Supplementary information

S1. Stock and flow diagram of the Lake Chilika model

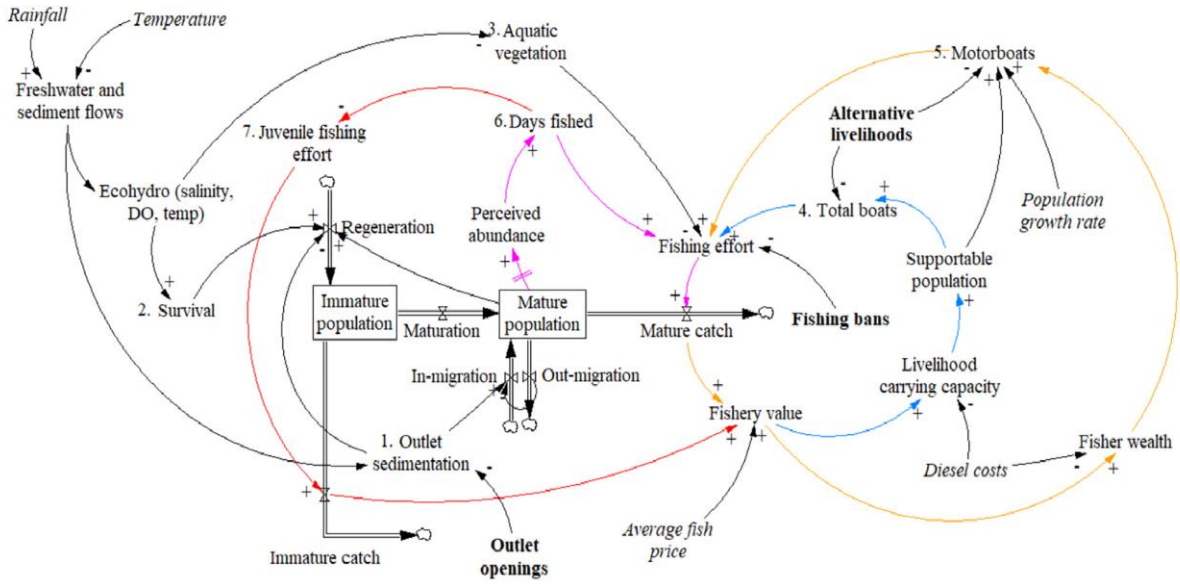

Figure S1: Stock and flow diagram depicting the four key feedback loops driving rates of fish catch, as described in Methods and Materials. Driver key: italicised – external to the lake (as shown in Table S3: only 'Population growth rate' is simulated here; 'Rainfall' and 'Temperature' are held constant); bold – governance (only 'fishing bans' are simulated here). Socioeconomic feedbacks: blue – total fisher population growth; orange – motorboat uptake by relatively wealthy traditional fishers; pink – days fished as a function of perceived stock density; red – increased juvenile catches to compensate for lost days fished. DO – dissolved oxygen. '+' positive driver-output polarity; '–' inverse driver-output polarity. Figure originally published by Cooper and Dearing (2019).

S2. Future scenario trajectories

Table S2: Parameter values of the four scenario types simulated in the Lake Chilika model: (i) do-nothing management scenarios where only random fisher population growth rates are modelled, (ii) instantaneous ban scenarios, where in addition to the fisher growth rates, random ban extents (between 0 and 100% of the lake's area) are modelled, (iii) the implementation of the bans are *delayed* by different numbers of years following fishery collapse, and (iv) the bans are *phased-in* linearly over different number of years following fishery collapse.

Management approach	**Scenario dimensions**				**Number of simulations**
	Fisher population growth rate	**Fishing ban extent (% of lake surface area)**	**Delayed ban introduction (years)**	**Ban phasing-in length (years)**	
Do-nothing management	-0.014 to 0.18	0	0	0	2000
Instantaneous bans	-0.014 to 0.18	0 to 100	0	0	2000
Delayed bans	-0.014 to 0.18	0 to 100	1, 2, 3, 5, 10, 15, 20	0	14,000 (2000 per *delay* length)
Phased-in bans	-0.014 to 0.18	0 to 100	0	1, 2, 3, 5, 10, 15, 20	14,000 (2000 per *phase-in* length)

