

Fighting Risky Population Synchronization: Desynchronization and Stabilization in Spatially Structured Ecological Systems

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Population synchronization exists ubiquitously in ecological systems, of which the underlying causes and the roles in species extinction remain a perplexing puzzle¹⁻⁸. It is generally believed that the coherence of population dynamics is detrimental and regarded as a major cause of global extinction⁹⁻¹². A central but unsolved question in ecology of great importance for conservation and biological control is how to destroy the pernicious coherent structures^{9, 10, 13}. Here, a top-down approach is adopted to tackle the challenge¹⁴. A feedback strategy accordingly is applied to stabilize the metacommunity, i.e., to reduce excessive metapopulation fluctuations by means of introducing or removing a planned number of individuals. As a result, the feedback desynchronizes correlated population oscillations¹⁴, giving rise to either complex asynchronous travelling waves or “amplitude death”, cessation of all individual population cycles^{15, 16}. Together with the construction of corridors, my method may provide an efficient way to protect those species threatened as a result of, e. g. habitat fragmentation. I anticipate my essay providing a general mechanism against widespread harmful synchronization in physical and biological systems, for example, for developing of a “brain anti-pacemaker” for neurological diseases such as Parkinson’s disease and epilepsy closely linked to pathologically synchronized neuronal discharges^{17, 18}.

Species extinction is an important phenomenon in nature. Over 99% of all species ever lived are now extinct¹⁹. One of the most fundamental factors responsible for species extinction is habitat fragmentation^{20, 21}. Pathways, so-called “conservation corridors”, are hence constructed to connect isolated habitats to increase migration between different patches²². Unfortunately, although migration may have the expected effects of promoting rescue effects, thus renewing extinct or declining populations, they may also have the unexpected effects of synchronizing population fluctuations, thus raising the risk of global extinction^{9-12, 22}.

Population synchronization is another crucial and attractive issue in ecology⁵⁻⁸. It is believed to take an important role in the process of species extinct. Synchronous oscillations in populations may bring about concurrent local extinction in all patches thus making the rescue effect impossible, and eventually leading to extinction of the entire metapopulation⁹⁻¹². Moreover, fully synchronized local populations would grow and shrink simultaneously and produce extra-large metapopulation oscillations^{23, 24}. The violent metapopulation fluctuations lead to extremely small metapopulation heightening global extinction risk as well as extremely large metapopulation increasing the possibility of several adverse conditions such as over-crowding, insects and diseases outbreak, etc.²⁵. For these reasons, preventing harmful population synchronization poses a key problem in conservation ecology. However, it seems to be a formidable task in consideration of extraordinary complexities of individual population dynamics and of metapopulation structures, as well as the enigmatic underlying causes of population synchronization.

Here, I overcome the big challenge via an innovative top-down approach¹⁴. Hence, a feedback strategy is then used to suppress violent metapopulation fluctuations, removing excessive individuals (by means of harvesting and hunting, etc.) when the metapopulation size is large; or introducing of additional individuals when the metapopulation size is small. The number of individuals added/removed is proportional to the difference between the present and the past metapopulation size. Suppose the controlled species is x , the feedback x_c , namely the number added/removed, is determined as follows

$$x_c(t) = -g(x(t) - x(t - \tau)) \quad (1)$$

where g is a coefficient, called feedback gain, and τ is the time difference between the past and the present, called time-delay. Feedback method described by equation (1) is referred to 'time-delayed feedback', which is used for chaos control and stabilization of uncertain steady states of low-dimensional dynamic system²⁶. In my studies, I found that although these management processes are rather simple, they have quite profound effects on dynamical behaviors both of metapopulation and of its constituent populations. With appropriate time-delay τ , feedback gain g , and proper controlled species x (ensuring the controllability of the metacommunity), the feedback (1) stabilizes the metapopulation and hence destroys the coherent population cycles, producing either desynchronized wave or suppression of all local populations depending upon migration magnitude and dynamics of isolated patches.

