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ANALYSIS



# Natural tipping dynamics as catalysts of human cooperation ☆

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## ABSTRACT

The importance of natural tipping elements and regime shifts is broadly recognized, and their mechanisms, risks, and interactions are increasingly well understood. However, less is known about the interrelation between social processes and regime shift dynamics. In particular, the question of how natural tipping dynamics affect sustainable collective action remains open. Here, we introduce a game-theoretic model of collective action within natural tipping dynamics. Explicit social interactions, such as reciprocity, agreements, or communication, are well-known for promoting cooperation. We exclude these in our model to study the isolated effects the tipping dynamics have on the prospects for sustainable collective action. We find that all three classic social dilemma types (Prisoner's Dilemma, Chicken, Stag-Hunt) plus two Harmony games emerge robustly in our model's parameter space. Thus, it is possible to transform any of these collective-action regimes into any other without explicit social processes. We highlight the flexibility of our modeling approach by analyzing agent heterogeneity, boundedly rational learning dynamics, and multiple empirical tipping elements and regime shifts. Our findings reveal the cooperation-promoting potential of the actors' ecological embeddedness and introduce ecological reciprocity as a mechanism for the emergence of cooperation.

## 1. Introduction

Humanity is embedded in Nature, yet we consistently exceed the limits of the biosphere's regenerative capacity (Millennium Ecosystem Assessment, 2005). Since the 1950s, human demands for Nature's provisioning services, such as food, water, timber, and non-living materials, have decreased Nature's ability to provide supporting and regulating services. These services include waste decomposition, pollination, soil regeneration, water purification, and maintaining the biosphere's gaseous composition. The distinction between provisioning services and supporting and regulating services is crucial (Dasgupta and Levin, 2023). Provisioning services are humanity's direct demands from Nature, ultimately used to improve Human development. Supporting and regulating services create provisioning goods. For example, cultivating crops requires pollination and soil regeneration.

In addition to being often overlooked and non-substitutable, a significant challenge for preserving many supporting and regulating services is the occurrence of ecological tipping points and regime shifts (Rockström et al., 2024). These are large, persistent, and often surprising changes in the function and structure of ecosystems (Rocha et al., 2015). They occur across all scales within aquatic, terrestrial, and climate systems. Examples include freshwater eutrophication (Scheffer, 1998), soil salinization (Abrol et al., 1988), or the thermohaline circulation (Clark et al., 2002). While the importance of ecological regime shifts is broadly recognized (Folke et al., 2004; Lenton et al., 2008; Richardson et al., 2023), and their mechanisms, risks, and interactions are increasingly well understood (Rocha et al., 2018; Lenton et al., 2023; Wunderling et al., 2024), less is known about the interrelation between social processes and regime shift dynamics (Biggs et al., 2018). In particular, the question of how natural tipping dynamics affect sustainable collective action remains open. A deeper understanding of this interrelation is required to value humanity's embeddedness in Nature adequately and not miss opportunities to govern the planetary commons (Rockström et al., 2024).

Rapid and large-scale collective, cooperative action is vital to sustaining Nature's supporting and regulating services — safely away

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from dangerous tipping points. While rapid and large-scale collective action is likewise required for many provisioning goods, we here put the focus on supporting and regulating services, as they have often been overlooked. The central challenge for cooperation to emerge is the presence of social dilemmas (Dawes, 1980). Here, individual incentives and collective welfare are not aligned. Individuals profit from free-riding, exploiting others, or fear exploitation by others, while, at the same time, collective welfare is maximized if all choose to cooperate (Macy and Flache, 2002). Addressing the issue of cooperation still poses profound theoretical challenges (Cumming, 2018), which are critical to determining whether and how we can achieve a sustainable future for humanity (Levin, 2020).

The prevailing view is that cooperation in the commons requires explicit social interactions such as reciprocity, agreements, communication, and social norms (Ostrom, 1990; Barrett, 2005; Nowak, 2006; Rand and Nowak, 2013; Nyborg et al., 2016; Pizziol and Tavoni, 2024). These alter the actors' incentives, making cooperative behavior viable. For example, in direct reciprocity, agents consider past behavior when deciding whether to cooperate. Agents can punish non-cooperative behavior by not cooperating in the next round. This way, cooperation becomes possible (Trivers, 1971). However, most works on the emergence of cooperation neglect the possibility that actors can influence their socio-ecological environment, which, in turn, affects their well-being.

