Supporting Information

Williams and Lenton 10.1073/pnas.0800244105

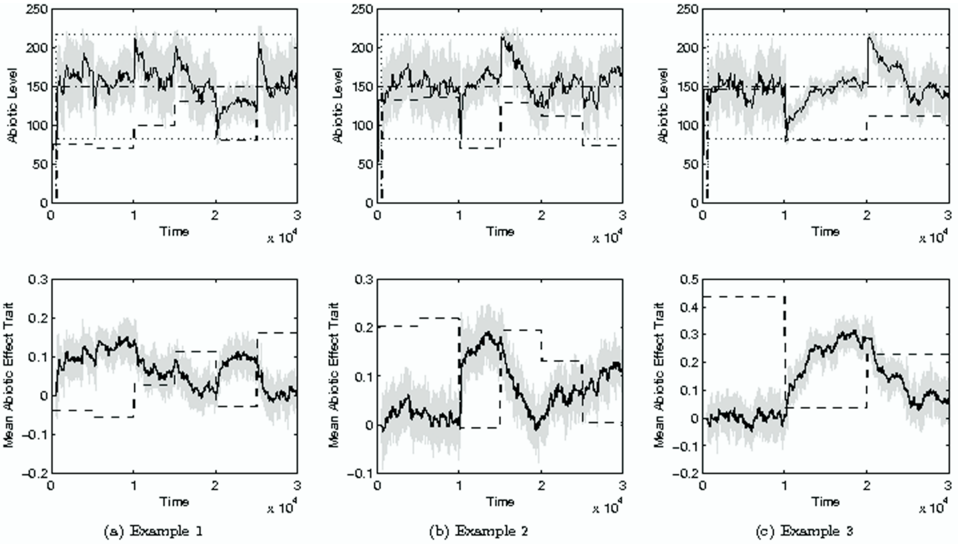
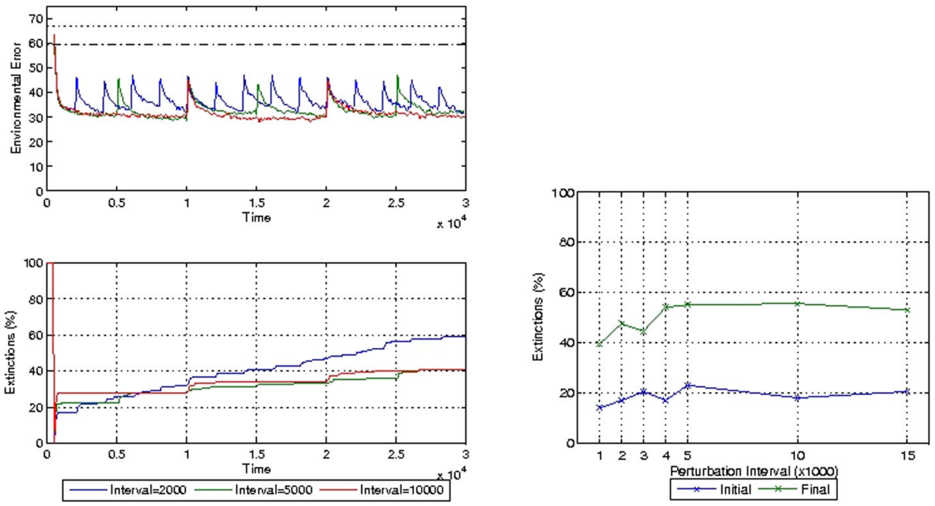


Fig. S1. Additional examples of environmental regulation. Data are shown for typical runs (F = 10 flasks, R_D = 1% diffusive between-flask mixing per time step) with random reassignment of external abiotic influx every 5,000 time steps (examples 1 and 2) or every 10,000 time steps (example 3). (*Upper*) The state of the abiotic environment (mean value across all flasks; the shaded area shows ±1 SD) remains close to the ideal growth conditions (dash-dot line) and within the boundaries of the habitable region (dotted lines). The ''dead'' abiotic state (dashed line) shows the state of the environment if no organisms were present and demonstrates the perturbing effect of changes in external forcing. (*Lower*) The mean allele value across the whole community (solid line; the shaded area shows ±1 SD) for genes controlling the metabolic by-product effects of organisms on the abiotic environment changes in response to external forcing [dashed line (not to scale)].



