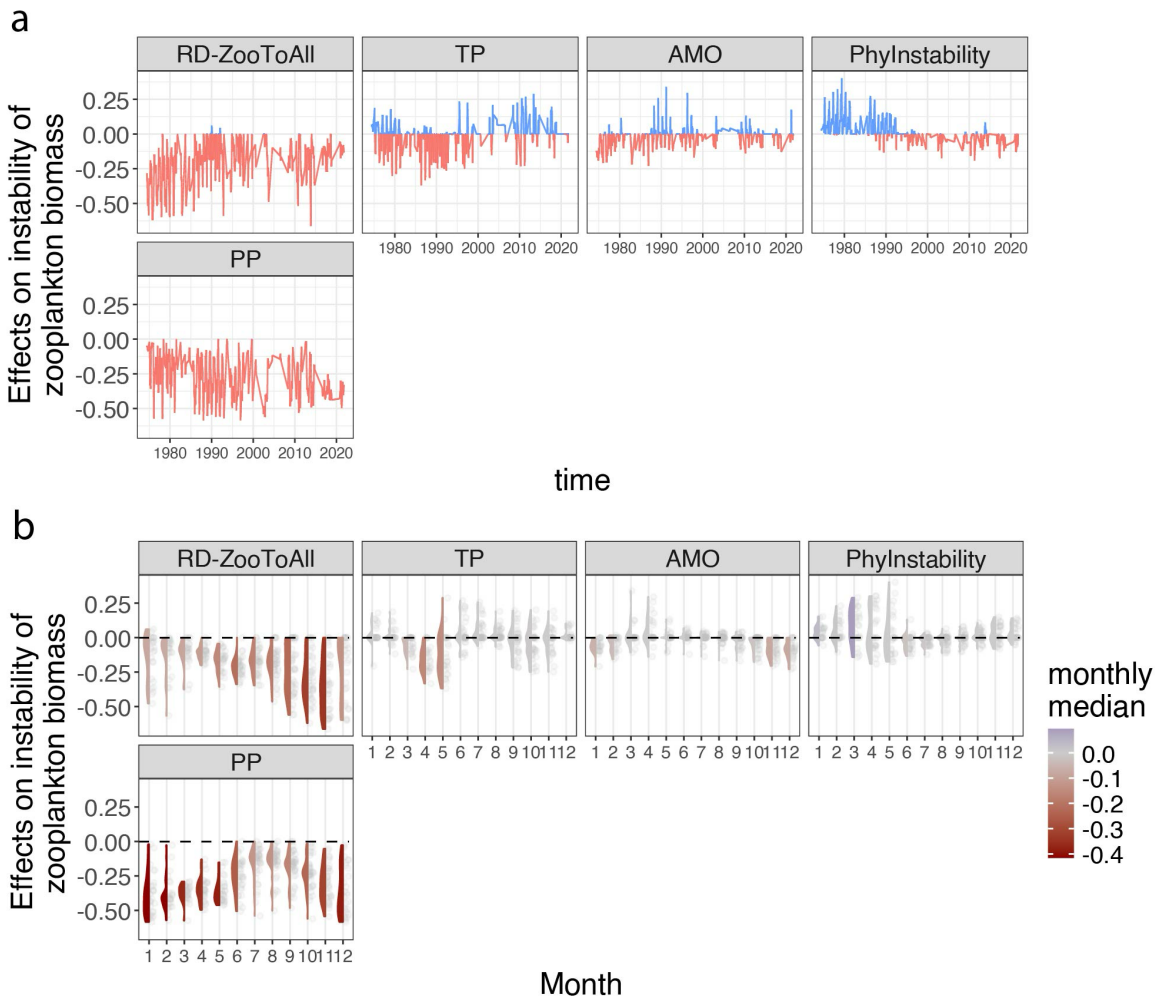
SI Figure 1. Monthly time series data of environmental variables, response diversity, plankton biomass, primary production, and plankton instability. The acronym of each variable used in this work is shown on top of each panel; the full name is shown as the Y-axis label. Source data are provided as a Source Data file.