Even when changing environments are considered, solutions to the cooperation problem typically entail explicit social mechanisms. For example, research on tipping games converges on the finding that the risk of a catastrophic loss of well-being provides an escape from the tragedy of the commons by converting the social dilemma into a coordination challenge, given sufficient certainty about the threshold (Tavoni and İriş, 2020; Li et al., 2024). Coordination must then be achieved via reciprocity, communication, or international environmental agreements (Vasconcelos et al., 2013; Lindahl et al., 2016; Tavoni et al., 2011; Barrett, 2013). In the context of more general ecological dynamics (Weitz et al., 2016; Tilman et al., 2020; Wang and Fu, 2020), the cooperation problem is typically also addressed via explicit social interactions (Tavoni et al., 2012; Schlüter et al., 2016; Tilman et al., 2017; Calvo and Rubio, 2013).

Methodologically, these findings draw on behavioral experiments (James, 1992; Milinski et al., 2008; Barrett and Dannenberg, 2012; Dannenberg et al., 2015; Schill et al., 2015; Domingos et al., 2020) or models of strategic equilibria (Diekert, 2017; Wagener and de Zeeuw, 2021; Nkuiya and Diekert, 2023) or evolutionary dynamics (Wang et al., 2009; Santos et al., 2012; Chakra and Traulsen, 2012; Hilbe et al., 2013, 2018). Models of strategic equilibria typically assume entirely rational agents without cognitive constraints and are unable to account for actor dynamics and the time required to reach an equilibrium. Models of evolutionary dynamics can assess actor dynamics. However, they tend to be highly simplified regarding the variations between actors, the ecological context, and the underlying cognitive factors that lead to behavior (McNamara, 2013). Eventually, we require an integrated modeling approach that incorporates dynamic, boundedly rational decision-making by diverse actors who discount the future and operate in a changing environment that includes risky choices and tipping points (Madani, 2013; Levin and Xepapadeas, 2021; Barfuss et al., 2025).

In this work, we address the research gap left open by the focus on explicit social interactions as a means to facilitate cooperation: What is the cooperation-promoting potential that stems solely from the fact that all decision-makers are embedded in the same ecological environment? Imagine an idealized situation in which all direct provisioning services of Nature are entirely privatized, and there is complete anonymity among actors, so they cannot reciprocate, communicate, or form agreements. Collective action is mediated only implicitly via Nature's supporting and regulatory services, into which all actors are embedded (Barfuss et al., 2018, 2020). Each actor who overuses Nature risks degrading these services, with potential future consequences for all actors. Specifically, we show that ecological tipping dynamics alone can facilitate game-theoretic incentive regimes where cooperation prevails without requiring any additional explicit social mechanism. Thus, ecological dynamics alone can serve as catalysts for fully cooperative regimes. Depending only on factors concerning the individual-nature relationship, all classic social dilemma types (Prisoner's Dilemma, Chicken, Stag Hunt) plus two Harmony regimes can emerge from the actors' ecological embedding. Hence, it is possible to transform any social incentive regime (i.e., game type) to any other without requiring explicit social interactions. We highlight the flexibility of our modeling framework by refining it to heterogeneous and dynamic, boundedly rational actors, and illustrate how our theoretical model can be mapped to empirical regime shifts and tipping elements. Our model is not intended to capture a specific empirical case in which, typically, different motivations and incentives, arising from a mix of jointly managing provisioning goods and regulating services, overlap. Instead, we aim to isolate the effects of actors' ecological embeddedness by considering no explicit social interactions. We do not aim to suggest that explicit social mechanisms are not helpful or should not be used. More research is urgently needed on how to scale explicit social mechanisms, such as social norms, to induce planetary cooperation for a sustainable future. With this work, we aim to assess how Nature can best help us with that.

## 2. Model description and analysis

Here, we present a stochastic game model of collective action in commons within a natural tipping element (Fig. 1A). Two representative decision-makers repeatedly interact (in discrete time steps) within an environment of two states, a prosperous and a degraded one. In the prosperous state, each agent must choose between a conservation and an intensification action, which affects the environment. For example, intensification corresponds to emitting a large, business-as-usual amount of carbon into the atmosphere, a high rate of rainforest deforestation, or a high level of freshwater extraction. In contrast, conservation corresponds to a sustainable level of greenhouse gas emissions, deforestation, or freshwater extraction within the ecological environment's recovery capacity.

