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Socioecological regime shifts in the setting of complex social interactions

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The coupling between social and ecological system has become more ubiquitous and predominant in the current era. The strong interaction between these systems can bring about regime shifts which in the extreme can lead to the collapse of social cooperation and the extinction of ecological resources. In this paper, we study the occurrence of such regime shifts in the context of a coupled social-ecological system where social cooperation is established by means of sanction that punishes local selfish act and promotes norms that prescribe nonexcessive resource extraction. In particular, we investigate the role of social networks on social-ecological regimes shift and the corresponding hysteresis effects caused by the local ostracism mechanism under different social and ecological parameters. Our results show that a lowering of network degree reduces the hysteresis effect and also alters the tipping point, which is duly verified by our numerical results and analytical estimation. Interestingly, the hysteresis effect is found to be stronger in scale-free network in comparison with random network even when both networks have the same average degree. These results provide deeper insights into the resilience of these systems, and can have important implications on the management of coupled social-ecological systems with complex social interactions.

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I. INTRODUCTION

In the twenty-first century, human domination on Earth has created tremendous impact towards its ecosystem. Our world is now threatened by the potential occurrence of massive climate change [1,2], pollution, and resource scarcity [3]. In addition, significant deterioration of forests [4], waters, and hydrologies [5], as well as biodiversity [6] has been observed. As the interaction between human and ecology becomes more and more common, we need an integrated science on socioecological phenomena [7]. Moreover, from a practical point of view, a proper understanding of a coupled socioecological system is relevant in guiding public policy decisions. In fact, ill-conceived governmental policies have led to pest outbreak in Balinese padi rice fields [8], failure of water management by state institution [9], and poor forest protection by the government in comparison to forests that were locally managed [10].

In contrast to traditional studies on deterioration of ecosystems, recent attempts have been made to model a coupled socioecological system by taking into account both social and ecological factors [11–13]. In the studies of a coupled socioecological system (SES), the social agents act not only as external factors that influence the ecological system, they can also adjust their behavior in response to any ecological alteration. One specific coupled SES is based on the availability of a common pool resource. In a common pool resource system, all related individuals have open access to the resource such that it can be depleted by all the users. This situation is known as the tragedy of the commons as described by Hardin [14]. The notion is that everyone will be

better off if they exercise restraint on the use of the resource. However, such a behavior is not followed by a rational and selfish person who is motivated by self-interest to maximize individual benefits. The common pool resource problem is very relevant to the current society where competition over limited resources is ubiquitous. Research indicates that we consume more resources than what the ecological system can regenerate [15]. The survival of our civilization thus depends on our ability to cooperate. Indeed, we observe cooperative behavior in many levels of societies that strive to protect the common benefit [16]. Several efforts have been made to investigate the common pool resource problems, whether by using a specific model [13,17–19] or empirical data and experiment [20–23].

In this paper, we investigate the common pool dilemma within the framework and assumptions used in previous models, especially those of the TSL (Tavoni-Schulter-Levin) model [13]. The TSL model takes the form of nonlinear equations that couple the dynamics of social cooperation to the dynamics of a renewable common pool resource. The model shows that cooperative behavior can be promoted through social ostracism against defectors who overuse the common pool resources. However, the TSL model assumes that the population interacts in a well-mixed manner, i.e., everyone interacts with everyone else. In this paper, we incorporate network structure to provide a more realistic representation of complex social interactions. In the context of such a social network, an individual is represented by a node with the edges corresponding to social interactions. Different social structures thus correspond to different network degrees and topology [24], and we expect different social interaction patterns to have a dissimilar impact on the promotion of cooperative behavior [24,25]. Moreover, our focus in this paper is to investigate the occurrence of social-ecological regime shift triggered by various social and ecological drivers [26].

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Various ecological regime shifts such as species extinction and massive biodiversity reduction, or the population explosion of certain species, for instance eutrophication, have been studied extensively [27,28]. Dramatic ecosystem regime shifts where lakes turn from clear to turbid [27] and Sahara regions collapsed suddenly into deserts [29] have been widely documented. However, the phenomena of social-ecological regime shift, where a breakdown of social cooperation coupled with a sudden drop in ecological resources, have yet to be thoroughly investigated.

A type of social-ecological regime shift of concerned in this paper relates to the phenomena of hysteresis. Such a shift happens suddenly which forces the system to enter a new stable region [30]. Specifically, the system undergoes a transition from one stable regime to another stable regime. Due to the presence of a feedback mechanism, the system may display resistance towards transition between stable states unless the perturbation is large enough. Therefore, the state of the system depends not merely on the variables and parameters but also on the history of the system. This path dependency gives rise to the effect of hysteresis. Hysteresis usually emerges via changes of certain driving parameter. When the state of the system is near the boundary of stable and unstable fixed points, tiny variation would push the system from one basin of attraction to another. The impact or regime shift can be disastrous because it may not be easily reversed by merely changing the parameter to its previous position [31]. Note that the effect of hysteresis has also been studied in other ecological models [32,33] and game theoretical models [34–36]. In this paper, we investigate how social network structure influences the phenomenon of hysteresis. While recent research has suggested that connectivity of a network structure is usually associated with a resistance to change [37], the study of how complex social-ecological interactions can alter bifurcation characteristics is still unexplored, and thus is the subject of investigation in this paper.