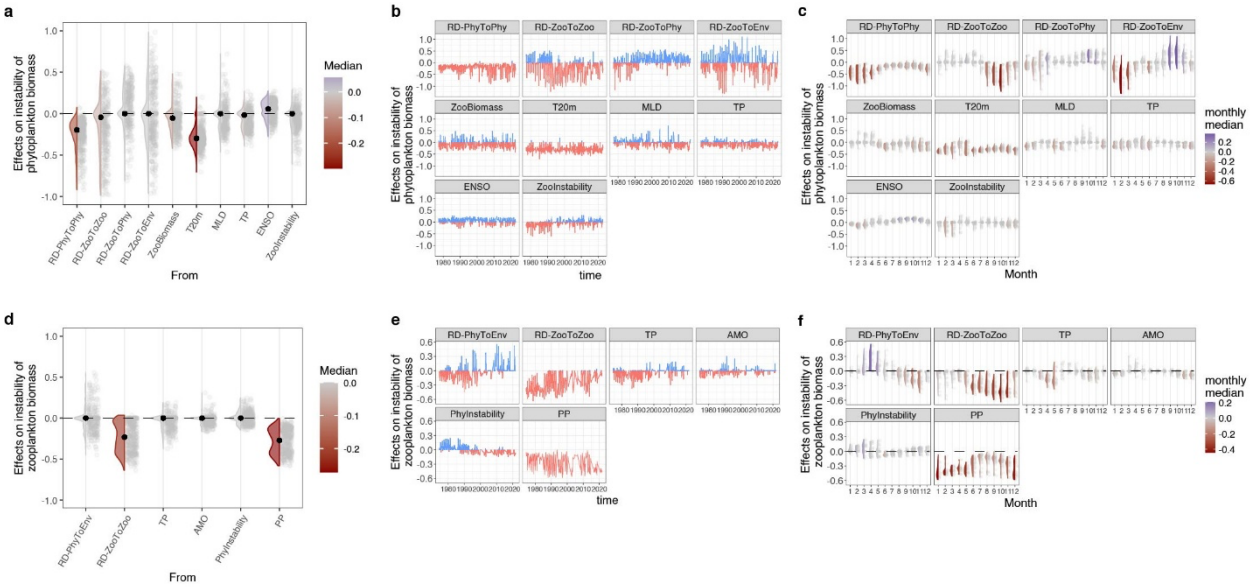
SI Figure 2. Monthly time series and seasonal variation of the effects of increasing selected variables on phytoplankton instability. Panel **(a)** shows the time series of the effect of each selected variable; red indicates negative, and blue indicates positive effects. Panel **(b)** summarizes seasonal variation. The violin color indicates the median effect. The target variable is instability, and thus, negative values indicate buffering effects against instability. RD-PhyToAll represents the response diversity of the phytoplankton community to all other plankton genera and environmental variables, and likewise for RD-ZooToAll. For the explanation of other variable names, see SI Figure 1. Analyses based on more detailed levels of response diversity are provided in SI Figure 5. Source data are provided as a Source Data file.



