The importance of transient social dynamics for restoring ecosystems beyond ecological tipping points

Romina Martin[a,1], Maja Schlüter[a], and Thorsten Blenckner[a]

[a]Stockholm Resilience Centre, Stockholm University, 114 19 Stockholm, Sweden

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Regime shift modeling and management generally focus on tipping points, early warning indicators, and the prevention of abrupt shifts to undesirable states. Few studies assess the potential for restoring a deteriorating ecosystem that is on a transition pathway toward an undesirable state. During the transition, feedbacks that stabilize the new regime are still weak, providing an opportunity to reverse the ongoing shift. Here, we present a social-ecological model that explores both how transient social processes affect ecological dynamics in the vicinity of a tipping point to reinforce the desired state and how social mechanisms of policy implementation affect restoration time. We simulate transitions of a lake, policy making, and behavioral change by lake polluters to study the time lags that emerge as a response to the transient, deteriorating lake state. We found that restoration time is most sensitive to the timing of policy making, but that the transient dynamics of the social processes determined outcomes in nontrivial ways. Social pressure to adopt costly technology, in our case on-site sewage treatment, was up to a degree capable of compensating for delays in municipal policy making. Our analysis of interacting social and ecological time lags in the transient phase of a shallow lake highlights opportunities for restoration that a stable state analysis would miss. We discuss management perspectives for navigating critical feedbacks in a transitioning social-ecological system. The understanding of transient dynamics and the interaction with social time lags can be more relevant than solely stable states and tipping points.

regime shifts | social-ecological systems | agent-based model | system dynamics | lake restoration

Ecological regime shifts are characterized by nonlinear dynamics that result from balancing and reinforcing biophysical feedbacks and their interactions with anthropogenic drivers (1). These complex dynamics make the timing of interventions to prevent or reverse a regime shift critical for successful management (2). Many shift-prone ecosystems in the world, such as shallow lakes, are already in transition or in an undesired state (3). It thus becomes increasingly important to understand how an ecosystem can be managed for a reverse shift toward a desired state (4). A timely reduction of a driver (e.g., nutrient loads or fishing pressure) during a transition phase when the new undesired state has not yet established, that is, when stabilizing feedbacks are still weak, may prevent a lock-in and enable restoration (2, 5). This transition phase or transient dynamics may provide a window of opportunity for management interventions (6). Whether an intervention is carried out in time to successfully restore a shifting ecosystem, however, depends on societal decisions and actions. At this time, little knowledge exists about the interplay between the transient dynamics of an ecosystem that is undergoing a regime shift and the transient dynamics of policy making and implementation aimed at reverting the ecosystem's transition. The implementation process often involves actors with different interests, whose willingness to change behavior may be low. These social processes can introduce significant time lags, which ultimately determine whether the manifestation of an undesired state can be prevented. Enhanced understanding of how these social time lags, as a feature of the transient social dynamics, interact with transient ecological dynamics in the vicinity of a tipping point and jointly determine the recovery potential of ecosystems is critical for developing integrative management measures for ecosystem restoration.

We investigate two social time lags: a policy lag, defined as the time that passes from the onset of the ecological regime shift (i.e., the moment when the tipping point toward the turbid state is transgressed) to the design of the policy; and an implementation lag, defined as the time from the design of the policy to its adoption by the majority of actors (Fig. 1). The social and ecological time lags that emerge from human decision making and its interaction with ecological feedbacks are important features of the transient dynamics of the ecosystem. Most regime shift models (e.g., ref. 2) do not consider the time needed for human behavioral change, but rather assume that management strategies take immediate effect; for example, fishing pressure is instantaneously removed. Approaches and models that take the two-way interactions between human adaptive behavior and ecological change into account provide a more integrated and nuanced understanding of the dynamics of social-ecological regime shifts (7–9). We aim to contribute to an understanding of transient social-ecological dynamics during a regime shift through a model-based analysis of the restoration of a shallow lake subject to nutrient inflows from insufficiently treated sewage water. The coupled social-ecological model explores the ecological regime shift from a clear to a turbid state in a shallow lake linked to relevant social responses by legislating and polluting actors. It includes the main ecological feedbacks that determine the state of the lake following a well-established lake model (10). The social model captures human responses to changes in the lake following a policy cycle from

Significance

Managing regime shifts is often associated with "turning back from the brink" assuming that once a system has transgressed a tipping point, it moves unavoidably toward the undesired state. We show that a regime shift is rather a slippery slope that can be managed and even reversed when transient dynamics and time lags in the coupled social-ecological system are taken into account. We constructed an empirically based simulation model that includes the combined effect from nonlinear ecological dynamics and human adaptation. Delayed policy response and slow implementation introduce time lags that can strongly affect lake restoration time. Our model demonstrates how time lags in municipal policy making can be compensated for by individual action mediated through social pressure.