S3. Graphical depiction of the different management approaches

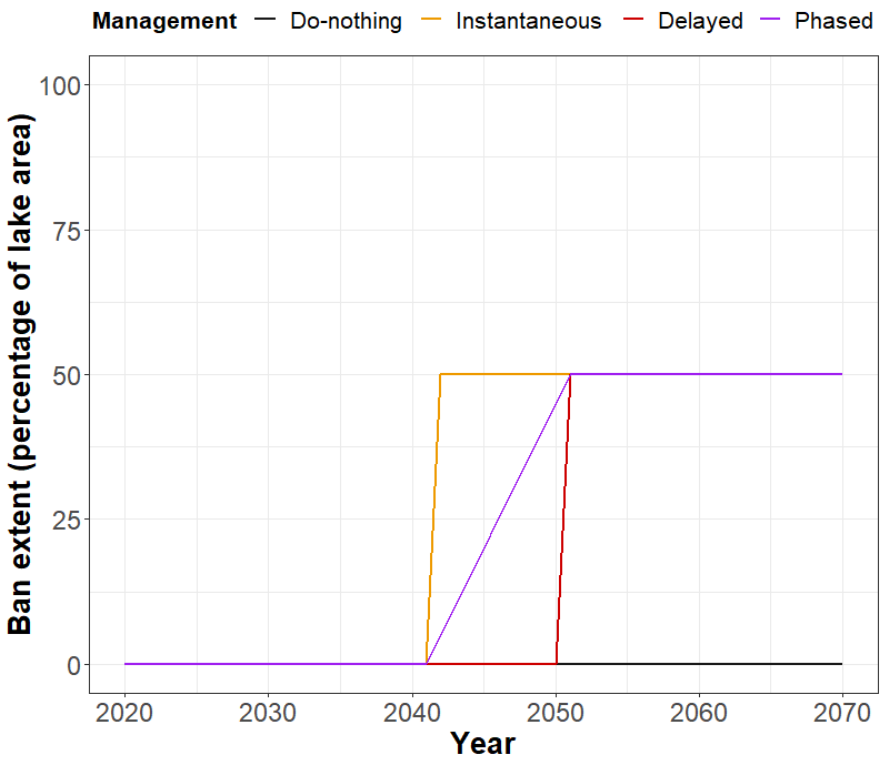

Figure S3: Illustrative timeseries of the four different management scenarios described in Table S2. As per the simulation depicted in Figure S5 (below), the management scenarios (as well as any associated delays or phase-in periods) are triggered once fish catch falls beneath 20% of Maximum Sustainable Yield (i.e. year 2041). In these illustrative scenarios, the randomly sampled fishing ban extent equals 50% of the lake's surface area. Note: all scenarios are active from 2020 – just that timeseries lines overlap before the triggering of the management scenario in 2041.

S4. Graphical depiction of fishery collapse and recovery

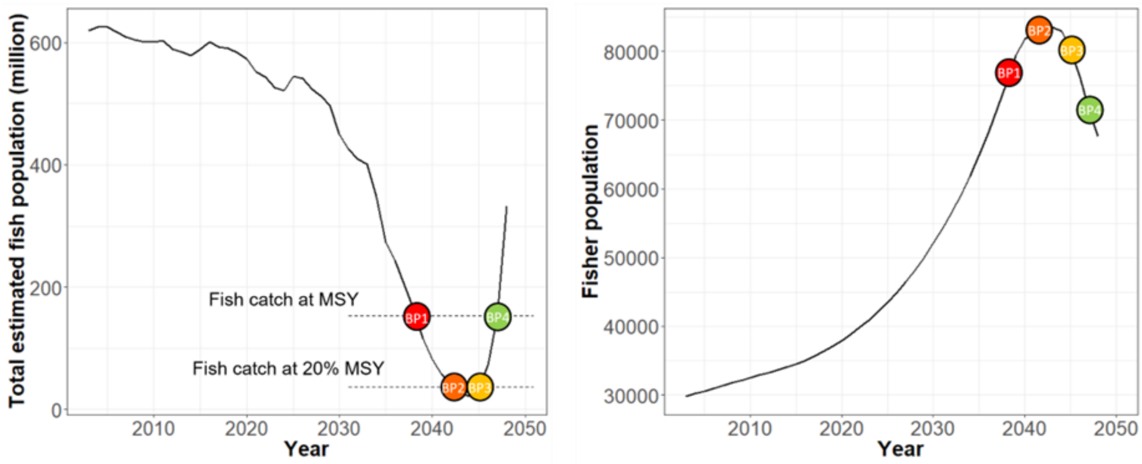

Figure S4: Graphical representation of the dimensions of ecosystem collapse, recovery, and associated hysteresis under an illustrative simulation; (left) time-series of the Lake Chilika fish population collapsing and recovering to a level that can support Maximum Sustainable Yield (MSY); (right) corresponding change in the fisher population over the same time period. Key: (BP1) time point at which fish catch falls to MSY during the collapse phase; (BP2) time point at which fish catch falls to 20% of MSY - signifying a collapsed fishery and triggering ecosystem management (Table 1); (BP3) time at which the fish population starts to recover by reaching 20% of MSY during the recovery phase; (BP4) time at which the fish population recovers to a level that can support MSY (i.e. point of recovery). *Recovery duration* is therefore the number of years between BP2 and BP4 (i.e. 4 years), while *hysteresis magnitude* is the absolute difference between the fisher population at BP2 and BP4 (i.e. ~11,000 fishers). In turn, the *recovery effort* equals the recovery duration multiplied by the hysteresis magnitude (i.e. ~44,000). Representing type 1 environmental limits (see Dearing et al., 2014), MSY and 20% of MSY are used by the international fishery community to assess the status of healthy and collapsed fish stocks (Pinsky et al., 2011; Worm et al., 2009).