(a) Ensemble data (200 runs of 30000 timesteps, $A = 1$, $F = 10$, $R_D = 1\%$) with perturbations applied at intervals of 2000, 5000 or 10000 timesteps.

(b) Extinctions after 10 perturbation events in ensembles (200 runs, $A = 1$, $F = 10$, $R_D = 1\%$) with perturbations applied at different intervals.

Fig. S2. Robustness to perturbation frequency: ensemble results showing error reduction and extinction rate over time for different perturbation frequencies. (*a*) Error reduction and occurrence of extinctions for runs in which random perturbations to abiotic fluxes (see *Methods*) are applied at intervals of 2,000, 5,000, or 10,000 time steps. In all ensembles, the mean environmental error (*Upper plot*) is rapidly reduced from a spike after each perturbation. Data are plotted together with habitability bound (dotted line) and predicted environmental error in absence of life (dash-dot line). After ecosystem establishment, any perturbation event can (with low probability) cause system-wide extinction; the number of extinctions depends on the number of perturbation events during the run (*Lower plot*). (*b*) Number of extinctions after 10 perturbation events in ensembles in which perturbations were applied at different intervals. Run duration was determined by perturbation interval (e.g., 10 perturbations at 5,000 time step intervals required a run of 50,000 time steps). This experiment controls for the number of perturbation events during each run and shows that there is not a strong relationship between perturbation frequency and extinction rate. There is a slight increase in extinction rate as perturbation interval rises, attributable to reduced diversity; less-diverse systems are likely to be less robust [the ecological insurance hypothesis: Naeem S, Li S (1997) Biodiversity enhances ecosystem reliability. *Nature* 390:507–509]. Long periods with fixed conditions reduce diversity by allowing more time for competitive exclusion.