SUSTAINABILITY SCIENCE

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[1]To whom correspondence may be addressed. Email: romina.martin@su.se.

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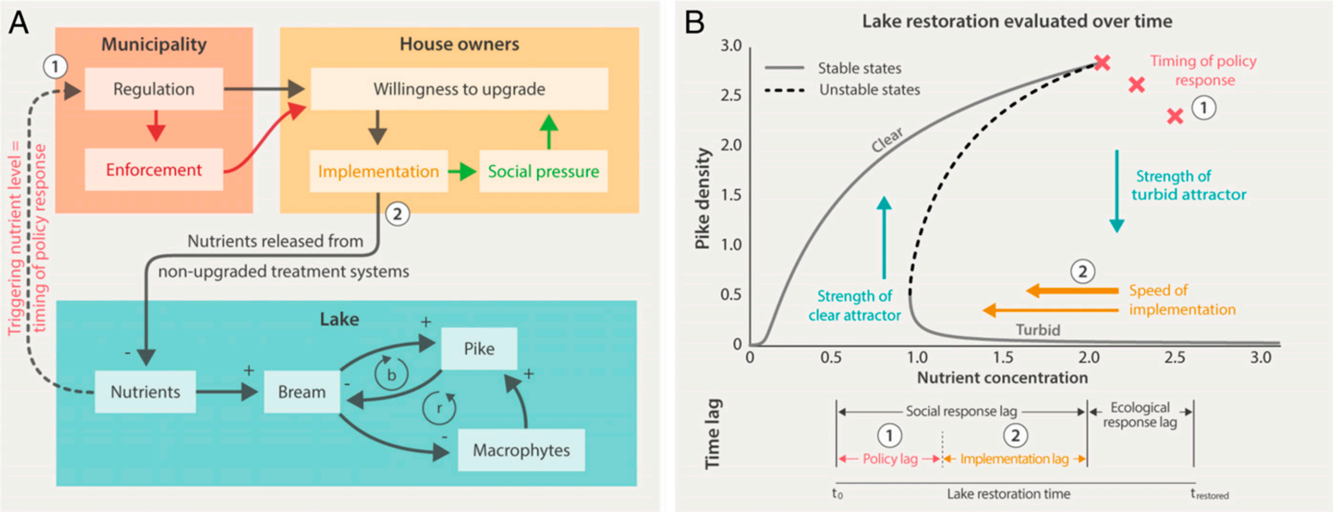

Fig. 1. (*A*) Social-ecological model with two alternative social mechanisms to reinforce reduction of nutrient outflow from private water sewage treatment: social pressure (green arrow) or central enforcement (red arrow). Boxes in the lake system denote stocks (10), and boxes in the social system depict processes by house owner agents or the municipality, respectively. (*B*) The hysteresis curve stemming from a fold bifurcation for the minimal lake model shows the stable and unstable equilibrium states between the driver, nutrients, and the response, pike fish. We reimplemented this model and linked it to an agent-based model with the ability to respond to and reduce the nutrient load over time. Two social parameters determine when the restoration starts (policy lag, red Xs, process 1) and how strongly it is implemented (implementation lag, orange, process 2), while the momentum of how quickly the lake shifts between the clear and the turbid state is a result of the nonlinear social and eventually ecological dynamics (blue). The lake restoration starts when the concentration of nutrients in the lake transgresses the tipping point to the turbid state and it ends when nutrient levels are below and pike levels above critical values again (further details in *SI Appendix*, Text S1 II.x.b). See main text for time lag definitions.