S5. Table of recovery timings

Table S5: Breakdown of the times taken for simulations from a select number of different management and stress scenarios to reach the different type 1 environmental limits (BP1 – BP4, see Figure S4). See Figures 2-4 for the full distribution of all simulations and scenario combinations. * Phased-in bans with a phase-in duration of 0 years are equivalent to instantaneous bans with an implementation ban of 0 years.

Scenario				Timing (years from simulation start)				
Management	**Ban extent (%)**	**Delay/ phase-in (years)**	**Stress**	**BP1**	**BP2**	**BP3**	**BP4**	**BP2 to BP4**
Do-nothing	0	0	Low	33	38	49	51	13
			Mid	28	33	42	43	10
			High	24	29	38	39	10
Instantaneous bans	25-35	0	Low	33	38	41	47	9.5
	45-55	0	Low	33	37	40	43	6
	65-75	0	Low	33	39	40	43	4
	25-35	0	Mid	28	34	37	42	8
	45-55	0	Mid	28	33	35	39	6
	65-75	0	Mid	28	33	35	37	4
	25-35	0	High	24	29	32	38	9
	45-55	0	High	24	29	31	35	6
	65-75	0	High	25	29	31	34	5
	25-35	10	Low	33	38	48	51	13
	45-55	10	Low	33	37	48	50	13
	65-75	10	Low	33	39	50	51	12
	25-35	10	Mid	28	34	42	44	10
	45-55	10	Mid	28	33	41	43	10
	65-75	10	Mid	28	33	41	43	10
	25-35	10	High	24	29	38	39	10
	45-55	10	High	25	29	38	40	11
	65-75	10	High	25	29	38	40	11
	25-35	20	Low	33	38	48	51	11
	45-55	20	Low	33	37	48	50	13

	65-75	20	Low	33	39	50	52	13
	25-35	20	Mid	28	34	42	44	10
	45-55	20	Mid	28	33	41	43	10
	65-75	20	Mid	28	33	41	43	10
	25-35	20	High	24	29	38	39	10
	45-55	20	High	25	29	38	40	11
	65-75	20	High	25	29	38	40	11
Phased bans*	25-35	10	Low	33	38	46	49	11
	45-55	10	Low	33	37	44	48	9
	65-75	10	Low	33	39	43	48	9
	25-35	10	Mid	28	34	41	43	9
	45-55	10	Mid	28	33	40	42	9
	65-75	10	Mid	28	33	40	42	9
	25-35	10	High	24	29	37	39	10
	45-55	10	High	25	29	36	39	10
	65-75	10	High	25	29	36	38	9
	25-35	20	Low	33	38	47	50	12
	45-55	20	Low	33	38	46	49	11
	65-75	20	Low	33	39	46	50	11
	25-35	20	Mid	28	34	41	44	10
	45-55	20	Mid	28	33	41	43	10
	65-75	20	Mid	28	33	41	42	9
	25-35	20	High	24	29	37	39	10
	45-55	20	High	25	29	37	39	10
	65-75	20	High	25	29	37	39	10