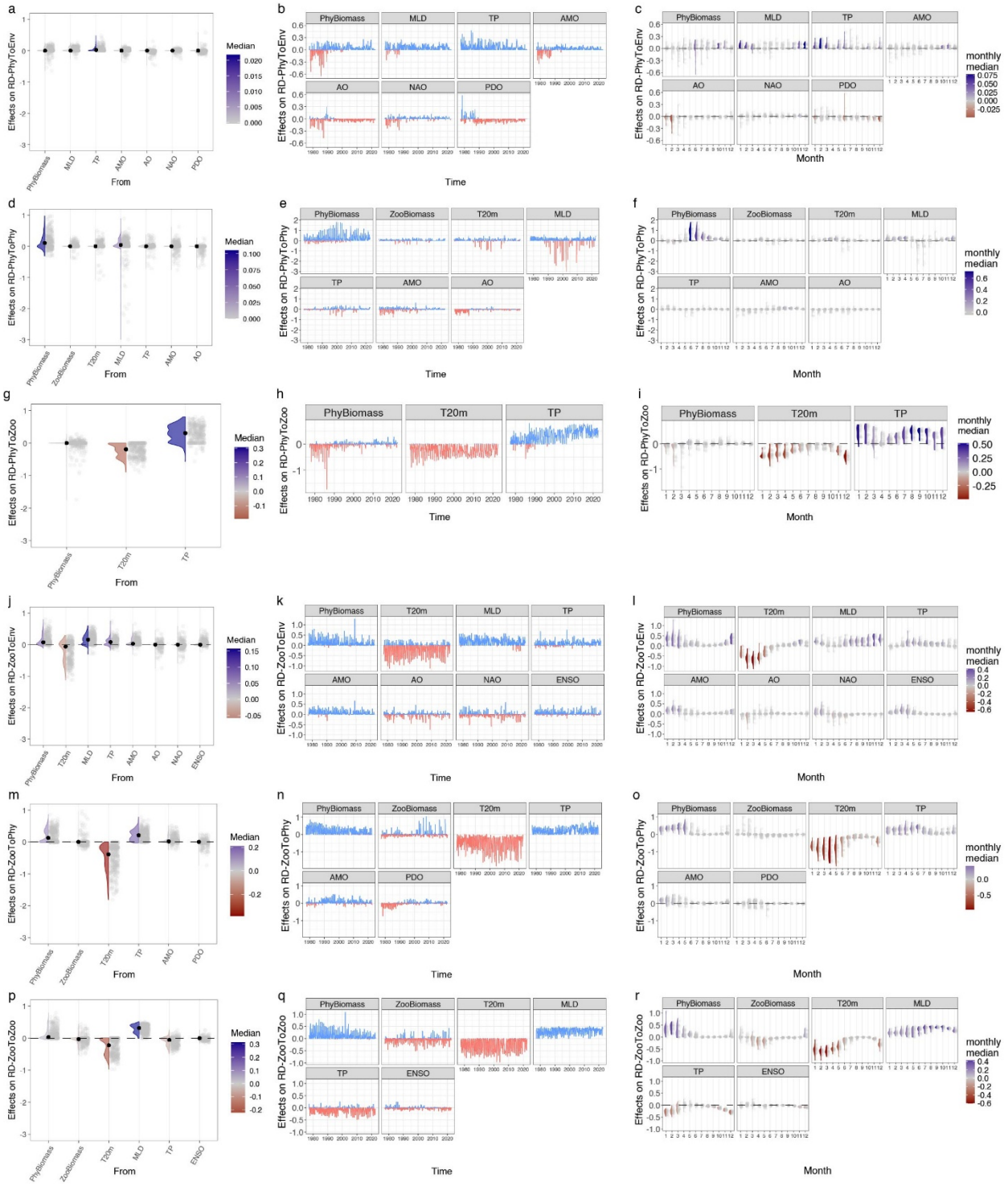
SI Figure 3. Magnitudes of the effects of increasing the selected variables on (a) phytoplankton and (b) zooplankton instability. Here, only the magnitude of the effect is considered, regardless of whether the effect is positive or negative. The violin color indicates the median effect. Source data are provided as a Source Data file.



SI Figure 4. Monthly time series and seasonal variation of the effects of increasing the selected variables on zooplankton instability. Panel **(a)** shows the time series of the effect of each selected variable; red indicates negative, and blue indicates positive effects. Panel **(b)** summarizes the seasonal variation. The violin color indicates the median effect. The target variable is instability, and thus, negative values indicate buffering effects against instability. RD-ZooToAll represents the response diversity of the zooplankton community to all other plankton genera and environmental variables. For the explanation of other variable names, see SI Figure 1. Analyses based on more detailed levels of response diversity are provided in SI Figure 5. Source data are provided as a Source Data file.