I demonstrate the method first with a food-web model with local dynamics described by a three level predator-prey-resource system, namely the uniform phase evolution and chaotic abundance (UPCA) model (Box 1)⁶. Isolated patches are connected by diffusive migration of strength D to form a metacommunity of spatially structured populations. For weak coupling, population in each patch cycles independently. With intermediate coupling strength, populations exhibit phase synchronization with locked phases and uncorrelated peak population abundances. For relatively strong coupling, populations fully synchronize with both their phases and their amplitudes are almost identical, resulting in rather extra-large fluctuations in metapopulation size⁶.

The considered food-web model can be stabilized by different choices of controlled species, such as the control of vegetation metapopulation or of herbivore metapopulation, etc.. In the illustrated numerical example, the vegetation and herbivore metapopulations are used for feedback. Individuals added/removed are distributed uniformly in all local patches. As shown in Fig. 1, the uncontrolled metapopulations undergo extremely large oscillations (Fig. 1a, b, and c, black line). By contrast, the controlled metapopulations exhibit only noise-level fluctuations around some constant metapopulations U_0 , V_0 , and W_0 , respectively (Fig. 1a, b, and c, red line). A remarkable feature of the strategy is that once the constant metapopulations are reached, the efforts required are minimized because of the vanishing state differences ($U(t) - U(t - \tau) \approx 0$, $V(t) - V(t - \tau) \approx 0$), as shown in Fig. 1d and Fig. 1e.

The most exciting effect of this fairly simple feedback, however, is its dramatic impact on the dynamic behaviors of spatially extended populations. It destroys the full synchronization in population cycles (Fig. 2a). Therefore, local populations oscillate independently (Fig. 2b), resulting in asynchronous dynamic structures (s1, UPCA.avi). Because of its vanishing property (Fig. 1d and e), the feedback would have little effects on the individual population oscillations, which are lessened however by the migration (comparing Fig. 2c with Fig. 2d).

The above results carry strong implications for conservation ecology. In the case of complete synchronization induced by large-scale migration, it is possible that all the patches simultaneously undergo “bad years” (Fig. 3a), which makes the “rescue” impossible as well as leads to extremely small metapopulation size, thereby greatly increasing the possibility of global extinction⁹⁻¹². On the other hand, it is also possible that all the patches concurrently experience “harvest years” (Fig. 3b), which gives rise to high densities making the system susceptible for disease outbreak and

“over-crowding”, etc²⁵.. The proposed management measures rule out all these adverse situations even with minimal efforts. They not only eliminate the possibility of “bad years” and “harvest years” (Fig. 1c, and d), but also produce asynchronous population dynamics (Fig. 3c, d, s1) thereby promoting the “rescue effect”, thus significantly decreasing the danger of global extinction. My results are also of great importance in medical science, where there is a significant clinic need for mild stimulation techniques for patients with neurological diseases (such as Parkinson’s disease and essential tremor), to suppress abnormal neural synchrony without changing the individual neuronal behaviors^{17, 18}.

Once local population oscillations are desynchronized, migration may also lead to “amplitude death”, a situation where all populations cease to cycle and go into their steady states¹⁵. I show this amazing phenomenon with a food-web of Lotka-Volterra (LV) systems²⁷. The prey-predator system is inherently unstable with the enemy-victim interactions eventually leading to an extinction of (at least) one of the species²⁸. Previous studies have shown that migration provides a possible stabilizing factor for large metapopulation: it stabilizes the populations if they are out of sync^{24, 29}. However, migration tends to synchronize population cycles. So the key challenge is to find a mechanism that maintains desynchronization in the presence of migration²⁹.

In the considered food-web of LV systems, even small migration strength D is capable of synchronizing the populations (Fig. 4a). The patches act like a single big patch. Both metapopulation and its constituent populations exhibit large-amplitude cycles (Fig. 4b, c). The feedback is constructed based on the overall both predator and prey metapopulation (similar results are obtained via the control either of predator or of prey metapopulation) with $g = 0.1$ and $\tau = 4.0$, and is scattered evenly among local patches. It stabilizes the metapopulation (Fig. 4d) thus desynchronizing the population cycles (Fig. 4e). Consequently, the migration quenches all the patches (Fig. 4f). There are only incoherent noise-level population fluctuations, the amplitudes of which decrease with the increase of migration strength D . The evolutions of spatial dynamics in time with and without feedback are presented in s2, Lotka-Volterra.avi.