S6. Fisher population and fish population at the point of collapse

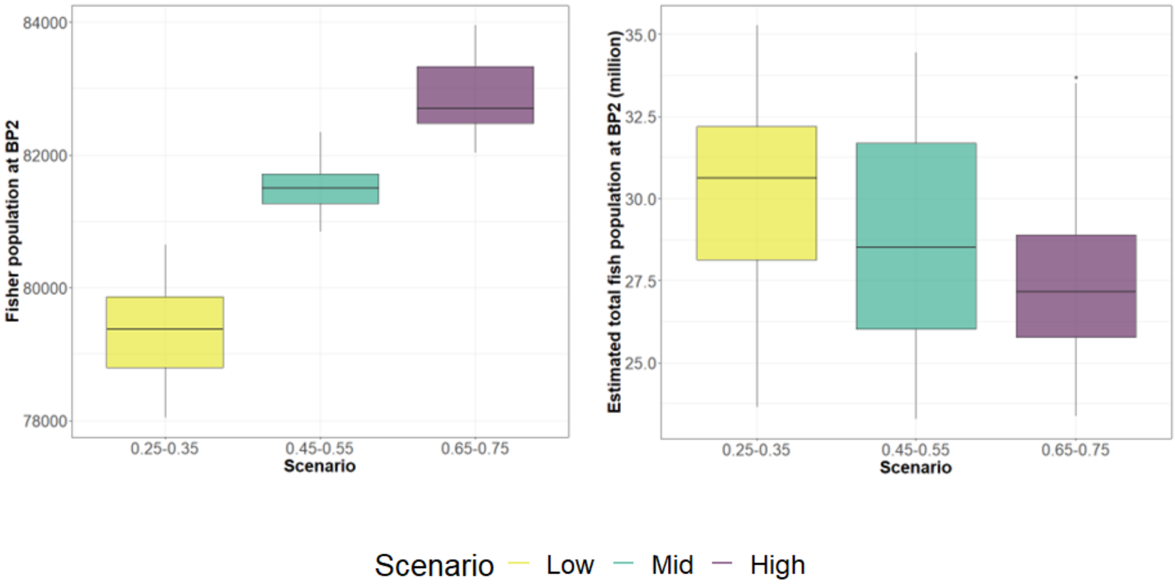

Figure S5: Boxplots depicting the distributions of (left) the corresponding fisher populations at BP2, and (right) the corresponding estimated total fish populations at BP2, across the three different 'do nothing' stress scenarios (i.e., as depicted as timeseries in Figure 1). One commonly measured metric of social-ecological resilience considers the magnitude of disturbance a social-ecological system can withstand before socioeconomic and/or ecological outcomes become undesirable (Folke, 2006; Renaud et al., 2010). This property combines both the sensitivity of a system to change and the precariousness of the system to an undesirable threshold, such as a regime shift or an abrupt threshold-dependent change.

S7. Recovery effort under alternative ban extents

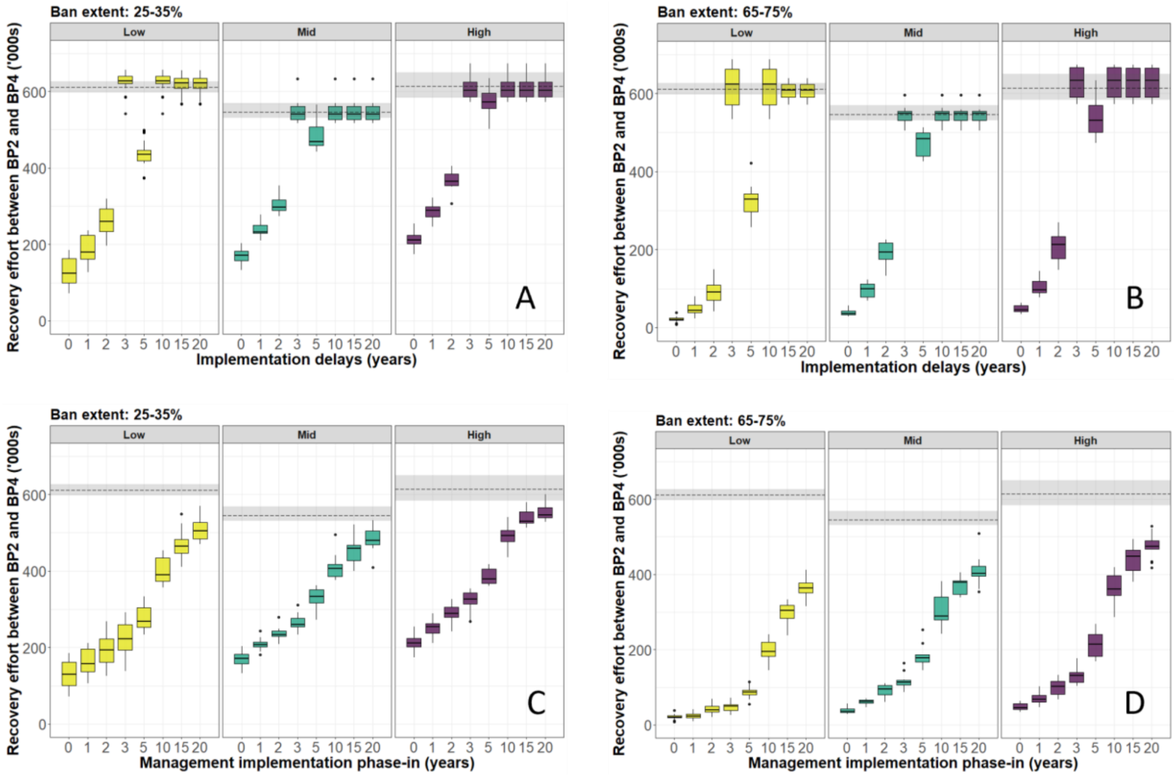

Figure S6: Boxplots depicting the distributions of recovery effort across four different fishing ban and three stress level (low, mid, high) scenarios: (A) bans covering 25-35% of the lake's surface area, with implementation *delayed* by a different number of years, (B) bans covering 65-75% of the lake's surface area, with implementation *delayed* by a different number of years, (C) bans covering 25-35% of the lake's surface area, with implementation *phased-in* over a different number of years, and (D) bans covering 65-75% of the lake's surface area, with implementation *phased-in* over a different number of years. For reference, the grey shading represents the interquartile range of the baseline simulations under each stress scenario (i.e. do-nothing scenarios), and the horizontal dashed lines represent the associated median values.