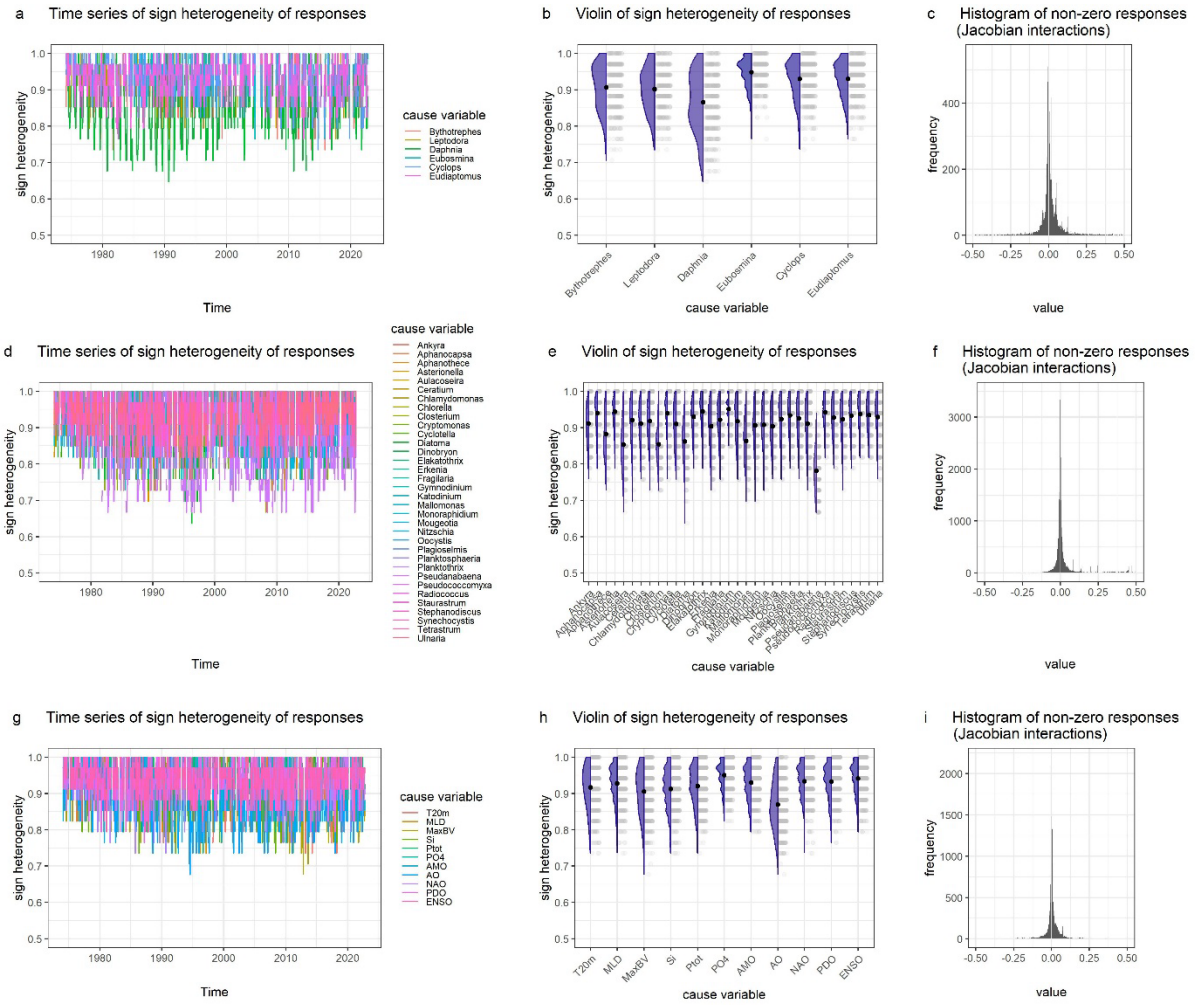


SI Figure 5. The effects of increasing the selected variables on (a, b, c) phytoplankton and (d, e, f) zooplankton instability with more detailed levels of response diversity indices. The violin plots show how the **(a)** phytoplankton or **(d)** zooplankton total biomass instability was influenced by various categories of response diversity and environmental variables. Panels **(b & e)** show the time series of the effect of each selected variable; red indicates negative, and blue indicates positive effects. Panels **(c & f)** summarize the seasonal variation. The violin color indicates the median effect. The target variable is instability, and thus, negative values indicate buffering effects against instability. For the explanation of variable names, see SI Figure 1. Source data are provided as a Source Data file.