A very simple method has been proposed to suppress population synchronization in complex ecological systems. It is easy to be implemented because it only relies on time series of the metapopulation. My method could be applied to offset the adverse effects of conservation corridors to protect the endangered populations. Of course, its applications should be further

investigated with respect to control effectiveness, system stability, and control efficiency in consideration of required efforts. For example, large g and τ induces instability of the controlled system. However, small feedback gain g and time delay τ decreases the control effectiveness. What's more, small time delay τ leads to frequent investigation of metapopulation. Thus, future studies will be carried out to find an optimal pair of feedback gain g and time delay τ . Another practical question is controllability of a metapopulation. Although full-state feedback control, i.e., the control of all species in the food-web, may ensure stability of a metapopulation, but it is inefficient with respect to efforts needed to conduct metapopulation investigation. Because my approach is independent of any information of practical physical, biological systems, it should also find applications against unwanted synchronization in many different contexts. It is particularly suitable for those extremely complex systems, such as human neural networks, where detailed models are difficult or impossible to obtain, but overall mean activities are easily available such as local potential field (LPF)³⁰.

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Box 1 The chaotic three-level food-web model⁶

I used the N -patch model:

$$\begin{aligned}\dot{u}_i &= a_i u_i - \alpha_1 f_1(u_i, v_i) \\ v_i &= -b_i v_i + \alpha_1 f_1(u_i, v_i) - \alpha_2 f_2(v_i, w_i) + D \sum_j (v_j - v_i) \\ w_i &= -c_i (w_i - w^*) + \alpha_2 f_2(v_i, w_i) + D \sum_j (w_j - w_i)\end{aligned}\quad (2)$$

where u_i , v_i , and w_i represent the vegetation, herbivore and predator populations in i th patch, respectively. Parameters a_i , b_i , and c_i represent the respective growth rates of each trophic species within patch- i in the absence of inter-specific interactions. $f_1(u_i, v_i)$ and $f_2(v_i, w_i)$ are consumer-resource and predator-prey interactions, respectively. Coefficients α_1 and α_2 are strength of the inter-specific interactions. Patches are connected through diffusive migration of mobile species (i.e., coupled via v_i and w_i variables) with migration magnitude D . For the simulation results reported here, parameters $a_i = 1.0$, $c_i = 10.0$, b_i are random numbers uniformly distributed in $[0.95, 1.05]$. The consumer-resource interaction is the Holling type II term $f_1(u_i, v_i) = \frac{u_i v_i}{1 + k_1 u_i}$ with $k_1 = 0.05$, and the predator-prey interaction is the Lotka-Volterra term $f_2(v_i, w_i) = v_i w_i$. $\alpha_1 = 0.2$ and $\alpha_2 = 1.0$. The “metacommunity” is modeled as a 30×30 lattice. Each patch is locally coupled to its nearest (eight, five, or three) neighbors (inner, boundary, and angular patch) with constant migration $D = 0.1$.

Box 2 The Lotka-Volterra predator-prey food-web model²⁷

I used the N -patch model:

$$\begin{aligned}\dot{x}_i &= -\mu x_i + \gamma_1 x_i y_i + D \sum_j (x_j - x_i); \\ \dot{y}_i &= \sigma y_i - \gamma_2 x_i y_i + D \sum_j (y_j - y_i)\end{aligned}\quad (3)$$

where x_i is the predator population of patch- i that decays with rate μ in the absence of a prey. y_i is the prey population of patch- i that grows with a constant birth rate σ in the absence of a predator. γ_1 , γ_2 are the relative increase (decrease) of the predator (prey) populations due to the interaction between species, correspondingly. Patches are connected through diffusive migration, and D is the migration strength. The food-web is also modeled as an 20×20 lattice with each patch locally coupled to its nearest (eight, five, or three) neighbors (inner, boundary, and angular patch). For the simulation results reported here, μ_i are randomly chosen uniformly from $[0.95, 1.05]$, $\sigma = 1.0$, $\gamma_1 = 1.0$, $\gamma_2 = 1.0$, and the migration strength $D = 0.5$.