S8. Social-ecological outcomes

S8.1. Composite social-ecological outcome metric under alternative ban extents

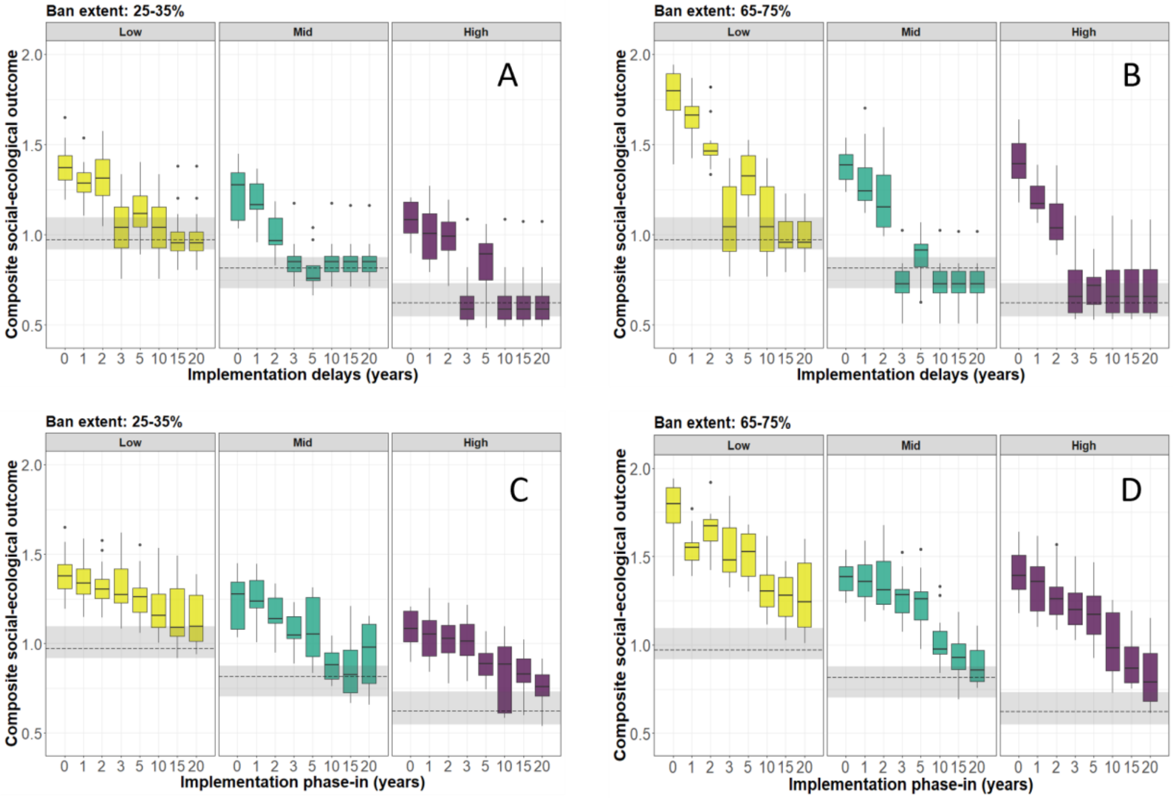

Figure S7.1: Boxplots depicting the distributions of the composite social-ecological outcome across four different fishing ban and three stress level (low, mid, high) scenarios: (A) bans covering 25-35% of the lake's surface area, with implementation *delayed* by a different number of years, (B) bans covering 65-75% of the lake's surface area, with implementation *delayed* by a different number of years, (C) bans covering 25-35% of the lake's surface area, with implementation *phased-in* over a different number of years, and (D) bans covering 65-75% of the lake's surface area, with implementation *phased-in* over a different number of years. For reference, the grey shading represents the interquartile range of the baseline simulations under each stress scenario (i.e. do-nothing scenarios), and the horizontal dashed lines represent the associated median values.