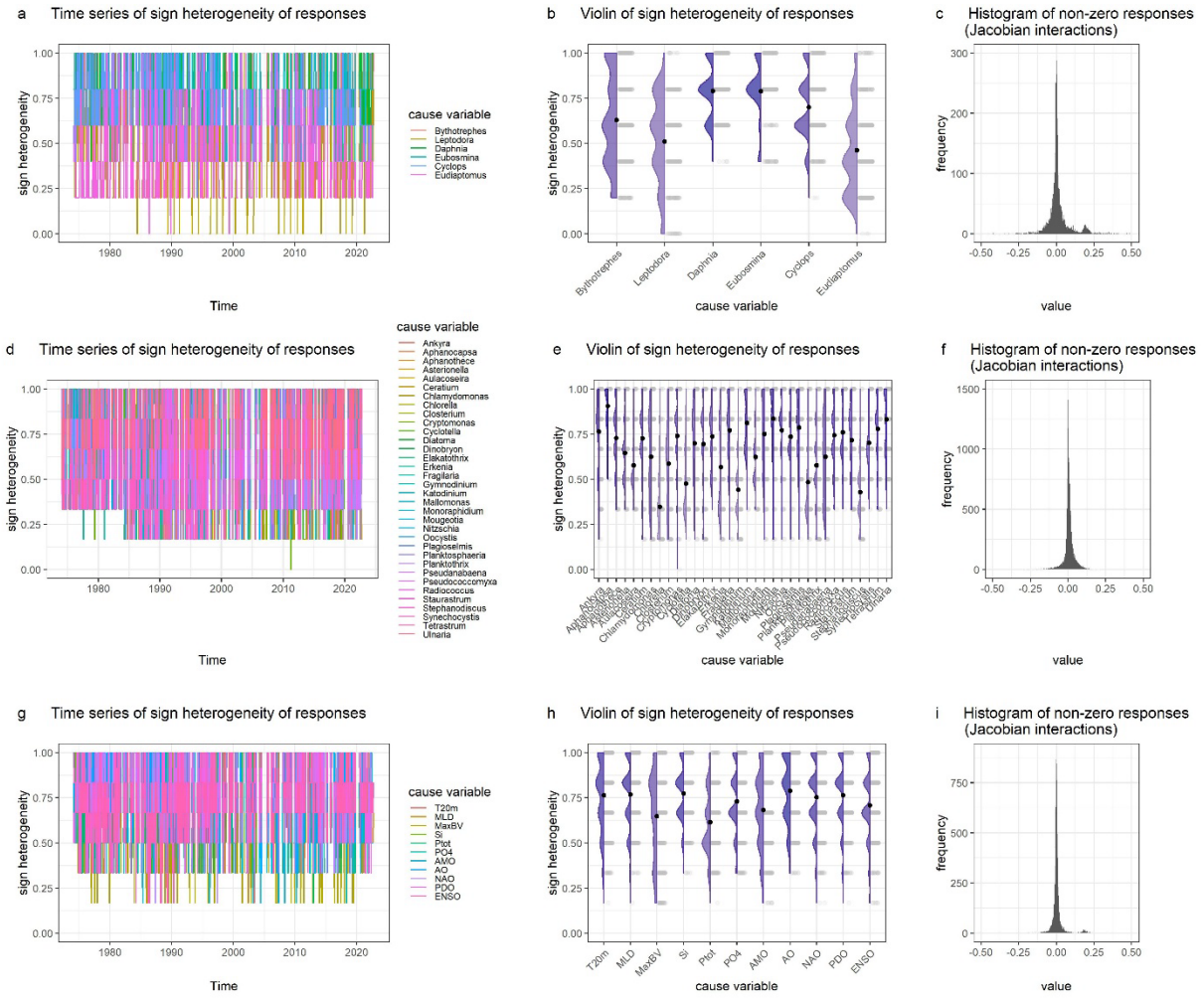


SI Figure 6. Effects of increasing environmental variables and plankton biomass on various categories of response diversity of the phytoplankton and zooplankton community. Response diversity was inferred based on how phytoplankton responded to **(a, b, c)** environmental variables, **(d, e, f)** other genera of phytoplankton (i.e., within-trophic level