problem recognition topolicy formation to policy implementation (and evaluation) (11). This is an oversimplified representation of the policy processes, but serves as a starting point for exploring social dynamics and their effect on ecological feedbacks. The objectives of this social-ecological modeling study are to better understand how transient social dynamics, particularly the social time lags resulting from delayed policy response (policy lag) and delayed policy implementation (implementation lag), influence transient, nonlinear, ecological dynamics during the transition between an undesired and a desired state; identify under which conditions transient societal responses can shift an ecosystem back into a desired state through weakening or strengthening ecological feedbacks; and in particular, investigate the possibility of compensating for a lag in one phase of the policy process by reducing the lag in another phase (e.g., compensate fora policy lag with a faster implementation of the policy by reducing the implementation lag).

Model

We combine a system dynamics model of lake ecology with an agent-based model of social dynamics to serve as a virtual laboratory for investigating transient processes (Fig. 1*A* and ref. 12). The purpose is to better understand how actions of policy makers and house owners in response to lake degradation affect lake restoration time. Restoration time is measured as the period from the year at which nutrient levels transgress the ecological tipping point (t_0) to the turbid state and the year when all trophic levels are restored to clear state values (t_{restored}) (Fig. 1*B*).

The Ecological Model. We implemented a minimal lake model that shows regime shift behavior (10). The clear state is characterized by a low nutrient level with few planktivorous fish (bream) and abundant piscivorous fish (pike), which reverses when nutrient levels increase and the lake shifts to the turbid state (10, 13). Submerged plants (macrophytes) reinforce the shifts between the clean and turbid states; for example, an increase in bream decreases the amount of macrophytes, which decreases the amount of pike, which further increases the amount of bream, leading to the turbid state (Fig. 1, blue box, r-loop). The ecological processes are driven by nutrient inflows to the lake released from nonupgraded sewage treatment systems. A high nutrient concentration causes harmful algae blooms, which decrease the attractiveness of the lake for recreation. Moreover, pike levels drop, while bream become abundant (13) until the municipality and house owners take action to devise a policy and upgrade their sewage treatment system, respectively (*SI Appendix*, Texts S1 III.iv.a and S2).

The Social Model with Policy and Implementation Time Lags. The agent-based model of the policy process represents a municipality and 100 house owners who emit nutrients into the lake before they upgrade their on-site sewage treatment system (OSS). The municipality is responsible for managing the lake in the interest of lake users who prefer a clear lake, which provides opportunities for pike angling and swimming. It takes regulatory action to reduce nutrient inputs when the state of the lake deteriorates beyond a management threshold to prevent the shift into the turbid state (14). The agent-based model represents three phases of the policy process; namely, the problem perception, the design of a policy, and the implementation of the policy.

The municipality monitors nutrient concentrations in the lake and takes action when effects of eutrophication are visible, both in terms of high nutrient levels and decreasing pike abundance. We define the nutrient concentration at which policy makers perceive the lake state as critical as the triggering nutrient level (Fig. 1*B*). The time span starting when the lake crosses the ecological tipping point until when the municipality takes action we define as policy lag (Fig. 1*B*, process 1). It represents a lag because the lake system has already crossed the ecological tipping point and moved into the basin of attraction of the turbid state, where just stopping the nutrient inflow is insufficient.

When the triggering nutrient level is passed, the municipality issues a policy that obliges house owners to upgrade their OSS. Each house owner agent has an intrinsic willingness-to-upgrade its OSS, which affects its decision to implement the policy. The willingness-to-upgrade is modeled as a probability for installing the new system. Its initial value is low because house owners are confronted with a high-cost, low-gain decision. Noncompliance with the policy, however, can introduce significant time lags in the implementation. We model the top-down and horizontal social mechanisms to increase compliance mentioned here as either central enforcement, where the municipality incentivizes house owners to invest into the costly technology (red arrows, Fig. 1*A*), or social pressure, where house owners feel pressure to follow the law and upgrade their system when they see their neighbors doing so (green arrows, Fig. 1*A*). Both measures increase the willingness-to-upgrade probability of a house owner by 50% after a fixed delay (central enforcement) or each time a neighbor performed the upgrade (social pressure). The time it takes from the introduction of the policy until 95% of the house owners have updated their sewage system is defined as implementation lag (Fig. 1*B*, process 2). The implementation lag emerges from the probabilistic adoption of the new technology by individual house owners, which can be enhanced through social pressure or central enforcement by the municipality. The duration of this lag thus depends on the initial willingness-to-upgrade value and the enforcement mechanism (*SI Appendix*, Texts S1 and S2 and Table S3).