S8.2. Social-ecological outcomes under the ‘do-nothing’ management scenario

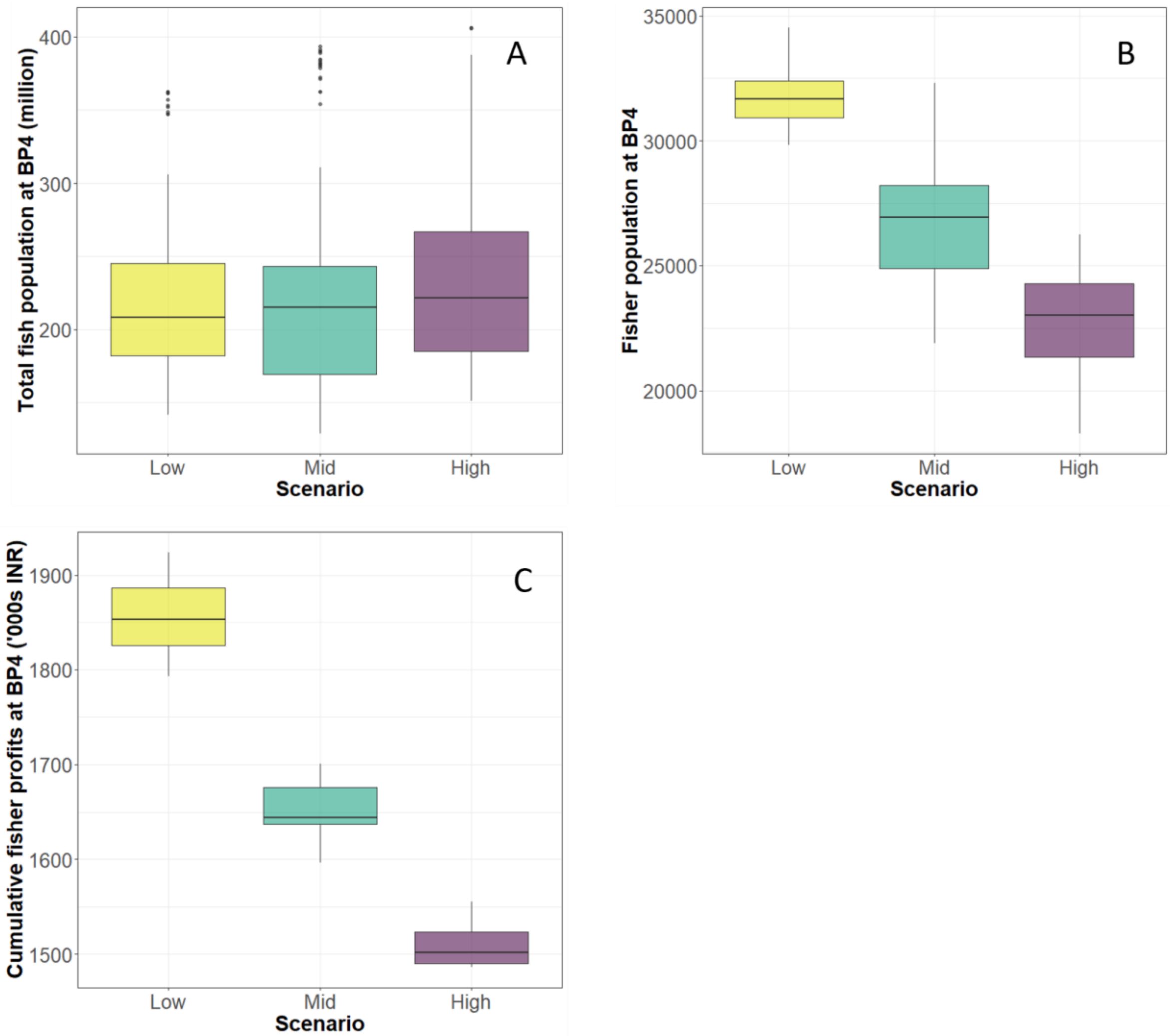

Figure S7.2: Boxplots depicting the distributions of the three outcomes underlying the composite social-ecological metric under the do-nothing management scenario (i.e. baseline) for three stress levels (low, mid, high): (A) total fish population at BP4, (B) total fisher population at BP4, and (C) cumulative profits generated by fishers at BP4.