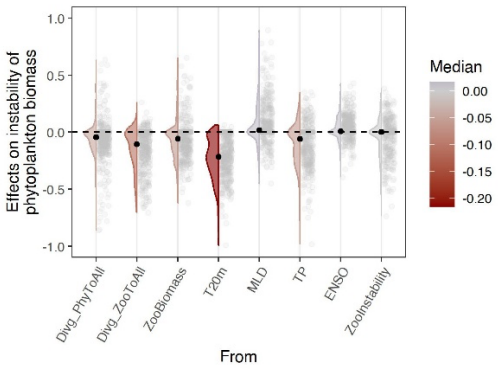
responses), and **(g, h, i)** genera of zooplankton (i.e., cross-trophic level responses); how zooplankton responded to **(j, k, l)** environmental variables, **(m, n, o)** genera of phytoplankton (i.e., cross-trophic level responses), and **(p, q, r)** other genera of zooplankton (i.e., within-trophic level responses). Violin plots summarize environmental effects on **(a, d, g, j, m, p)** each level of response diversity. Panels **(b, e, h, k, n, q)** show the time series of the effect of each selected variable; red indicates negative, and blue indicates positive effects. Panels **(c, f, i, l, o, r)** summarize the seasonal variation. The violin color indicates the median effect. For the explanation of variable names, see SI Figure 1. Source data are provided as a Source Data file.



SI Figure 7. Sign heterogeneity in phytoplankton responses. Panel **a**, **d**, and **g** illustrates the monthly time series of community-level sign heterogeneity in phytoplankton's response to each zooplankton genus, each phytoplankton genus, and each environmental variable, respectively. Values consistently above zero confirm the existence of sign heterogeneity in response. Violin plots (**b**, **e**, and **h**) summarize the distribution of the sign heterogeneity in response to each of the forcing variables. See *Index of sign heterogeneity in response at the community level* for the explanation of the computation. The overall long-term distribution of $J_{i,j}$ (**c**, **f**, and **j**) reveals that both positive and negative responses are prevalent. The sharp peak around zero indicates that weak responses are the most common. Zero responses are excluded from the analyses. Source data are provided as a Source Data file.



SI Figure 8. Sign heterogeneity in zooplankton's responses. Panel **a**, **d**, and **g** illustrate the monthly time series of community-level sign heterogeneity in zooplankton's response to each zooplankton genus, each phytoplankton genus, and each of the environmental variables, respectively. Values consistently above zero confirm the existence of sign heterogeneity in response. Violin plots (**b**, **e**, and **h**) summarize the distribution of the sign heterogeneity in response to each of the forcing variables. See *Index of sign heterogeneity in response at the community level* for the explanation of the computation. The overall long-term distribution of $J_{i,j}$ (**c**, **f**, and **j**) reveals that both positive and negative responses are prevalent. The sharp peak around zero indicates that weak responses are the most common. Zero responses are excluded from analyses. Source data are provided as a Source Data file.



SI Figure 9. Violin plots showing effects of response divergence and environmental variables on total phytoplankton biomass instability. Instability of total phytoplankton biomass was, on average, buffered by increasing response divergence of phytoplankton, zooplankton, and lake water temperature, although considerable variation was observed. Effects of other influential variables showed no consistent sign over time. Total biomass instability was quantified using dynamic eigen-values (Methods). Influential variables were identified with Convergent Cross Mapping to assess dynamic causality (Table S1), and their effects on instability were estimated by MDR S-map across time intervals. Because instability is the target variable, negative effects estimated by MDR S-map indicate buffering against instability. Violin color and the position of the black point represent the median effect, while the grey dots beside each violin represent the monthly estimates. Divg-PhyToAll represents the response divergence of the phytoplankton community to all other plankton genera and environmental variables, and likewise for Divg-ZooToAll. For the definition of other variable names, see SI Figure 1. Source data are provided as a Source Data file.

SI Tables

Table S1. Results of Convergent Cross Mapping (CCM) for identifying causal variables of the instability of phytoplankton total biomass (PhyInstability) and zooplankton total biomass (ZooInstability), respectively. This table summarizes the CCM skill and p-value (in brackets) calculated using 100 seasonal surrogates. Bold values indicate significant CCM results (i.e., $p < 0.05$), whereas - indicates that the variable is not included in the analysis for the respective instability index. Only significant variables were included in the MDR-Smap analysis.