II. MODEL DESCRIPTION

Here, we review the common pool dilemma and ostracism mechanism described by the TSL model [13]. In the TSL paradigm, there exists coupling between the ecological and social system. In this paper, we have modified the model by incorporating local discrete updating so that the social and ecological variables are updated in every time step. In this section, we shall provide the basic framework of the model, and give certain details and derivation of the model and parameters in the Appendix.

A. Ecological system

We define the ecological state to be the amount of natural resource (for instance, fresh water) available for human exploitation. The amount of available resource R is described by an explicit inflow and outflow mechanism against time t . Specifically, we assume a constant resource inflow which increases the available resource, while the outflow causes resource depletion through natural depreciation and human extraction. This leads to the following equation for resource

dynamics:

$$\frac{\Delta R}{\Delta t} = c - d \left[\frac{R}{R_{\max}} \right]^2 - qER. \quad (1)$$

The first term of the equation is the constant resource inflow c , the second term is the natural depreciation which is parametrized by the constant d , and the last term is the loss due to human extractive effort. Note that q is the technological parameter associated with the efficiency of resource utilization, while E represents the total extractive effort which is defined in Eq. (3) below. In the absence of human extraction, the resource would equilibrate to its maximum capacity $R_{\max}$ for $c = d$. Since the time step is assumed to be $\Delta t = 1$ in this paper, the equation of resource dynamics has been rewritten in the discrete form as follows:

$$R_{t+1} = R_t + c - d \left[\frac{R_t}{R_{\max}} \right]^2 - qE_t R_t. \quad (2)$$

B. Social system

The human population is assumed fixed which implies the absence of movement of people into and out of our society. The total population N is divided into two categories: the cooperator N_c and the defector N_d . The cooperator would extract the available resource by putting in effort e_c , while the defector would extract more resource by putting in a larger effort e_d . Therefore, the total effort of our society is given by

$$E = N_c e_c + N_d e_d = N[f_c e_c + [1 - f_c] e_d], \quad (3)$$

where f_c is the fraction of cooperators in the society.

The cooperators agree to abide by the norm and stick to the community efficient effort ($e_c = e_{\text{eff}}$). On the other hand, the defectors violate the rule by maximizing their individual payoff through putting in effort $e_d = e_{\text{nash}}$. Here, e_d is the Nash equilibrium of individual effort. The whole society and ecosystem would be better off if all the individuals cooperate. However, at the individual level, it is more rational to defect because of the enhanced individual incentive. Each individual would face this dilemma.

The payoff of each individual is given by the difference between income and cost. The income is derived from a fraction of the total production yield F , which is assumed to relate positively to the availability of natural resource and the total effort of the society. F takes the form of the Cobb-Douglas production function as follows:

$$F = \gamma E^\alpha R^\beta, \quad (4)$$

where γ is the production constant. While the parameters α and β represent the output elasticity of labor and resource respectively, they obey the relation $\alpha + \beta < 1$ to ensure that F has the characteristic of diminishing returns. On the other hand, we assume that the cost depends linearly on the individual effort, with the proportionality constant being w signifying the opportunity cost of labor. With this, the payoff for the cooperator is written as

$$\pi_c = \frac{e_c}{E} F(E, R) - w e_c, \quad (5)$$

while the payoff for the defector is

$$\pi_d = \frac{e_d}{E} F(E, R) - we_d. \quad (6)$$

However, there is an additional social cost to be paid by norm violators. Each defector would be socially ostracized from the community of neighboring cooperators (n_c) via a denial of service or in the form of social disapproval. Since the interaction between individuals is constrained by the underlying network structure, the neighbor of a particular agent is defined as its nearest neighbor in the network. In other words, ostracism towards a particular defector is mediated through these connected neighbors. Quantitatively, we model social ostracism through the Gompertz function:

$$O(n_c) = he^{\tau e^{gn_c}}, \quad (7)$$

where the parameter h represents the amplitude of ostracism. The parameters τ and g govern the shape and effective threshold of the ostracism function.

In the case of equity driven ostracism, the strength of the social sanction not only depends on the number of cooperators but also on the payoff difference between defector and cooperator. The consequence of equity driven ostracism leads to the following utility for defectors:

$$U_d(n_c) = \pi_d - O(n_c) \frac{\pi_d - \pi_c}{\pi_d}, \quad (8)$$

whereas the utility of the cooperator remains the same without any payoff reduction from the social pressure:

$$U_c = \pi_c. \quad (9)$$

With these expressions, we are able to calculate the utility of every agent and to determine whether they choose the cooperative or defective strategy. The average utility of the agent would then serve as a measure of success. The evolution of the agent's strategy is based on a comparison of its utility by means of an updating mechanism discussed in the next subsection.

C. Updating mechanism

There are numerous updating rules in evolutionary games [38]. The basic mechanism in these games is the adoption by an agent on the more profitable strategy after making a comparison with their neighbor's utility through an iterative process. Examples of evolutionary games are the birth-death, death-birth [39], imitation [40], link dynamics [41], pairwise comparison [42], and global updating [34]. The birth-death and death-birth updating is more suitable in the biological context while the imitation, link dynamics, and pairwise comparison is usually employed in the social context.

In our case, we employ asynchronous pairwise comparison such that at each time step a random individual is selected to update his strategy by comparing against a randomly matched neighbor. This mechanism is shown in Fig. 1(a). If the utility of his matched neighbor is higher than his utility, he will adopt his neighbor's strategy with a certain probability. This probability is proportional to the utility difference between him and his matched neighbor. This local interaction adds additional complexity to the socioecological system.