*Provisioning goods and short-term benefits.* In a prosperous environment, the biosphere's supporting and regulating services function sufficiently well, and the environment can deliver provisioning goods to the agents. To isolate the effects of the tipping dynamics on the prospects of cooperation, we assume the idealized case of these goods being entirely privatized, i.e., their benefits do not depend on the other agent's action. Each agent opting for conservation receives a benefit $b_{\mathrm{C}}$. Each agent opting for intensification receives a higher benefit $b_{\mathrm{I}} > b_{\mathrm{C}}$. In the degraded state, however, the biosphere's maintenance and regulating services are not functioning. Thus, whenever the environment collapses into or is in the degraded state, all agents receive only a benefit $b_{\mathrm{D}} < b_{\mathrm{C}}$ independent of their action. As benefits come without scale and reference point, we summarize these three benefits into a single model parameter, the short-term conservation incentive, $\Delta r = f(b_{\mathrm{C}}) \in [0, 1]$ by transforming all benefit parameters according to $f(x) = (x - b_{\mathrm{D}})/(b_{\mathrm{I}} - b_{\mathrm{D}})$. $\Delta r$ describes how much less immediate benefit conservation delivers (in comparison to the collapse impact $b_{\mathrm{D}}$) compared to intensification. Thus, a larger $\Delta r$ denotes either a larger conservation benefit, a smaller, more severe degradation benefit, or a smaller intensification benefit.

*Ecological tipping and transitions.* Each agent employing intensification also increases the probability of triggering the tipping element and collapsing the environment into the degraded state. We parameterize the overall collapse probability $p_c$ by the collapse leverage $q_c \in [0, 1)$ each intensification actor exerts on the environment. The total collapse probability $p_c = 0$, if no actor chooses intensification, $p_c = q_c/2$ if one

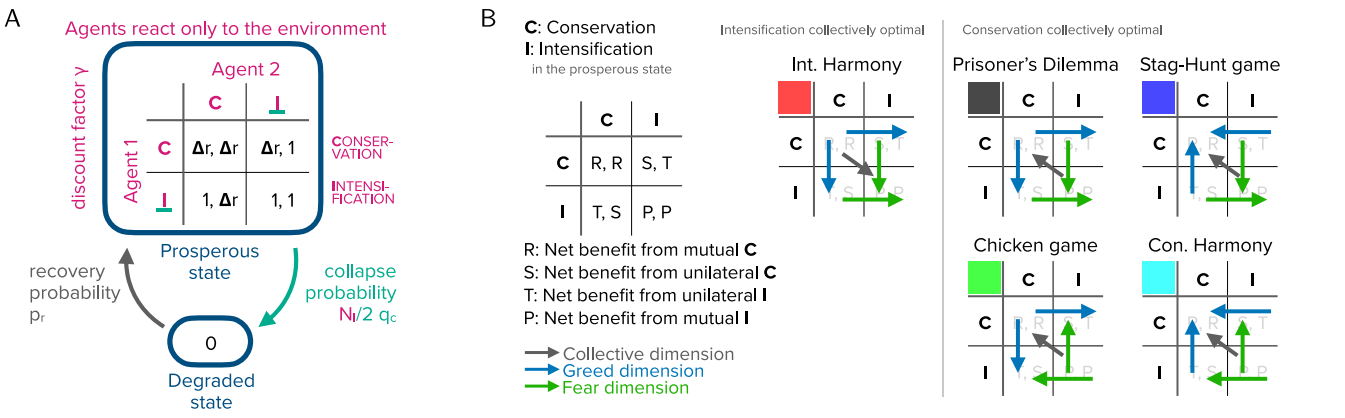



**Fig. 1. A: Model.** Agents choose between a conservation and an intensification action, influencing the state of the environment, while the environment, in turn, affects the agents' immediate benefits. Interactions between agents are mediated only indirectly through the environment. **B: Analysis.** We compute the long-term discounted net benefits for each strategy combination of conservation and intensification. We assess (i) whether conservation or intensification is collectively optimal, (ii) whether an individual has an incentive to exploit the other (greed), and (iii) whether an individual must fear being exploited by the other. Based on these three dimensions, five (out of eight combinatorial possible) collective-action regimes emerge: Intensification Harmony, Prisoner's Dilemma, Chicken game, Stag-Hunt game, and Conservation Harmony.

actor chooses intensification, and $p_c = q_c$ if both do. In the degraded state, the agents cannot influence the environment and have to wait on average for $1/p_r$ rounds, parameterized by the recovery probability $p_r$, until they enter the prosperous state again.