<u>S8.3. Social-ecological outcomes under alternative management scenarios</u>

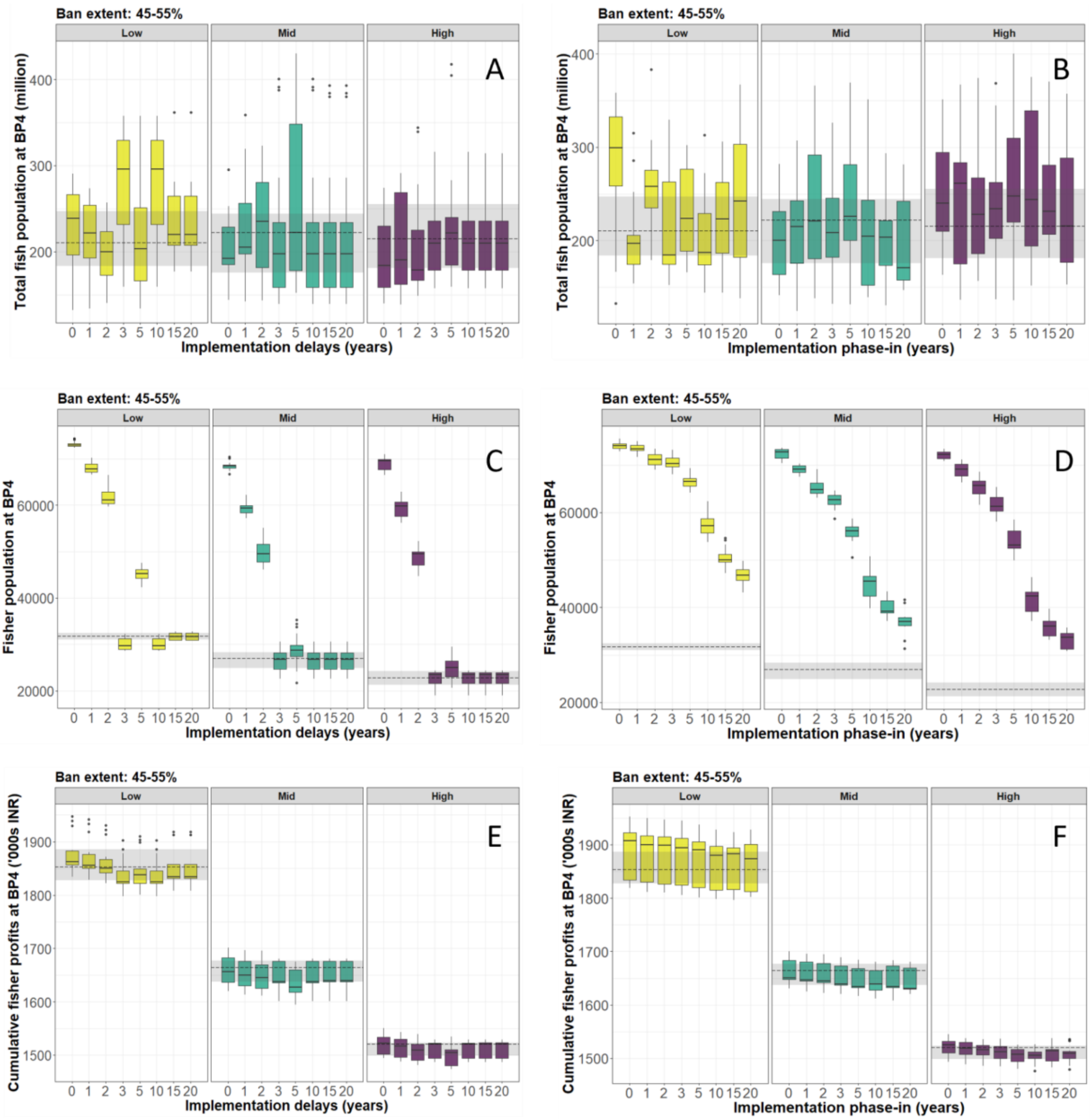

Figure S7.3: Boxplots depicting the distributions of the three outcomes underlying the composite social-ecological metric under (left panel) bans of different implementation *delays*, and (right panel) bans *phased-in* over different time periods across three stress levels (low, mid, high). (A-B) total fish population at BP4, (C-D) total fisher population at BP4, and (E-F) cumulative profits generated by fishers at BP4. For reference, the grey shading represents the interquartile range of the baseline simulations under each stress scenario (i.e. do-nothing scenarios), and the horizontal dashed lines represent the associated median values.

S9. Regression model of the composite social-ecological outcome metric value

Table S9: Regression outputs from a generalised linear model run in the statistical software R to quantify the determinants of the composite social-ecological outcome metric value across the different stress and fishing ban scenarios.

Dependent variable	Estimate	Std. error	t-value	p-value
(Intercept)	1.523	0.0038	397.4	< 0.001
Stress rate (R rate)	- 5.636	0.0242	-232.9	< 0.001
Fishing ban extent	0.343	0.0045	75.72	< 0.001
Delay or phasing duration	- 0.018	0.0002	-94.86	< 0.001
Delay or phasing approach (dummy variable, where delay = 0 and phasing = 1)	0.141	0.0026	53.90	< 0.001

S10. ReadMe guide for reading the model output files

All model outputs are available in the zip folder titled ‘Hysteresis_SharedSimulations’. The zip folder contains three subfolders, namely (i) ‘NoBans_shared’, which features the model outputs for the simulations under the ‘do-nothing’ governance scenario, (ii) ‘StaticBans_shared’, which features the model outputs for the simulations under the ‘instantaneous’ ban governance scenarios, where the ban extent takes one time-step to increase from 0% of the lake’s surface to the randomly sampled proportion of the lake area (i.e. up to 100%) for that given simulation, and (iii) ‘PhasedBans_shared’, which features the model outputs for the simulations under the ‘phased-in’ ban governance scenarios, where the ban extent increases linearly over time from 0% of the lake’s surface to the randomly sampled proportion of the lake area (i.e. up to 100%) for that given simulation (see Figure S3 for a graphical representation of the different governance scenarios).

The folder also contains a copy of the system dynamics model (‘NoBans_shared.stmx’) used to generate the ‘NoBans_shared’ simulations. The model file was built in ISEE Systems STELLA Architect v.1.6.1, and can be opened and run in the full version of STELLA (download link: https://www.iseesystems.com/) and the free STELLA online version (download link: https://www.iseesystems.com/store/products/stella-online.aspx). Instructions on how to run the model are detailed in the first module of the model (see the box titled ‘Instructions for Running the Model’).