FIG. 1. (Color online) Updating mechanism. Here, cooperators are represented by circles marked with C while defectors are represented by circles marked with D . The updating mechanism in (a) represents the process of selection. At each time step, a random individual compares his utility with that of a random neighbor. The probability of an individual changing his strategy to the opposite strategy is proportional to the utility difference. The updating mechanism in (b) represents the process of random mutation. At a certain mutation period, a random individual is selected to flip its strategy (for example, from cooperative strategy to defective strategy, and vice versa).

The updating mechanism described above involves selection without mutation. In this case, no change in strategy is to be expected when all the agents have the same strategy. In particular, the system will not be able to evolve to another stable region if it is in either the all co-operator or all defector state. To study the socioecological regime shift, we consider periodic mutation in our simulation. This flips the strategy of a randomly chosen player after a certain period of time. Specifically, we have $m_p = N^2$. In other words, a player will be chosen randomly to switch its strategy into the alternate strategy after every N^2 selection processes. This mechanism is illustrated in Fig. 1(b).

III. RESULT

A. Analytical result

With the social and ecological model and the updating mechanism, we can construct a master equation of the probability of f_c at time t , i.e., $P(f_c, t)$. The details of the construction are given in the Appendix. The master equation takes the following form:

$$\frac{d}{dt} P(f_c, t) = - \left(\frac{d}{df_c} \{ P(f_c, t) [T^+(f_c) - T^-(f_c)] \} \right). \quad (10)$$

Then, the condition of equilibrium $dP(f_c, t)/dt = 0$ and $dR/dt = 0$ [or set $R_t = R_{(t+1)}$ in Eq. (2)] being applied to Eqs. (10) and (1) respectively leads to

$$\sum_i \rho_i^* O(n_{c_i}) = \pi_d(e_d, R^*), \quad (11)$$

and

$$R^* = -E + \left(\sqrt{E^2 + 4c \frac{d}{R_{\max}}} \right) \frac{R_{\max}^2}{2d}. \quad (12)$$

Note that ρ_i^* gives the equilibrium probability distribution of occurrence of the fraction of n_{c_i} cooperators in the defectors

neighborhood. The derivation of these quantities can be found in the Appendix. In fact, Eqs. (11) and (12) give the stable and unstable fixed points of our coupled SES, in addition to those given by $f_c = 0$ and $f_c = 1$.

From another perspective, Eqs. (12) and (11) are the consequence of Eq. (1) and the following differential equation:

$$\frac{df_c}{dt} = f_c[1 - f_c] \frac{\pi_d - \pi_c}{\pi_d} \left[\sum_i \rho_i O(n_{c_i}) - \pi_d \right] \quad (13)$$

respectively.

In our model, availability of the resource is updated after every update of the agent's strategy. One can include more strategy updates before updating the amount of available resources to create a time scale difference between the social and ecological variables. Alternatively, one can also scale the update of the resource by a small number after every update of the agent's strategy to observe the effect of time scale difference. We had investigated these two situations and do not find any difference in the results. Essentially, this is a consequence of the following results from Ref. [43]. In Ref. [43], the authors explain that slow-fast systems can be presented in a form where time is scaled by a small positive constant $\varepsilon \ll 1$ such that the dynamical equation can be re-expressed in the following form:

$$\frac{df_c}{dt} = F(f_c(t), R(t)), \quad (14)$$

$$\frac{dR}{dt} = \varepsilon G(f_c(t), R(t)). \quad (15)$$

Our model can be placed precisely in this form and hence the argument in Ref. [43] applies to our case. Specifically, if we were to change our system to one with a faster time scale for a social variable than an ecological variable, we would expect the social system to reach equilibrium eventually while the amount of available resources remains constant. This would give a value of f_c at a quasisteady state which would then influence the slow dynamics of the ecosystem. Hence, the dynamics of the coupled system will be different if different time scales are considered. However, our interest in this paper is in the equilibrium states of the coupled system, i.e., when $\dot{f}_c = 0$ and $\dot{R} = 0$. From the equations above, we can easily observe that time scale difference does not affect the solution of the equilibrium state (i.e., when $\dot{f}_c = 0$ and $\dot{R} = 0$, the solutions are the same independent of the value of ε). Thus, the results on hysteresis characteristics are robust against time scale difference.

Equation (13) gives the mixed equilibrium when cooperators and defectors coexist. For the existence of a mixed equilibrium, the absolute magnitude of the production yield per effort (F/E) has to be of the same order as the parameter for the opportunity cost w , while the maximum ostracism h has to be of the same order as the defector's payoff π_d . If the ostracism $O(1) > \pi_d$, there exists a cooperator equilibrium which is stable. On the other hand, a stable mixed equilibrium exists when $O(1) < \pi_d$. Similarly, a stable defector equilibrium exists if $O(0) < \pi_d$, while a stable mixed equilibrium exists when $O(0) > \pi_d$. The parameters used in our study are chosen such that bistable state exists for $0 < c < 60$. The values of

the parameters can however be multiplied by any scaling factor to model realistic empirical production of a particular system of common pool resource. For example, if the parameter γ is to be multiplied by a factor κ to give a realistic amount of production, both w and h have to be multiplied by the same factor in order to ensure the existence of the hysteresis phenomenon.