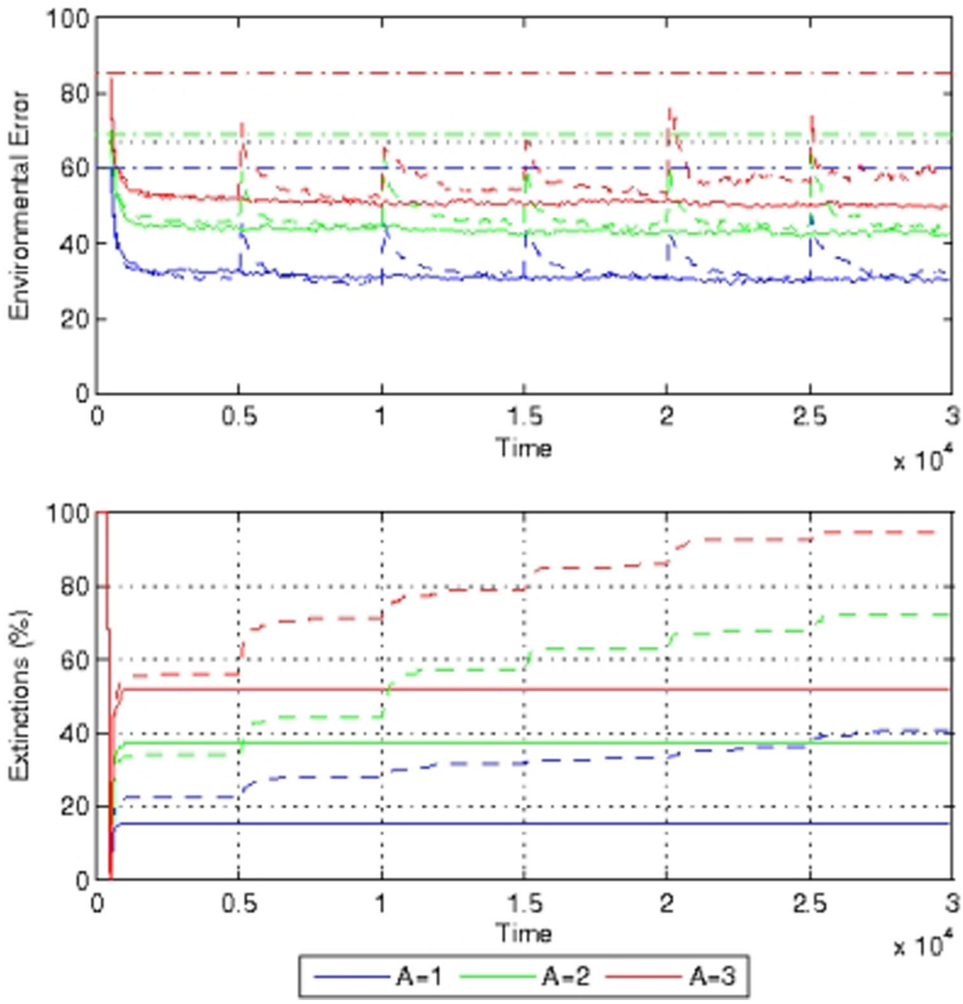


Fig. S3. Regulation of multiple abiotic factors. Ensemble results showing error reduction and extinction rate over time for different numbers of abiotic factors ($A = \{1, 2, 3\}$) demonstrate that behavior qualitatively similar to the standard case ($A = 1$) is seen with $A = 2$ and $A = 3$. Mean environmental error is reduced after perturbation, and most extinctions occur at initialization or after perturbation. Data are shown for ensembles (200 runs, $F = 10$ flasks, $R_D = 1\%$ diffusive between-flask mixing per time step) with random reassignment of external abiotic influx every 5,000 time steps. Optimum conditions are set to be $a_1 = 150$ for $A = 1$, $(a_1, a_2) = (100, 150)$ for $A = 2$, and $(a_1, a_2, a_3) = (50, 100, 150)$ for $A = 3$. (*Upper*) Data for unperturbed (solid lines) and perturbed (dashed lines) ensembles are plotted together with habitability bound (dotted line) and predicted environmental error in absence of life (dash-dot lines). The definition of environmental error (see *Model Description*) means that the predicted error in the absence of life is higher for $A = 2$ and $A = 3$. This implies a more difficult error-reduction task for the biota, and the observed error values are correspondingly higher. (*Lower*) Extinction data for unperturbed (solid lines) and perturbed (dashed lines) ensembles. The increased difficulty of the regulation task for $A = 2$ and $A = 3$ is exhibited in increased rates of extinction. As with $A = 1$, most extinctions in the $A = 2$ and $A = 3$ ensembles occur at initialization or after perturbation. Overall levels of extinction for $A = 2$ and $A = 3$ are higher than those with $A = 1$.