Qualitative Evaluation of Policy and Implementation Lags on the Lake. The processes of policy design and implementation influence the lake system by decreasing the lakes' nutrient concentration (maximum ±0.1/y; Fig. 1*A*). We use the hysteresis curve that depicts the behavior of the ecological model in a state space (15) to evaluate simulated trajectories of the coupled social-ecological model. Fig. 1*B* shows the state space analysis of two ecological variables (nutrient concentration and pike density), and we added the points at which the policy design and implementation interact with lake dynamics. Red crosses indicate the timing of the policy (process 1); the further to the right the crosses lie, the further the lake has shifted into the turbid state, with lower pike density, and it becomes more difficult to restore the clear water state because the lake has moved into the domain of the turbid attractor. The longer the implementation lag, the longer it takes until the lake returns to the point where the clear water attractor reappears. Yellow arrows indicate the duration of the implementation lag (process 2). The greater the probability of house owners to perform the upgrade, the faster the aggregated nutrient load toward the lake, and ultimately its concentration, decreases.

Results

A Delay in Policy Action Significantly Affects Restoration Time (Ecological Response Pattern). The tipping point that separates the clear from the turbid lake attractor in the ecological model lies at a nutrient concentration of 2.1 [evaluated from the original model (10)]. Nutrient levels greater than 2.1 inevitably lead to a turbid lake unless the nutrient load is reduced. If we assume no implementation lag and a proactive strategy of policy action at a triggering nutrient level of 2.0, pike levels immediately drop to their initial value and lake restoration is easily achieved (Fig. 2*A*, blue curve). With an intermediate strategy at a triggering level of 2.5, pike levels drop quite significantly and need ca. 20 y to recover toward initial levels (Fig. 2*A*, green curve). These scenarios are comparable with other models (e.g., ref. 2) that study the effect of policy on ecological regime shifts without considering implementation lags resulting from the human behavioral changes necessary to implement a policy.

The picture changes when we analyze the full social-ecological model, including the time lag resulting from the implementation process. In the baseline with no enforcement, pike densities always drop below initial levels (Fig. 2 *B*–*D*), even with a proactive strategy where a policy is made before the ecological tipping point is passed (Fig. 2*B*). The later the policy response, the longer it takes until the pike population recovers to initial densities. In the case of a late policy, pike density does not recover fully within the simulated time frame (Fig. 2*D*). Such a delayed response would result in a restoration time that is about four times as long as when a proactive action is taken. The longer, transient response of the lake to the policy is the result of increasing strength of the turbid attractor the closer the lake state moves toward it.

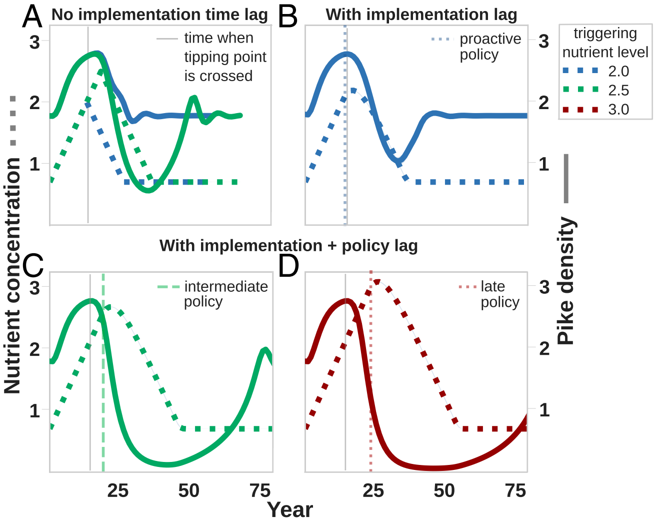

Fig. 2. Time series of lake nutrients concentration (dashed lines) and corresponding pike density (solid). Simulations with (*A*) no implementation lag (i.e., nutrient concentration is linearly decreased at two different nutrient triggering levels), (*B*) with implementation lag and a proactive policy (no policy lag), (*C*) with implementation and an intermediate policy lag, and (*D*) with implementation and a strong policy lag (i.e., a late restoration). The start of policy is marked by vertical dashed lines, and colors indicate the triggering nutrient level. House owners are parameterized with an intermediate willingness-to-upgrade (0.2) and no enforcement.