Next, let us obtain an analytical approximation to Eq. (10). This requires us to view the social connections between cooperators and defectors to be of two types: random and clustered. In other words, the connection pattern among the two types of agents is neither purely random nor purely clustered but somewhere in between. In fact, it is easy to perceive a tendency for the defector to cluster together to protect their community from being ostracized. These assumptions imply that ρ_i^* can be decomposed into $\rho_{ran_i}^*$ and $\rho_{clus_i}^*$ for the case of random and clustered interactions respectively. Note that the details of the form of $\rho_{ran_i}^*$ and $\rho_{clus_i}^*$ have been given and derived in the Appendix. Then, by letting p_{rn} be the probability that the interaction is completely random and p_{cl} be the probability that the interaction is completely clustered with $p_{cl} + p_{rn} = 1$, the following equation is obtained after putting all the information into Eq. (10):

$$p_{rn} \sum_i \rho_{ran_i}^* O(n_{c_i}) + p_{cl} \sum_i \rho_{clus_i}^* O(n_{c_i}) = \pi_d(e_d, R^*), \quad (16)$$

where $p_{cl} = f_c(1 - f_c)$. This equation together with Eq. (1) would enable us to calculate the stable and unstable fixed points and to compare them against those obtained through numerical computation.

B. Numerical result

The SES under study can adopt either a cooperative or a defective regime. For our studies, initial conditions are chosen such that the system resides in a cooperative regime at the beginning. To ensure that the system is in the steady state, we evolve the system for a sufficiently long time before altering the control parameter. For the first half of a hysteresis cycle, we increase the control parameter continuously and quasistatically, driving the system gradually along the steady state values within a particular regime. The state of the system is then recorded when a new equilibrium is reached after each alteration. This process is repeated until a critical parameter is exceeded and the system undergoes a regime shift. We then reverse the process to evolve the system towards its initial state. Note that each complete cycle of parameter alteration gives a hysteresis curve.

Figure 2 shows the hysteresis curve of a SES with well-mixed population which is driven by variation in the amount of resource inflow. Results are averaged over 100 simulations. In this simulation, social interaction among the population is represented by a complete graph (where all individuals are connected to all individuals). Here, increments of resource inflow have gradually led the society to behave less and less cooperatively until a critical point is reached. When the system is near the first transition point c_1 , a further increment in the amount of resource triggers a critical transition towards the defector equilibrium. Instead of a gradual change, the result is

FIG. 2. Simulation results for hysteresis driven by variation of resource inflow ($0 \leq c \leq 60$). Here, state variable of the hysteresis is represented by fraction of cooperators. Social interaction among the population of size $N = 50$ is represented by a complete graph. Parameters used are $d = 50$, $R_{\max} = 200$, $q = 1$, $\alpha = 0.6$, $\beta = 0.2$, $\gamma = 10$, $w = 15$, $h = 0.34$, $g = -10$, and $\tau = -150$. Each point is run for a period of 10^4 time steps for the system to reach equilibrium. After the system reaches equilibrium, the parameter c is increased (or decreased) by an amount of 0.1 and the process is repeated. Results are averaged over 100 ensembles.

a drastic change (a breakdown in cooperation and a collapse of available resource level) in the state of the system. Once the transition takes place, previous states of the system cannot be restored through reversing the same path. During the second half of the hysteresis cycle, cooperativeness of the population does not increase sharply back to its previous values at c_1 as we decrease the amount of resource inflow. Instead, it increases gradually by following a different path before a second transition point c_2 is reached. Again, a further decrease in the amount of resource inflow triggers another transition, this time from the defective regime to the cooperative regime.

Next, we simulate hysteresis cycles for populations that interact in a complex way. Here, the Erdos-Renyi graph with a size of $N = 50$ is used as the social network and we vary the average degree (k) of the network to model a society with different average number of social connection. The set of hysteresis curves obtained are shown in Fig. 3. We observe that as the average degree k decreases, the width ($\Delta c = |c_1 - c_2|$) of the hysteresis curve reduces. As shown in Fig. 3, critical transitions happen around $c_1 = 50$ and $c_2 = 22$ for population with $k = 45$. For social network with a lower degree (for example $k = 25$), the regime shift towards the defective regime happens earlier (at $c_1 = 40$) while the regime shift towards the cooperative regime occurs at slightly larger values of resource inflow ($c_2 = 25$). Interestingly, a hysteresis curve is no longer observed for a population with a very low number of social connection (i.e., $k = 5$). In this society, the fraction of cooperators decreases faster as the control parameter increases. During the second half of the cycle, the system regains its original state following the same path as we reverse the process. We have also compared our numerical results with analytical approximation where we have found

FIG. 3. (Color online) Simulation results for hysteresis in social cooperation driven by variation of resource inflow ($0 \leq c \leq 60$) for populations connected through Erdős-Rényi random graphs with $N = 50$ and $k = 45$ (squares), 25 (triangles), 15 (circles), or 5 (stars). Note that the value of the other parameters employed are the same as those used in Fig. 2. Results are averaged over 100 ensembles.

good agreement (see Fig. 4). The details of our analytical assumptions and approximation can be found in Sec. III A as well as the Appendix.