Effect \ Cause	ZooBio--mass	PhyBio--mass	RD-PhyToAll	RD-ZooToAll	RD-PhyToPhy	RD-PhyToZoo	RD-PhyToEnv	RD-ZooToZoo	RD-ZooToPhy	RD-ZooToEnv
PhyInstability	**0.5 (<0.01)***	-	**0.21 (<0.01)***	**0.33 (<0.01)***	**0.14 (0.02)***	0.1 (0.11)	0.04 (0.18)	**0.27 (<0.01)***	**0.26 (<0.01)***	**0.36 (<0.01)***
ZooInstability	-	0.34 (0.1)	0.14 (0.19)	**0.41 (0.03)***	0.08 (0.24)	0.18 (0.37)	**0.22 (<0.01)***	**0.45 (<0.01)***	0.38 (0.15)	0.25 (0.43)

Effect \ Cause	T20m	MLD	TP	AMO	AO	NAO	PDO	ENSO	ZooInst--ability	PhyInst--ability	PP
PhyInstability	**0.62 (<0.01)***	**0.47 (<0.01)***	**0.5 (<0.01)***	0.11 (0.14)	0.05 (0.19)	0.05 (0.17)	**0.11 (0.05)***	**0.11 (0.02)***	**0.69 (<0.01)***	-	-
ZooInstability	0.79 (0.59)	0.36 (0.43)	**0.64 (<0.01)***	**0.22 (0.02)***	0.04 (0.23)	0.02 (0.33)	0.05 (0.17)	0.06 (0.18)	-	**0.47 (<0.01)***	**0.41 (<0.01)***

Effect \ Cause	Divg-PhyToAll	Divg-ZooToAll
PhyInstability	**0.26 (<0.01)***	**0.26 (<0.01)***
ZooInstability	0.33 (0.57)	0.35 (0.12)

Table S2. Results of Convergent Cross Mapping (CCM) for identifying causal variables of the six categories of response diversity, respectively. The table summarizes the CCM skill and p-value (in bracket) calculated using 100 seasonal surrogates. Bold values indicate significant CCM results (i.e., $p < 0.05$), whereas - indicates that the variable is not included in the analysis for the respective instability index. Only significant variables were included in the MDR-Smap analysis.

Effect \ Cause	Zoo--Biomass	Phy--Biomass	T20m	MLD	TP	AMO	AO	NAO	PDO	ENSO
RD-PhyToPhy	**0.19 (0.02)***	**0.27 (<0.01)***	**0.34 (<0.01)***	**0.35 (<0.01)***	**0.29 (0.01)***	**0.08 (0.04)***	**0.16 (<0.01)***	0.07 (0.08)	0.07 (0.12)	0.06 (0.06)
RD-PhyToZoo	0.24 (0.1)	**0.16 (0.01)***	**0.43 (0.02)***	0.24 (0.07)	**0.31 (0.05)***	0.12 (0.1)	0.08 (0.08)	0.05 (0.17)	0.05 (0.14)	0.02 (0.26)
RD-PhyToEnv	0.1 (0.26)	**0.18 (<0.01)***	0.27 (0.12)	**0.23 (0.02)***	**0.24 (0.02)***	**0.11 (0.04)***	**0.12 (<0.01)***	**0.07 (0.05)***	**0.07 (0.05)***	0.01 (0.47)
RD-ZooToZoo	**0.44 (<0.01)***	**0.29 (<0.01)***	**0.74 (<0.01)***	**0.39 (<0.01)***	**0.52 (<0.01)***	0.15 (0.06)	0 (0.41)	0.01 (0.39)	0.06 (0.09)	**0.19 (<0.01)***
RD-ZooToPhy	**0.32 (<0.01)***	**0.29 (<0.01)***	**0.69 (<0.01)***	0.33 (0.09)	**0.55 (<0.01)***	**0.15 (0.03)***	0.02 (0.31)	0 (0.4)	**0.1 (0.01)***	0.02 (0.26)
RD-ZooToEnv	0.28 (0.24)	**0.38 (<0.01)***	**0.71 (<0.01)***	**0.34 (<0.01)***	**0.52 (<0.01)***	**0.18 (0.01)***	**0.11 (0.01)***	**0.1 (0.02)***	0.04 (0.25)	**0.12 (0.01)***