Figure Captions

- Fig. 1 Stabilization of the UPCA food-web metapopulations. Time courses of uncontrolled (black) and controlled (red) vegetation $U = \sum_j u_j$ (a), herbivore $V = \sum_j v_j$ (b), and predator $W = \sum_j w_j$ (c) metapopulations, respectively, and of feedbacks of vegetation $U_c = -g(U(t) - U(t - \tau))$ (c) and herbivore $V_c = -g(V(t) - V(t - \tau))$ (d). $g = 0.2$, $\tau = 5.0$.
- Fig. 2 (a) Time courses of synchronized predator population cycles without control. (b) Time courses of desynchronized predator population cycles with control. (c) and (d) Phase portraits of a single UPCA oscillator without and with control, respectively.
- Fig. 3 Snapshots of herbivore populations in “bad year” (a) and “harvest year” (b) in the uncontrolled system, and different asynchronous structures (c) and (d) in the controlled system.
- Fig. 4 (a) Time courses of the coherent predator population oscillations. (b) and (c) Plots of the metapopulation ($X = \sum_j x_j$ and $Y = \sum_j y_j$) and a single population as functions of time without control. (d) Plot of the metapopulation (X, Y) as a function of time. (e) Time courses of the incoherent noise-level local population fluctuations. (f) Plot of a single controlled predator-prey population as a function time. $g = 0.1$, $\tau = 4.0$. Note that the magnitude of the feedback is even smaller than that of the migration strength.