FIG. 4. (Color online) A comparison between hysteresis given by numerical results and analytical estimation for populations with sparse ($k = 5$) and dense ($k = 45$) connections. Note that the numerical results are represented as either stars ($k = 5$) or squares ($k = 45$). Analytical estimations are represented by lines. The solid line represents the set of stable fixed points and the dashed line represents the set of unstable fixed points. The analytical estimation is obtained by assuming that the probability distribution of the cooperator to defector interaction lies between that of a random and clustered configuration [see Eq. (16)]. The value of the parameters employed are the same as those in Fig. 2.

FIG. 5. (Color online) Simulation results for hysteresis driven by variation of resource inflow ($0 \leq c \leq 60$) for populations connected through Erdős-Rényi random graphs with $N = 50$ and $k = 45$ (squares), 25 (triangles), 15 (circles), or 5 (stars). Here, state variable of the hysteresis is represented by the amount of available resource R^* . Again, the value of the parameters used are the same as those of Fig. 2. Results are averaged over 100 ensembles.

A critical transition affects not only social variables but also ecological variables of a coupled SES. The counterpart to the aforementioned social regime shift is the ecological regime shift. While the resource inflow basically increases the amount of resource level, it also induces defective behaviors among the population. During a critical transition, breakdown of cooperation leads to a collapse of the resource level. The collapse of resource level triggered by a minute increase in resource inflow is prevented by hysteresis to be restored back to its original level through reducing the resource inflow by the same amount. Figure 5 shows a set of hysteresis curves in terms of the amount of available resource. A similar dependence on the number of social ties is observed. Analogous to the social regime shift, as the average social connection decreases, the width of the hysteresis curve decreases. The occurrence of transitions to the defective regime is observed to move to the left as the network degree decreases. On the other hand, the occurrence of transitions to the cooperative regime during the second half of the cycle is observed to move slightly to the right as the network degree decreases. In addition, the result shows that ecological regime shift occurs at the same critical location as the social regime shift. Again, in the case of a society with sparse connection, hysteresis is no longer observed.

Next, let us study the regime shift driven by social factors. Here, we present two different social controlling parameters: ostracism strength and opportunity cost. In the case of ostracism strength, the result does not exhibit any hysteresis as shown in Fig. 6. In fact, when the regime shift occurs from the cooperative to the defective state, it is impossible to re-establish the cooperative state. This is exhibited by the curves continuing to maintain in the defective state beyond the critical transition points without flipping as shown in Fig. 6.

FIG. 6. (Color online) Simulation results for hysteresis driven by variation of ostracism strength ($0 \leq h \leq 1$). Here, state variable of the hysteresis is represented by fraction of cooperators. Social interactions among the population are represented by Erdős-Rényi random graphs with $N = 50$ and $k = 45$ (squares), 25 (triangles), 15 (circles), or 5 (stars). Parameters used are $c = d = 50$, $R_{\max} = 200$, $q = 1$, $\alpha = 0.6$, $\beta = 0.2$, $\gamma = 10$, $w = 15$, $g = -10$, and $\tau = -150$. Each point is run for a period of 10^4 time steps for the system to reach equilibrium. After the system reaches equilibrium, the parameter c is increased (or decreased) by an amount of 0.1 and the process is repeated. Results are averaged over 100 ensembles.

It results from the fact that even though a defector connects to a cooperator, there are too few cooperators since it is in the defective state. This implies that the social cost of defection lies at the low end of the ostracism function. Hence, the ostracism strength h has no effect. Furthermore, because π_d is always greater than π_c , the utility of the cooperator can never exceed that of the defector. There is thus no way for the defector to switch to the cooperative state. Finally, we again notice a delay in the transition from the cooperative to the defective state as the network degree increases, which is consistent with our prior results.

Figure 7 shows a hysteresis curve with the opportunity cost as controlling parameter. The opportunity cost depends on the economics and the market situation, such as the existence of alternative jobs or opportunities. Here, the resource inflow is fixed at $c = 50$. As in the ecological-driven hysteresis, we observe a similar set of hysteresis curves driven by a socioeconomical factor. The transition from cooperative regime to defective regime is achieved by a decrease in the opportunity cost. Reversing the process causes a second transition from defective regime to cooperative regime. Again, our result shows that the bifurcation characteristic of a SES is fragile against the decrement in the number of social ties. For populations with sparse social connections, we observe an absence of the irreversible hysteresis behavior.

C. Effect of topology and network size

Most real world social networks are not random graphs. Here, we study the effect of different topology on a regime

FIG. 7. (Color online) Simulation results for hysteresis driven by variation of opportunity cost ($14 \leq w \leq 20$). Here, state variable of the hysteresis is represented by fraction of cooperators. Social interactions among the population are represented by Erdős-Rényi random graphs with $N = 50$ and $k = 45$ (squares), 25 (triangles), 15 (circles), or 5 (stars). Parameters used are $c = d = 50$, $R_{\max} = 200$, $q = 1$, $\alpha = 0.6$, $\beta = 0.2$, $\gamma = 10$, $h = 0.34$, $g = -10$, and $\tau = -150$. Each point is run for a period of 10^4 time steps for the system to reach equilibrium. After the system reaches equilibrium, the parameter c is increased (or decreased) by an amount of 0.1 and the process is repeated. Results are averaged over 100 ensembles.

shift in SES. Specifically, we compare the results obtained for two different network topologies: the Erdos-Rényi network and the scale-free network generated by using the Chung-Lu algorithm [44]. In addition, we consider a larger network size of $N = 200$. Simulation results are shown in Fig. 8. There is a slight difference between the two hysteresis curves shown in Fig. 8. Reduction in the hysteresis width is observed to be smaller for populations with the scale-free interaction networks.