Social Pressure Accelerates Implementation Early in the Implementation Phase, While Central Enforcement Achieves Full Implementation Earlier (Social Response Pattern). The implementation lag strongly affects the effectiveness of the policy, as shown here (Fig. 2 *B*–*D*). Enforcement can accelerate the adoption of the new technology, and hence the reduction of nutrient inflows. The two enforcement mechanisms (central enforcement and social pressure) differ in their dynamic pattern, affecting the rate of adoption (Fig. 3). Directly after the introduction of the policy, the rate is mainly influenced by each individual's initial willingness-to-upgrade. After a few years, the rate increases fastest in the social pressure scenario. However, later on, the central enforcement scenario results in higher adoption rates and a faster achievement of full implementation. The scenario with no enforcement shows the slowest implementation rates, and nutrient concentrations in the lake react accordingly.

Lake Restoration Is More Sensitive to Policy Timing than Policy Implementation (Lake Sensitivity). We assessed the combined effects from policy and implementation lags (with and without enforcement) on lake restoration time (Fig. 4*A*). To better understand why the restoration time becomes longer with greater policy lags, we plot the simulated trajectories onto the hysteresis curve from the stable state analysis (Fig. 4*B*). The shorter the policy lag, the quicker the trajectory surpasses the threshold to the desired state. Differences between scenarios with different initial willingness-to-upgrade values are smaller than between scenarios with different triggering nutrient levels. Thus, the lake restoration time reveals that restoration success is more sensitive to the policy timing than to the individual drivers of the implementation lag

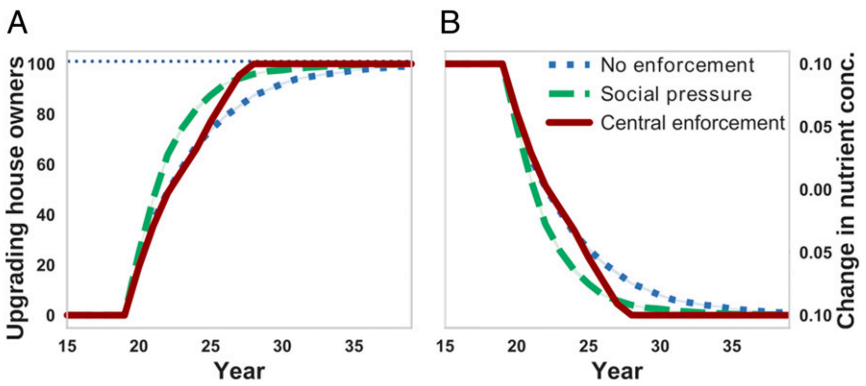

Fig. 3. Time series of household upgrades (implementation lag, *A*) and corresponding change in the nutrient concentration (*B*) for different reinforcement mechanisms: no enforcement (dotted), social pressure (dashed), and central enforcement (solid).

(willingness-to-upgrade and social enforcement; *SI Appendix*, Text S2 and Fig. S3).

Faster Implementation Can Compensate a Late Policy Response under Some Conditions (Time Lag Substitutability). A quantitative analysis of the effects of different policy and implementation lags on lake recovery confirms the semiqualitative results of Fig. 4*B* (Fig. 5*A* and *SI Appendix*, Table S4). An increase in the policy lag (triggering nutrient level) has a stronger effect on the total restoration time than differences in the enforcement mechanism (*SI Appendix*, Fig. S3). With the early, proactive policy response (2.0), the reinforcing feedbacks for the turbid state are still weak, and restoration measures show effect relatively fast in terms of decreasing nutrient concentration. It takes much more time to revert the ecological dynamics at a later stage (intermediate policy at 2.5), but lake restoration time increases less rapidly when the policy response is even later (late policy at 3.0).