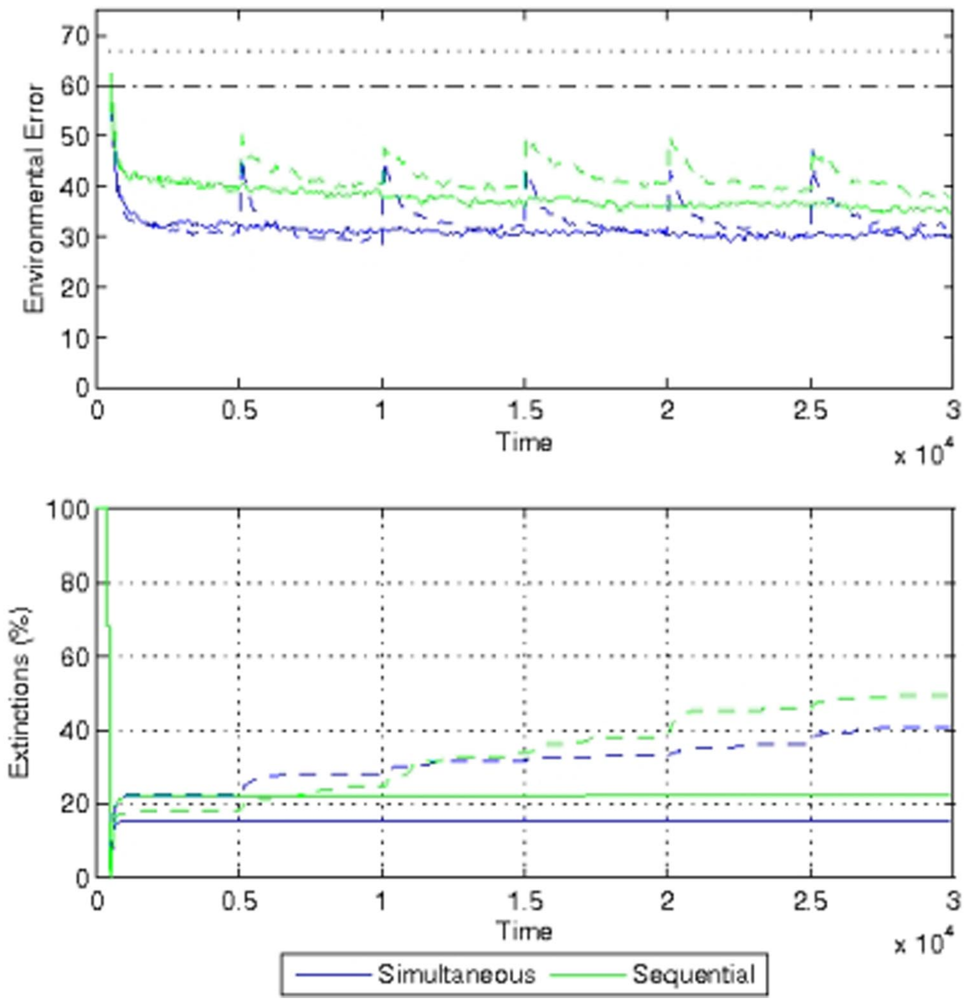


Fig. S4. Robustness of results to different update algorithms. Ensemble results showing error reduction and extinction rate over time for simultaneous and sequential update schemes demonstrate that qualitatively similar behavior is seen in both cases. Data are shown for ensembles (200 runs, $F = 10$ flasks, $R_D = 1\%$ diffusive between-flask mixing per time step) with random reassignment of external abiotic influx every 5,000 time steps. Simultaneous update is the standard form described in *Method* and *Model Description*. Sequential update is implemented by updating each individual in random sequence at each time step, with the order of update being randomized afresh at every iteration. Resources are allocated on a ''first come, first served'' basis until exhausted, and individual demand is not scaled to fit availability. Thus, when a nutrient is scarce, some individuals will receive their full requirement, whereas others will receive nothing. (*Upper*) Data for unperturbed (solid lines) and perturbed (dashed lines) ensembles are plotted together with habitability bound (dotted line) and predicted environmental error in absence of life (dash-dot line). Less error reduction is observed with sequential update than with simultaneous update, because in this scenario higher-level selection for environmental improvement is less effective. With sequential update, when nutrients are scarce, only a small subset of the community will metabolize nutrients (and thereby cause a by-product alteration to the abiotic environment) at each time step. The species composition of this subset is a random sample of the total community; thus, sampling error causes significant variance in net environmental effects at each time step. This introduces noise that weakens the correlation between community composition and environmental state and, hence, weakens the correlation between community ''phenotype'' and community ''fitness.'' This reduces the efficacy of the higher-level selection for environment-improving communities. However, the model with sequential update still demonstrates error reduction and environmental regulation. (*Lower*) Extinction data for unperturbed (solid lines) and perturbed (dashed lines) ensembles show that extinction rates are higher for sequential update than for simultaneous update, because the regulatory mechanism is less effective.

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Other Supporting Information Files

SI Appendix 1 (PDF)