In turn, there are nine subfolders under each of the ‘StaticBans’ and ‘PhasedBans’ folders: one each containing raw model outputs from each of the eight different delay/phase-in durations (i.e., 0, 1, 2, 3, 5, 10, 15 and 20 years), and one folder containing the summary statistics/outputs of each simulation (e.g., dates of breakpoints, and hysteresis magnitudes and recovery durations between BP2 and BP4). In the subfolders containing simulations with bans, the durations of the delays and phasing-in periods are denoted by the number suffixed after the underscore; for example, under the ‘StaticBans’ folder, the folder named ‘Delay_5’ contains the simulations where the implementation of the fishing ban was delayed for 5 years after the collapse of the fishery beneath 20% of maximum sustainable yield (BP2, see Figure S4).

Under each of the eight folders are seven CSV files containing the raw model outputs for the model variables analysed in the main manuscript:

1. ‘TotalFishPopulation.csv’ - monthly timeseries of the estimated modelled total fish population in Lake Chilika from 1973-2100
2. ‘TotalFisherPopulation.csv’ - monthly timeseries of the estimated modelled total fisher population on Lake Chilika from 1973-2100
3. ‘TotalFishCatch.csv’ - monthly timeseries of the estimated modelled total fish catch (tonnes) from Lake Chilika from 1973-2100
4. ‘RRate.csv’ - Monthly timeseries of the modelled ‘RRate’ (i.e., the net difference between the birth and death rates of the fisher population per 1000 population) from 1973-2100
5. ‘AveragePerCapitaProfits.csv’ - Monthly timeseries of the modelled average fishing profits per fisher, as a weighted average of fishers using traditional and motorised boats from 1973-2100.

6. ‘EndRRate_MCA.csv’ - Representing the stress from a growing fisher population, this file contains the randomly generated R Rate (i.e., final trajectory) of each simulation, where higher numbers produce more rapidly growing fisher populations.
7. ‘BanRate_MCA.csv’ - Representing the randomly sampled ban extent per simulation, ranging between 0% and 100% of the lake’s surface area.

Also stored in the zip folder are two R code files:

1. ‘Hysteresis_MainManuscriptGraphs.R’ - R code required to produce the graphs presented in the main manuscript, i.e., Figures 1-5.
2. ‘Hysteresis_HysteresisOutputsExample.R’ - R code required to generate the measures of hysteresis for each simulation, as featured in the Output files stored in the zip folder, including the recovery duration, hysteresis magnitude, and total recovery effort. The code shared is based upon the ‘static’ governance scenarios, with a delay time of one year, i.e., randomly sampled fishing bans covering between 0 and 100% of the lake’s surface area are implemented one year after the annual fish catch falls below 20% of maximum sustainable yield.

In order to run these R codes, you will need to have the statistical software R installed on your machine (e.g., see the link here for Windows operating systems).

Supplementary references

Cooper, G.S., Dearing, J.A., 2019. Modelling future safe and just operating spaces in regional social-ecological systems. Sci. Total Environ. 651. https://doi.org/https://doi.org/10.1016/j.scitotenv.2018.10.118

Dearing, J.A., Wang, R., Zhang, K., Dyke, J.G., Haberl, H., Hossain, M.S., Langdon, P.G., Lenton, T.M., Raworth, K., Brown, S., Carstensen, J., Cole, M.J., Cornell, S.E., Dawson, T.P., Doncaster, C.P., Eigenbrod, F., Flörke, M., Jeffers, E., Mackay, A.W., Nykvist, B., Poppy, G.M., 2014. Safe and just operating spaces for regional social-ecological systems. Glob. Environ. Chang. 28, 227–238. https://doi.org/http://dx.doi.org/10.1016/j.gloenvcha.2014.06.012

Folke, C., 2006. Resilience: The emergence of a perspective for social–ecological systems analyses. Glob. Environ. Chang. 16, 253–267. https://doi.org/http://dx.doi.org/10.1016/j.gloenvcha.2006.04.002

Pinsky, M.L., Jensen, O.P., Ricard, D., Palumbi, S.R., 2011. Unexpected patterns of fisheries collapse in the world's oceans. Proc. Natl. Acad. Sci. 108, 8317 LP---- 8322. https://doi.org/10.1073/pnas.1015313108

Renaud, F., Birkmann, J., Damm, M., Gallopín, G., 2010. Understanding multiple thresholds of coupled social–ecological systems exposed to natural hazards as external shocks. Nat. Hazards 55, 749–763. https://doi.org/10.1007/s11069-010-9505-x

Worm, B., Hilborn, R., Baum, J., Branch, T., Collie, J., Costello, C., Fogarty, M., Fulton, E., Hutchings, J., Jennings, S., Jensen, O., Lotze, H., Mace, P., Mcclanahan, T., Minto, C., Palumbi, S., Parma, A., Ricard, D., Rosenberg, A., Zeller, D., 2009. Rebuilding Global Fisheries. Science 325, 578–585. https://doi.org/10.1126/science.1173146