Transient dynamics and the relative contributions of the social versus the ecological time lags are shown in Fig. 5*C*. The contribution of the social lag is highest with an early policy response when the ecological feedbacks reinforcing the turbid state are still weak, and hence ecological response time is low. It has a minimum with an intermediate policy lag and increases slightly with an even larger policy lag (late policy). In other words, our results suggest that the relative contribution of social time lags to transient lake restoration dynamics is large when the lake is still on the brink of the turbid state, it is small when the lake reaches the strongest momentum to turn turbid, and it increases again when the turbid attractor cannot accelerate further.

Finally, we test the sensitivity of total lake restoration time with different social enforcement mechanisms against the initial willingness-to-upgrade (Fig. 5*B*). We observe a higher effectiveness of the central enforcement mechanism with a willingness-to-upgrade smaller than 0.2 (Fig. 5*B*), but for greater values, the social pressure mechanism is better able to reduce the implementation time. The contribution of the emerging social time lag to lake restoration time decreases with greater willingness-to-upgrade, since faster decision making and interaction among households enables a faster reduction of nutrient inflows, and hence faster restoration (Fig. 5*D*). This analysis reveals the degree to which a delay in policy response can be compensated for by an increase of the initial willingness-to-upgrade. At a point where the lake shows the greatest momentum to shift to the turbid state, a delay of the policy by approximately 5 y would require an increase in willingness-to-upgrade by 50% to restore the lake in the same time frame (*SI Appendix*, Table S4).

Discussion

Restoring ecosystems such as shallow lakes can be difficult because of ecological feedbacks that reinforce the undesirable state (16). These feedbacks can become effective long before an ecosystem has visibly shifted into a new state. However, they need time to establish, which opens up opportunities for navigating the ecosystem away from the undesired state. A better understanding of how transient, individual and collective, social processes interact with transient ecological dynamics can help to evaluate which decisions and actions delay or reinforce ecological transition processes. Our analysis of a social-ecological model of lake restoration provided

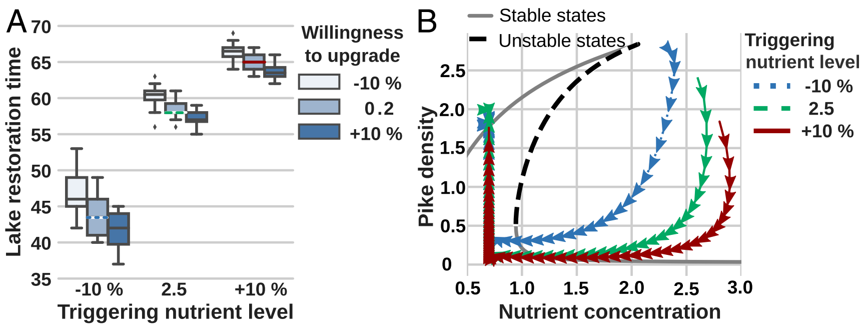

Fig. 4. (*A*) The effect of the policy lag (given by the triggering nutrient level) and willingness-to-upgrade on lake restoration time. (*B*) Simulated trajectories of nutrient concentration and pike density with an intermediate willingness-to-upgrade (0.2) and no enforcement. The trajectories (shown from the onset of regulation) are placed in the state space together with the corresponding hysteresis curve from the uncoupled ecological model to illustrate the periods of the lake within the undesired space.