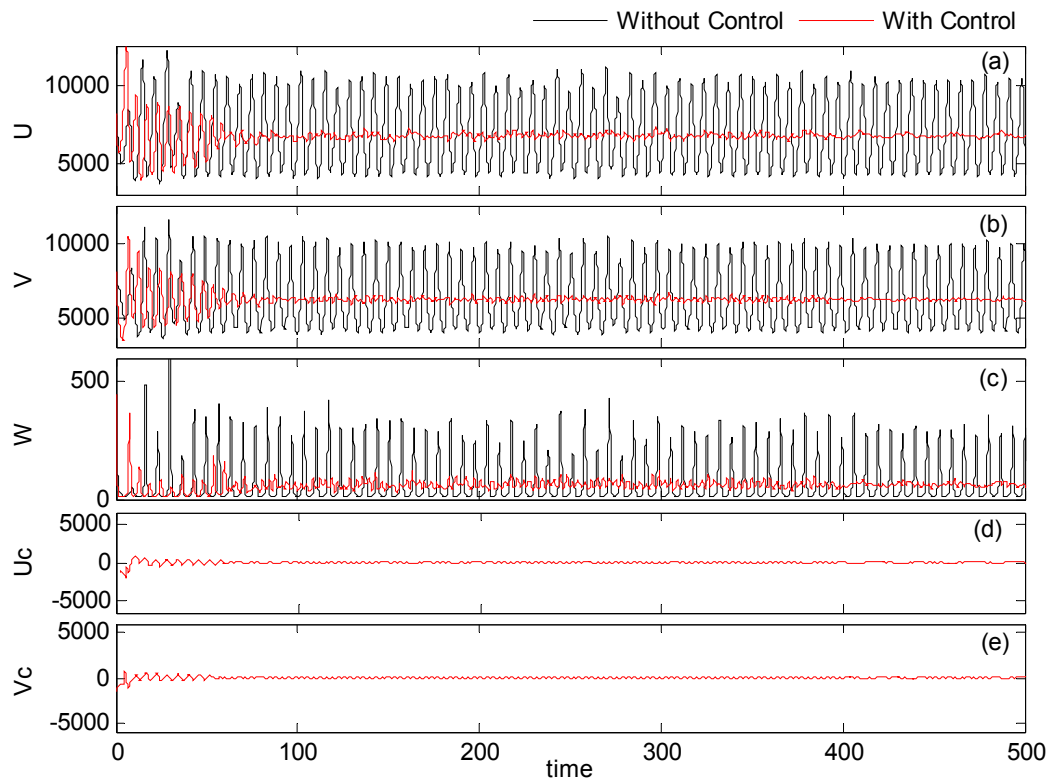


Fig. 1

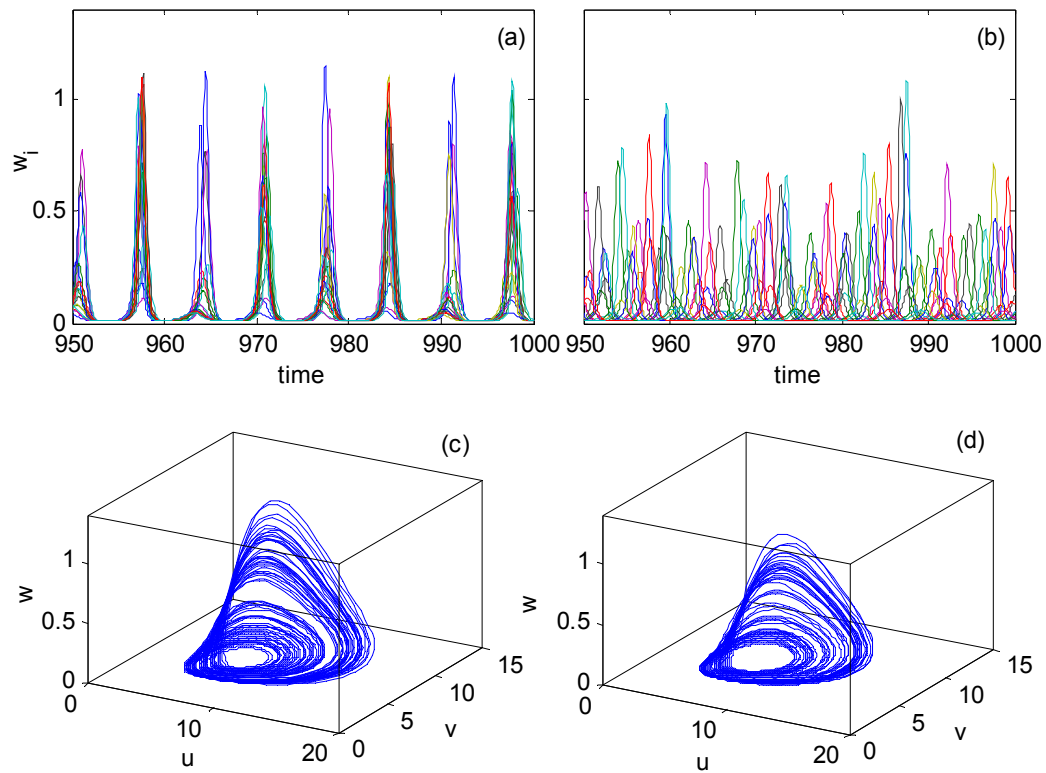


Fig. 2

