Files for Comparing Resilience of Cyanobacteria to Contrasting P Load
Lake Mendota 2019, 2020, 2021

The steps were performed in sequence from the top to bottom of the table. See notes below the table for sources of the methods.

R scripts were written and tested with R 4.1.1 and RStudio 2023.06.2 + 561. R Studio will prompt the user to install the necessary packages or updates if they are not installed already.

Runtimes for 100 bootstrap cycles are estimates on a Dell Precision 3240 Compact desktop computer. R reports using 20 cores.

Acronyms: BGA = blue-green algae, a common name for Cyanobacteria; DDJ = drift-diffusion-jump model; DLM = dynamic linear model

Step of Analysis	**Purpose**	**R scripts**	**Input files**	**Output files**
Data preparation	Create a pooled dataset for 2019-2021, z-transform log10(phycocyanin RFU) using the 3-year mean and standard deviation	Zscore_2019-2021_with_common_mu+sigma_2023-04-20.R	Me_BGA+cov_1min_2019.Rdata Me_BGA+cov_1min_2020.Rdata Me_BGA+cov_1min_2021.Rdata	Zscore_lBGA_19-20-21.Rdata
Figure 1	Plot cumulative drivers	Fig1_Plot_Cumulative_Drivers_2019-2021.R	Buoy+PLppt_daily19.Rdata Buoy+PLppt_daily20.Rdata Buoy+PLppt_daily21.Rdata	None; Fig. 1 is plotted to screen
Fit DLM to z-scored log10 phycocyanin	Compute the standardized level of the z-score of log10(phycocyanin RFU) as a stationary index of Cyanobacteria biomass	Step1_DLM_Mendota_Pool_2019-2021.R ODLMAR_NoBoot_NoEigen_2020-12-20.R	Zscore_lBGA_19-20-21_2023-06-15.Rdata	DLM_result+idoy+means_Pool_2019-2021.Rdata
Diagnostics for stationarity & Markov property	Determine if the data need further de-trending for stationarity or time-lagging to	Diagnostics_ADFstationarity_ARIMA_Markov_2023-09-05.R	DLM_result+idoy+means_Pool_2019-2021.Rdata	None; result is printed to screen

	meet Markov assumption			
Figures 2 and 3	Plot time series and densities of the standardized level of the z-score of log10(phyocyanin RFU)	Figs2+3_Plot_Pooled_Phycocyanin+ DLM_2019-2021.R	DLM_result+idoy+means_ Pool_2019-2021.Rdata	None; Figs. 2 and 3 are plotted separately to screen
Reconstruct drift-diffusion-jump model	Estimate drift, diffusion, and jump functions for standardized level of the z-score of log10(phycocyanin RFU) each year 2019-2021	DDJ_Mendota_2019-2021_optAR_ByYear_v0.R DriftDiffJumpFunction.R EPFunction+EQ.R	DLM_result+idoy+means_ Pool_2019-2021.Rdata	DDJ_2019_from_pool_ thinopt.Rdata DDJ_2020_from_pool_ thinopt.Rdata DDJ_2021_from_pool_ thinopt.Rdata
Figure 4	Plot drift-diffusion-jump functions including conditional variance	Fig4_Plot_mfcol_DDJ_functions_ 3years_2023-08-11.R	DDJ_2019_from_pool_ thinopt.Rdata DDJ_2020_from_pool_ thinopt.Rdata DDJ_2021_from_pool_ thinopt.Rdata	None; Fig 4 is plotted to screen
Figure 5	Plot effective potential and first derivative	Fig5_Plot_EPF_2019-2021.R	DDJ_2019_from_pool_ thinopt.Rdata DDJ_2020_from_pool_ thinopt.Rdata DDJ_2021_from_pool_ thinopt.Rdata	None; Fig 5 is plotted to screen
Figures 6 and 7	Plot drift function with noise envelopes to infer early warnings	Fig6+7_Squeals+Flickers_ 2019-2021.R	DDJ_2019_from_pool_ thinopt.Rdata DDJ_2020_from_pool_ thinopt.Rdata	None; Figs. 6 and 7 are plotted separately to screen