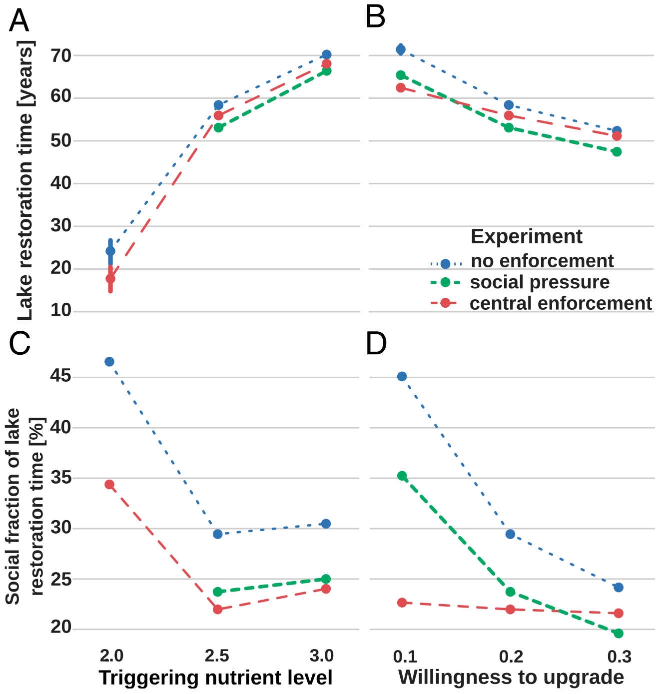

Fig. 5. (*A* and *B*) Restoration time for different policy lags (triggering nutrient level) with a willingness-to-upgrade of 0.2 (*A*) and different willingness-to-upgrade values with a policy lag at a nutrient level of 2.5 (*B*). (*C* and *D*) The relationship of the social to the ecological lag to identify which transients dominate at what time. (*A* and *C*) Social pressure scenario lacks a data point for the lowest nutrient level, since no lake restoration time can be measured. In this case, the social response is quick enough (<10 y) to prevent the pike level from dropping below the threshold from which an ecological restoration would be accounted for.

insights regarding the importance of transient dynamics, particularly time lags, for restoring shifting ecosystems.

Transient Dynamics. Accounting for transient, nonlinear social-ecological dynamics is critical because human action to reduce a driver of ecosystem change can still be effective and reverse a transition when the ecosystem has already crossed the ecological tipping point. Previous research has highlighted the importance of transient dynamics in ecological systems (6). Our study indicates that they are equally important in social-ecological systems, as they determine the outcomes of perturbations such as human interventions. In contrast to a steady state analysis, our advanced analysis of transient lake dynamics allows the exploration of how the reduction of the driving variable during the transition can change the trajectory of the system and return it to the desired state. In our model, the driving variable is the reduction of nutrient loading over time as a result of the policy and its implementation, affecting the ecological dynamics in a nonlinear way. That is, a small delay in social response had a disproportionately large effect on restoration time, moving the lake further into the undesired state attractor. Similarly, a small acceleration of the social response had large effects if the ecological feedbacks are still weak.

The Effect of Policy and Implementation Lags for Restoring Ecosystems. Beyond the trivial insight that early and fast responses are more successful than late and slow ones, our experiments provide a more nuanced understanding of the conditions under which interventions can reverse an ongoing regime shift. The effectiveness of restoration measures critically depends on the temporal patterns of reduction in anthropogenic driver. In our model, this reduction is nonlinear, as it emerges from the many decisions of individual house owners to adopt the new technology. These decisions are stochastic and may be reinforced by social interactions with other house owners or an enforcer. Restoration time is most sensitive to the timing of the policy response relative to the transient state of the ecosystem. The further the ecosystem has transitioned toward the undesirable state, the stronger and harder it is to reverse the ecological feedbacks. Accelerating policy implementation through social measures can to some extent counter the effects of policy delays, particularly when the ecosystem has already transitioned far into the undesired state. The relative effectiveness of bottom-up versus top-down enforcement mechanisms depends on the initial degree of noncompliance of house owners.

Generalizability of Model Findings. Our regime shift model investigates the impact of nonlinear, transient social dynamics on a transitioning ecosystem with the aim to enhance understanding of ecosystem restoration. Previous regime shift research largely focused on preventing a shift (2, 17), identifying tipping points (18) and early-warning signals (19). Our results confirm the importance of social dynamics for ecological regime shifts (7, 8, 12), particularly the timing of a policy (2, 20). They, however, go further by accounting for the dynamics of policy implementation with the aim of identifying the social and ecological mechanisms that determine transient ecological dynamics, and hence restoration time. Although our model has loosely been based on the realities of lake restoration in Sweden, the key qualitative insights that emergent social processes of policy implementation can result in different pathways of reduction in anthropogenic driver, and that these pathways, together with the timing of the policy response, affect the restoration of ecosystems in nonlinear ways, are relevant beyond this particular model. They are particularly relevant for cases of ecosystem restoration in which there are few direct incentives for actors to change their behavior. Testing the model on such cases would be an interesting next step. Generalizability is supported by the fact that both submodels have been based on stylized mechanisms that can be found across cases: the ecological model is a commonly used generic model of regime shifts; the social mechanisms have been implemented with reference to generic social processes such as norm-driven social pressure (21) or top-down enforcement.