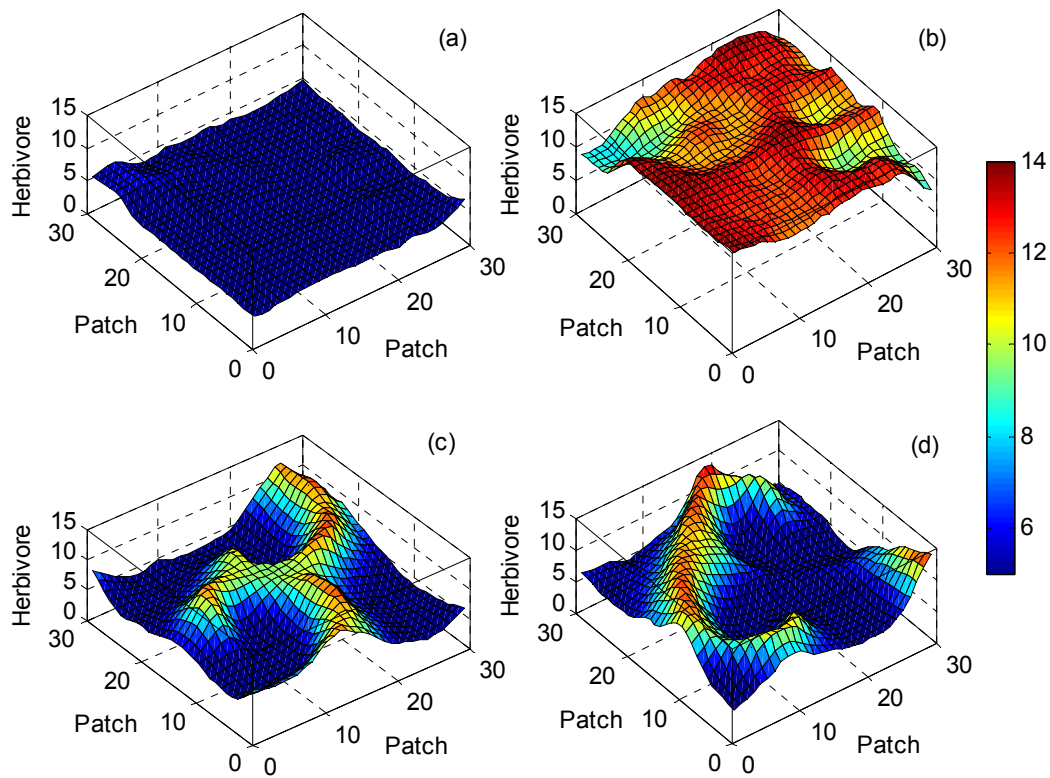


Fig. 3

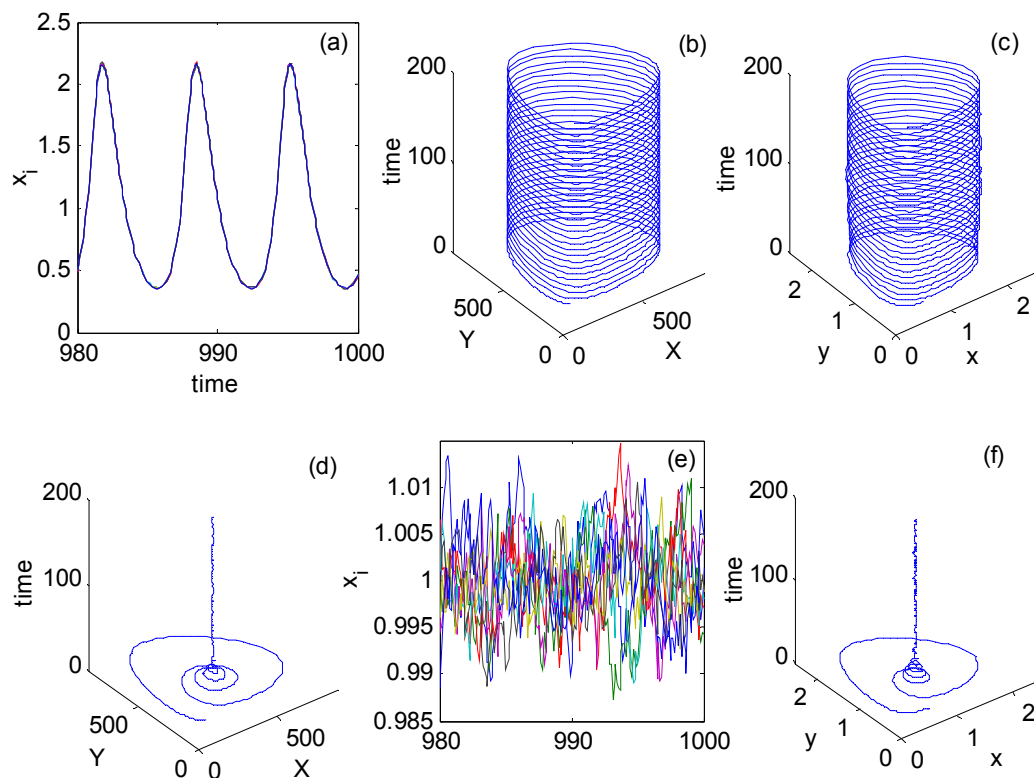


Fig. 4