IV. DISCUSSION AND CONCLUSION

It has been demonstrated many times that cooperation collapses as the resources become more easily available in previous studies on social dilemma. Such abrupt disruption of cooperation is commonly associated with hysteresis and regime shift in social dilemma (see for example Ref. [34]). In this paper, a similar breakdown of cooperation was observed although in a different context, namely social dilemma on the use of a natural resource under ecological constraint. Different from previous works, dynamics of the ecological system is studied explicitly in this paper. In particular, the available resource level is observed to collapse as social cooperation becomes untenable, giving rise to a socioecological regime shift. On the other hand, cooperation within the model of Ref. [34] is promoted by networked interaction between the players. No cooperation is observed when the populations interact in a well-mixed manner. In this case, multistable states and hysteresis occur as a result of the tendency for high-degree nodes to preserve their initial strategies. However, in our study,

FIG. 8. (Color online) Simulation results for hysteresis driven by variation of resource inflow ($0 \leq c \leq 40$). Here, state variable of the hysteresis is represented by fraction of cooperators. Social interactions among the population are represented by either Erdős-Rényi random graphs (squares) or scale-free networks (circles) with size $N = 200$ and average degree $k = 10$. Note that the scale-free topology is generated by the Chung-Lu algorithm. The value of the parameters employed are the same as those of Fig. 2. Results are averaged over 100 ensembles.

cooperation is promoted through social ostracism and it exists for both well-mixed and networked populations. Notably, we have demonstrated how complex social interactions can alter the occurrence of hysteresis and regime shift in coupled socio-ecological system.

With a small disturbance, the SES under study can transit from one regime to another regime when it is near the critical point. This results in a drastic and sometimes disastrous change in the socioecological state of the system. It is difficult for the system to restore to its previous state after shifting to an alternative state [45–47]. Hence, with the presence of this bifurcation characteristic, any SES with a state near the critical point is not resilient. This particular point is known as the tipping point and at this point, a small perturbation is enough to make a large irreversible change. In our model, the width of the hysteresis curve and the position of the tipping point are both dependent on the connectivity of the social networks. In particular, as network connectivity decreases, the critical point c_1 shifts from a lower value of f_c to a higher value of f_c . In this case, while maintaining a certain level of cooperativeness in a community with dense connection ensures resilience of the system, the same level of cooperativeness may not guarantee resilience in another community with sparse social connection. In this context, predictability of the tipping point and hysteresis width is important for the management of a common pool resource. It helps in determining the best policy for a particular system.

Here, our analysis has demonstrated how social connectivity affects tipping points and bifurcation characteristics of a SES. The impact of social connectivity on hysteresis width and hence resilience of a social-ecological system can be understood with what follows. In the case that the

socioecological system is initially in the cooperative regime, social ostracism is an important mechanism which promotes cooperation during the first half of the hysteresis cycle. It is less effective in promoting cooperation during the second half of the cycle since cooperators represent the minorities in this case. When there are a large number of social connections, the reduction or increment of a single cooperator has relatively less impact on the effectiveness of social ostracism. During the first half of the hysteresis cycle, a slight increment in the resource inflow would reduce the number of cooperators by a slight amount. This small decrease in the number of cooperators would not cause much change to the effectiveness of social ostracism. In this case, social sanction decreases gradually with the decrease of the number of cooperators. On the other hand, when the number of social ties is small, a reduction or increment of a single cooperator can have a large impact on the effectiveness of social ostracism within the local cooperator communities. As the resource inflow increases, effectiveness of social sanction decreases sharply with the decrease of number of cooperators. Hence, the system reaches the critical point very soon when social sanction can no longer balance the extra payoff offered by defective behavior. At this point, cooperation breakdown and the society is dominated by defecting strategy. Hence, the critical point where the system experiences a breakdown of cooperation is different for social networks with different degrees. Similarly, critical transition happens earlier for a population with a smaller number of social ties during the second half of the hysteresis cycle. Nonetheless, as effectiveness of social ostracism in promoting cooperation is not as strong in the defective regime, the second transition points do not differ as much for social networks with a different density of connectivity. In fact, the same argument applies to the case of Fig. 8 with the scale-free and random graph topologies. Although these graphs have the same average degree, a scale-free graph contains a greater proportion of nodes with a larger degree. This ensures that the ostracism mechanism is more effective in the scale-free graph during the cooperative regime. In consequence, the critical transition happens later. As before, the transition from the defective regime back to the cooperative regime occurs with a small difference in critical points. This results from ostracism exerting negligible influence within a larger population of defectors such that the degree structure of the network has a minimal effect. Nonetheless, the transition occurs because the reduction in resource inflow brings π_c closer to π_d , this enhances the ostracism effect such that at a critical moment, we observe a transition from the defective state to the cooperative state.

Last, we believe that the socioecological model discussed in this paper can be applied to specific real world socioecological system. Specifically, the use of the Cobb-Douglas production

function in the model has implied that an ecological resource can be viewed as production input (such as water in agriculture and industry) instead of the value of the resource itself (such as fish in fisheries). The result in this paper can be extended to the domain of decision making and management planning in a coupled socioecological system. While we have discussed the hysteresis effect and socioecological robustness, and how network properties can influence it, we would like to emphasize that a more detailed knowledge of the social network of a particular society will give additional implication for its proper management. By paying more attention to social network properties and also specific socioecological parameters, we can avoid an undesired regime shift.