Model Limitations. Our approach consists of a systematic investigation of the interplay of a delay in policy making (influenced by a social-ecological feedback) and an emergent, nonlinear social implementation time lag (influenced by social feedbacks) with nonlinear ecological dynamics (influenced by ecological feedbacks) and an assessment of the implications for restoring a lake that is transiting to a turbid state. While the outcomes of social feedback processes continuously affect ecological dynamics, the model does not include a continuous social-ecological feedback between changes in the ecosystem and human behavior. In the case of lake restoration in Sweden, house owners' decisions are more influenced by social pressure of peers or formal enforcement by authorities than by perception of ecological changes. It would be interesting, however, to include a continuous social-ecological feedback and investigate its effect on restoration time in a future study. Model outcomes should also be seen in light of our assumption that the adoption of the technology directly reduces nutrient inflows, as well as the omission of other processes that may affect lake recovery, such as the legacy of decades of nutrient accumulation in sediments (16) or contextual variables that affect policy making, such as lack of interest, resources to monitor the lake state, or interference of powerful actors. Furthermore, we have modeled the social norm as a pressure to do one's duty and follow the law as common in Swedish cases (22). Social norms can, however, also reinforce behavior that maintains the status quo (23). Changing these assumptions would make the outlook for lake restoration less optimistic. Despite these simplifications, our model advances understanding of the importance and implications of social-ecological interactions for ecosystem restoration and provides a first step toward unraveling complex transient dynamics of social-ecological systems.

Implications for Lake Management. Our results imply that understanding how the outcomes of transient social processes affect transient ecological dynamics may be more relevant for managing an ecosystem than analyses of ecological stability alone. A better understanding of how individual and societal responses to deteriorating ecological conditions bring about changes in anthropogenic pressure can help identify opportunities for strengthening desirable social or ecological feedbacks or weakening undesirable ones (24). The possibility of navigating a transition by accounting for the effects of social time lags is particularly interesting for lake management. While in theory a precautionary approach (i.e., an early response) would be best (25), in reality, the uncertainty of the actual state of the lake and difficulties in justifying costly measures while the ecosystem still looks healthy can impede early action. Given that a delayed policy response could partially be compensated forby improved policy implementation, it becomes particularly important to invest in mechanisms to enhance policy implementation and to lower the barriers that prevent behavioral change. The latter can be influenced by considering how house owners are approached and the policy is communicated (22).

In summary, our simulation-based study demonstrates the importance of integrating societal responses to ecological change and the resulting transient social dynamics into models of complex lake management problems. Neglecting the possibilities of nonlinearities and time lags in the social system may lead to wrong estimates of the potential and timeframe for restoration efforts in coupled social-ecological systems. Evaluations of regime shifts that focus on alternative equilibrium states often refer to a brink beyond which the ecosystem will transition to the undesirable state (2). We demonstrate that accounting for human actions in response to ecosystem change allows more nuanced insights. By looking more closely at emerging time lags within the transition phase, decisions, and actions that address critical social and ecological feedbacks, the brink becomes rather a slippery slope, which opens opportunities to return to the favorable state. For managers of a shift-prone ecosystem, this implies that understanding transient dynamics and interactions with critical social time lags can be more relevant than focusing solely on stable states and tipping points. Future research on managing regime shifts should address human behavior in response to social and ecological changes and the explicit delays expected from policy making and implementation.

Methods

Experimental Setup. The model LimnoSES is implemented in NetLogo and can be accessed at CoMSES.net (documentation in *SI Appendix*, Texts S1 and S2). The ecological model implementation was verified by comparing model outcomes with the results of the original model (10). We built confidence in the social and in the coupled model through iterative extensions, model analysis, and testing (ref. 12 and *SI Appendix*, Text S2 and Figs. S2—S4). The experiments compare the effect of individual parameters on social responses, ecological responses and overall restoration time. We deploy the model here to systematically analyze how social time lags are influencing continuously nonlinear ecological dynamics, and thereby affect total lake restoration time (*SI Appendix*, Text S2 and Table S2).

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