			DDJ_2021_from_pool_ thinopt.Rdata	
Figure 8	Compile all passage times by year and plot the distribution of directly-observed passage times	Direct_count_observed_transitions_ v1_2023-08-15.R EPFunction+EQ.R	DLM_Result+idoy+means_ Pool_2019-2021.Rdata DDJ_2019_from_pool_ thinopt.Rdata DDJ_2020_from_pool_ thinopt.Rdata DDJ_2021_from_pool_ thinopt.Rdata	None; Fig. 8 is plotted to screen and results are printed for Table 1.
Compute mean exit time	Compute mean exit time from DDJ functions as a first step for bootstrap analysis. Computations are done separately for each year	Step4_ET_DDJ_Mendota2019_ 2023-07-17.R Step4_ET_DDJ_Mendota2020_ 2023-07-17.R Step4_ET_DDJ_Mendota2021_ 2023-07-17.R EPFunction+EQ.R	DDJ_2019_from_pool_ thinopt.Rdata DDJ_2020_from_pool_ thinopt.Rdata DDJ_2021_from_pool_ thinopt.Rdata	ET_DirectMath_thinopt_ 2019pool.Rdata ET_DirectMath_thinopt_ 2020pool.Rdata ET_DirectMath_thinopt_ 2021pool.Rdata
Compute median survival time (half-life)	Compute median survival time (half-life) from DDJ functions as a first step for bootstrap analysis. Computations are done separately for each basin in each year	Survival_2019_Left_DDJ_ FromStep4_2023-07-19.R Survival_2019_Right_DDJ_ FromStep4_2023-07-19.R Survival_2020_Left_DDJ_ FromStep4_2023-07-19.R Survival_2020_Right_DDJ_ FromStep4_2023-07-19.R Survival_2021_Left_DDJ_ FromStep4_2023-07-19.R Survival_2021_Right_DDJ_	DDJ_2019_from_pool_ thinopt.Rdata DDJ_2020_from_pool_ thinopt.Rdata DDJ_2021_from_pool_ thinopt.Rdata ET_DirectMath_thinopt_ 2019pool.Rdata ET_DirectMath_thinopt_ 2020pool.Rdata ET_DirectMath_thinopt_	Survival_Left_Mendota2019.Rdata Survival_Right_Mendota2019.Rdata Survival_Left_Mendota2020.Rdata Survival_Right_Mendota2020.Rdata Survival_Left_Mendota2021.Rdata Survival_Right_Mendota2021.Rdata

		FromStep4_2023-07-19.R	2021pool.Rdata	
Compile all exit time and half life results	Organize results for Table 1	Read+List_Nominal_ET+Survival.R	ET_DirectMath_thinopt_ 2019pool.Rdata ET_DirectMath_thinopt_ 2020pool.Rdata ET_DirectMath_thinopt_ 2021pool.Rdata Survival_Left_Mendota2019.Rdata Survival_Right_Mendota2019.Rdata Survival_Left_Mendota2020.Rdata Survival_Right_Mendota2020.Rdata Survival_Left_Mendota2021.Rdata Survival_Right_Mendota2021.Rdata	Nominal_ET+S_2019-2021.Rdata
Bootstrap DLM by residuals	First step of bootstrapping mean exit time and half life (runtime about 12 minutes)	Bootstrap_DLM_Mendota_ 2019-2021_2023-08-13.R ODLMAR_for_Bootstrap_ 2020-11-23.R	DLM_Result+idoy+means_Pool_ 2019-2021.Rdata	DLM_boot_pool_2019-2021.Rdata
Bootstrap DDJ	Compute bootstrap realizations of the drift-diffusion-jump functions for each year from the bootstrap DLMs (runtime about 4 minutes for each year)	BootstrapDDJ_byYear_ fromPoolDLM_2023-08-13.R	DLM_boot_pool_2019-2021.Rdata	DDJ_boot_2019.Rdata DDJ_boot_2020.Rdata DDJ_boot_2021.Rdata
Bootstrap exit time and half life each year	From bootstrapped DDJ functions bootstrap stationary distribution, mean exit time, and half-life for each year (runtime about 6	BootALL_Step4_ET+Survival_DDJ_ 2019_2023-08-18.R BootALL_Step4_ET+Survival_DDJ_ 2020_2023-08-18.R BootALL_Step4_ET+Survival_DDJ_ 2021_2023-08-18.R	DDJ_boot_2019.Rdata DDJ_boot_2020.Rdata DDJ_boot_2021.Rdata	ET+Sboot_2019.Rdata ET+Sboot_2020.Rdata ET+Sboot_2021.Rdata

	minutes for each year)			
Bias-correct and plot exit time and half-life bootstrap distributions	Plot Fig. 9, distributions of mean exit time and median survival time, after bias correction.	Analyze_BiasCorrect_Plot_ET+S_v2_2023-08-18.R	Nominal_ET+S_2019-2021.Rdata ET+Sboot_2019.Rdata ET+Sboot_2020.Rdata ET+Sboot_2021.Rdata	None; Descriptive statistics, intermediate results, results for Table 1, and Fig. 9 are printed to the screen.

Sources

These R scripts were written for the manuscript "Stochastic dynamics in years of contrasting phosphorus load" by S.R. Carpenter and W.A. Brock. That manuscript explains the methods and cites the original literature that introduced the methods. Correspondence: srcarpen@wisc.edu

R scripts and original sources of methods Dynamic Linear Models , Drift-Diffusion-Jump model reconstruction, mean exit time, and median survival time are introduced in earlier publications (Arani et al. 2021; Brock and Carpenter 2012; Carpenter et al. 2020; Carpenter et al. 2022; Carpenter and Brock 2011).

R scripts for exit time, survival time, and their bootstrap error estimates update earlier versions (Carpenter and Arani 2021).

Literature cited

Arani, B. M. S., S. R. Carpenter, L. Lahti, E. H. van Nes, and M. Scheffer. 2021. Exit time as a measure of ecological resilience. Science **372:** eaay4895.10.1126/science.aay4895

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Carpenter, S. R., and B. M. S. Arani. 2021. Exit and survival time: New standard scripts. Zenodo.https://doi.org/10.5281/zenodo.6544226

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