APPENDIX: ANALYTICAL APPROXIMATION

In this section, we perform analytical estimation on the hysteresis curves that were obtained by numerical simulations. From the updating mechanism in Sec. II C, we can construct a master equation for the number of cooperators. Let $P(C)$ [$P(D)$] be the probability that a co-operator (a defector) is being selected to update its strategy respectively. $P(D|C)$ is the probability that a cooperator compares his payoff with a neighboring defector, while $P(C|D)$ is the probability that a defector compares his payoff with a neighboring cooperator. Then, the probability that the total number of cooperators would increase by 1 is given by

$$T^+(f_c) = P(D)P(C|D)(U_c - U_d) + P(D)\frac{1}{m_p}. \quad (\text{A1})$$

Note that the first term on the right relates to the replicator dynamics, where $P(D)P(C|D)$ corresponds to the probability that a defector would compare against a cooperator in his neighborhood as a result of random selection and random matching as discussed above. The comparison to be made is on their utility. In the algorithm, we implement the rule that the chosen defector will switch and become a cooperator if a number computed from a random number generator (with a uniform distribution) is less than $[U_c - U_d]$. Otherwise, the defector will not change. Thus, this gives rise to the factor $[U_c - U_d]$ within the first term on the right of the equation. Moreover, the second term on the right of Eq. (A1) gives the probability that a defector will flip to a cooperator due to the mutation mechanism, since if a defector is being chosen, its chance of being flip is $1/m_p$. Similarly, the probability that the number of cooperators would decrease by 1 is given as follows:

$$T^-(f_c) = P(C)P(D|C)(U_d - U_c) + P(C)\frac{1}{m_p}. \quad (\text{A2})$$

From the transition probability we can form the following master equation:

$$\begin{aligned} P\left(f_c, t + \frac{1}{N}\right) - P(f_c, t) = & P\left(f_c - \frac{1}{N}, t\right) T^+\left(f_c - \frac{1}{N}\right) - P(f_c) T^-(f_c) \\ & + P\left(f_c + \frac{1}{N}\right) T^-\left(f_c + \frac{1}{N}\right) - P(f_c) T^+(f_c). \end{aligned} \quad (\text{A3})$$

Next, we expand the master equation by using Taylor series in $1/N$ and neglect the higher order terms, and obtain the following:

$$P(f_c, t) + \frac{dP(f_c, t)}{dt} \frac{1}{N} - P(f_c, t) = \left(P(f_c, t) - \frac{dP(f_c, t)}{df_c} \frac{1}{N} \right) \left(T^+(f_c) - \frac{dT^+(f_c, t)}{df_c} \frac{1}{N} \right) - P(f_c) T^-(f_c) \\ + \left(P(f_c, t) + \frac{dP(f_c, t)}{df_c} \frac{1}{N} \right) \left(T^-(f_c) + \frac{dT^-(f_c, t)}{df_c} \frac{1}{N} \right) - P(f_c) T^+(f_c), \quad (\text{A4})$$

and

$$\frac{dP(f_c, t)}{dt} \frac{1}{N} = -\frac{1}{N} \left(\frac{dP(f_c, t)}{df_c} T^+(f_c) + P(f_c, t) \frac{dT^+(f_c, t)}{df_c} \right) + \frac{1}{N} \left(\frac{dP(f_c, t)}{df_c} T^-(f_c) + P(f_c, t) \frac{dT^-(f_c, t)}{df_c} \right). \quad (\text{A5})$$

Finally, we obtain the following approximate differential equation of the strategy dynamics:

$$\frac{d}{dt} P(f_c, t) = - \left(\frac{d}{df_c} \{ P(f_c, t) [T^+(f_c) - T^-(f_c)] \} \right). \quad (\text{A6})$$

The condition of equilibrium is satisfied when $T^+(f_c) - T^-(f_c) = 0$, i.e.,

$$0 = \left(P(D)P(C|D)(U_c - U_d) + P(D)\frac{1}{m_p} \right) \\ - \left(P(C)P(D|C)(U_d - U_c) + P(C)\frac{1}{m_p} \right). \quad (\text{A7})$$

By using the probability identity $P(C)P(D|C) = P(D)P(C|D) = P(CD)$, we can rewrite the previous equation in the following form:

$$0 = [P(CD)(U_c - U_d)] + \frac{1}{m_p} [P(D) - P(C)]. \quad (\text{A8})$$

Here, $P(CD)$ denotes the probability for a randomly selected pair to be a cooperator-defector pair. In the case when mutation is rare, we can approximate $\frac{1}{m_p} \cong 0$ and drop the mutation term. Moreover, $P(CD)$ is strictly larger than zero since the mutation mechanism ensures the existence of at least one cooperator and defector pair. The above equation reduces to $U_c = U_d$, which is then further simplified to the following form:

$$\pi_d = \sum_i \rho_i O(n_{c_i}), \quad (\text{A9})$$

where ρ_i gives the probability of occurrence of the fraction of n_{c_i} cooperators in the defectors neighborhood. This condition is important for the determination of the stable and unstable fixed points later.

The analytical approximation is achieved by solving the master equation for the social system and the resource equation for the ecological system. At equilibrium, we expect no change in the social and ecological variables. In consequence, the following two conditions are satisfied: $\frac{d}{dt} R = 0$ and $\frac{d}{dt} P(f_c, t) = 0$. We obtain the solutions of these two equations as follows:

$$R^* = \left(-E + \sqrt{E^2 + 4c \frac{d}{R_{max}}} \right) \frac{R_{max}^2}{2d}, \quad (\text{A10})$$

$$\sum_i \rho_i^* O(n_{c_i}) = \pi_d(e_d, R^*). \quad (\text{A11})$$

These equations give the stable and unstable fixed points. To solve the equation, we first assume that connections among cooperators and defectors are random. As a defector, the probability of connecting to a cooperator in the population is $C = \frac{Nf_c}{N-1}$. The probability of connecting to another defector in the population is then equal to $1 - C$. From this assumption, we can write the form of the cooperative probability distribution with respect to the direct neighbor of a defector:

$$\rho_i = \binom{k}{i} C^i D^{k-i}, \quad (\text{A12})$$

with $C = \frac{Nf_c}{N-1}$ and $D = \frac{N[1-f_c]-1}{N-1}$. Here, ρ_i denotes the probability that i neighbors of a randomly selected defector with degree k are cooperators.

By using this assumption, we plot in Fig. 9 the set of stable and unstable fixed points as a function of the control parameter c for various values of k . The solid line represents the set of stable fixed points and the dashed line represents the set of unstable fixed points. A regime shift occurs at the point where the stable and unstable fixed points intersect. This point is

FIG. 9. (Color online) Theoretical estimation of resource inflow-driven social hysteresis with population size $N = 50$. We have taken the graph degrees to range from $k = 5$ (magenta “innermost” line) to $k = 45$ (red “outermost” line) based on the assumption that the agents connect randomly among each other. Note that the solid line represents the stable fixed points and the dashed line represents the unstable fixed points. The contact point between stable and unstable fixed point is associated with the fold bifurcation which results in the hysteresis effect. Parameters used are the same as those of Fig. 2.

FIG. 10. (Color online) Theoretical estimation of resource inflow-driven social hysteresis with population size $N = 50$. We have considered the graph degrees to range from $k = 5$ (magenta “leftmost” line) to $k = 45$ (red “rightmost” line) based on the assumption of single cluster interaction between cooperators and defectors. The solid line represents the set of stable fixed points and the dashed line represents the set of unstable fixed points. The contact point between the stable and unstable fixed point is associated with the fold bifurcation which results in the hysteresis effect. Parameters used are the same as those of Fig. 2.

associated with the fold bifurcation which is the source of the phenomenon of hysteresis. Our analytical approximation affirms the existence of alternate stable states. In addition, as the network degree decreases, the width of the hysteresis curve decreases. As expected, the assumption of random connection gives underestimated hysteresis width reduction especially when the degree is small.

The variation of our analytical results as shown in Fig. 9 with that of the numerical results indicates that the two types of agents do not connect purely in a random way. Instead, individuals with the same strategy tend to cluster together under the replicator dynamics. In consequence, we next consider the possibility of clustering. In fact, the occurrence of grouping of the same strategy into several clusters is quite common

in evolutionary games [48,49], since it serves to enhance the survival of the clustered strategy. Here, we assume an extreme case with the formation of only a single defector cluster and a single cooperator cluster throughout the replicator dynamics. In particular, we assume that each defector connects to all other defectors when the degree is larger than or equal to the number of defectors in the system. This assumption indicates that a defector connects to $N[1 - f_c] - 1$ other defectors and $k - N[1 - f_c] + 1$ cooperators. Hence, the probability distribution of a cooperator being the direct neighbor of the defector takes the following form:

$$\rho = \begin{cases} 1, & \text{for } n_c = \frac{k+1-N[1-f_c]}{k}, \\ 0, & \text{for other } n_c. \end{cases} \quad (\text{A13})$$

When the number of defectors is larger than the degree of the social network, we assume that there exists at least one connection between cooperator and defector as otherwise the network will become two separate networks. We assume at most one cooperator connects to a defector with a probability of $\frac{k_{dc}}{N[1-f_c]}$, where k_{dc} is the number of connections between cooperators and defectors. Let k_{dd} be the connections within the defector cluster. Therefore, $k_{dd} + k_{dc} = Nk[1 - f_c]$. In this case the form of the probability distribution of the cooperators being a direct neighbor of a defector is given by

$$\rho = \begin{cases} 1 - \frac{rk}{r+1}, & \text{for } n = 0, \\ \frac{rk}{r+1}, & \text{for } n_c = \frac{1}{k}, \\ 0, & \text{for other } n_c, \end{cases} \quad (\text{A14})$$

and

$$r = k_{dc}k_{dd} = \frac{l}{N[1 - f_c] - 1}. \quad (\text{A15})$$

With this assumption, we plot in Fig. 10 the set of stable and unstable fixed points as a function of the control parameter c for various values of k . For a social network with a large degree, this assumption gives a similar prediction as the random connection assumption. Again, when network degree is lowered, the analytical approximation deviates from the numerical result. In fact, the numerical results lie between the predictions from these two analytical approximations. This results from the fact that the actual connection pattern among the cooperators and the defectors lies between purely random and purely clustered.

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