*Decision model.* We assume that each agent's conservation or intensification action is conditional solely on the current environmental state. They do not take longer histories, their own past choices, nor the choices of the other agent into account — either because they do not have the cognitive resources for more complex strategies (Simon, 1997) or because they cannot observe or make sense of the other agent's actions. But we assume that agents can plan their course of action into the future (Barfuss, 2022) and that they care about future rewards, but exponentially discount them with a discount factor $\gamma \in [0, 1)$.

*Summary.* Our model is determined by four parameters: the collapse leverage $q_c$, the recovery probability $p_r$, the short-term conservation incentive, $\Delta r$, and the long-term discount factor $\gamma$. All of them are in the range between 0 and 1 .

Our model does not consider any explicit social interactions. All short-term benefits are independent of the other agent's choice, which models Nature's provisioning goods as fully privatized and excludes any form of agreements or side payments. Agents do not consider past choices when making their decisions, nor do they observe any other trait of the other agent, excluding any form of social reciprocity and communication. Interaction between the agents is mediated only implicitly through the joint tipping environment, which models Nature's regulating and maintenance services. Thus, our model can serve as a reference point for assessing the cooperation-promoting potential of the actors' ecological embeddedness.

*Meta-game analysis of collective-action regimes.* We ask which effective social dilemma type emerges given a set of model parameters (Fig. 1B). For that, we realize that agents can effectively choose between two strategies: Intensification, I, where they take the intensification action, and Conservation, C, where they take the conservation action in the prosperous state. We compute the discounted net benefit $V_{\boldsymbol{X}}$ for each of the four joint strategies $\boldsymbol{X} \in \{\mathrm{CC}, \mathrm{CI}, \mathrm{IC}, \mathrm{II}\}$ using Bellman's equation.

With these long-term values, $V_{\boldsymbol{X}}$, we distinguish three dimensions: (i) what is collectively optimal, (ii) whether agents are greedy to exploit the other, and (iii) whether agents fear being exploited by the other (Macy and Flache, 2002):

(i) The collective is better off with conservation than intensification when $C \equiv V_{\mathrm{CC}} > V_{\mathrm{II}}$.
(ii) An individual is greedy to exploit the other when $G \equiv V_{\mathrm{IC}} > V_{\mathrm{CC}}$.
(iii) An individual fears to be exploited by the other when $F \equiv V_{\mathrm{CI}} < V_{\mathrm{II}}$.

Based on how these three binary dimensions align, we categorize different collective-action regimes, including the three social dilemma types. A Prisoner's Dilemma is present when $C \wedge G \wedge F$. A Chicken game appears when $C \wedge G \wedge !F$. A Stag-Hunt game exists when $C \wedge !G \wedge F$. We also find parameter solutions for two Harmony games, a Conservation Harmony when $C \wedge !G \wedge !F$ and an Intensification Harmony when $!C \wedge G \wedge F$.

*Two-period model analysis.* The Supplementary Information contains the analytical solutions for the long-term values and boundaries between neighboring regimes in parameter space for the full model. To provide some intuition about the parameter conditions required for specific collective-action regimes, we here analyze a simplified version of our model. It is simplified in two ways: First, we consider only the first two time periods. Second, we assume that the degradation benefit $b_{\mathrm{D}}$ occurs only after the environment has been degraded, not already during the transition. Doing so allows us to formulate the long-term values for a conserving and an intensifying actor,

$$V_{\mathrm{C}X} = b_{\mathrm{C}} + \gamma \left[ p b_{\mathrm{D}} + (1-p) b_{\mathrm{C}} \right],$$
$$V_{\mathrm{I}X} = b_{\mathrm{I}} + \gamma \left[ (p + \frac{q_c}{2}) b_{\mathrm{D}} + (1 - p - \frac{q_c}{2}) b_{\mathrm{I}} \right],$$

where $X$ denotes the strategy of the other actor and $p$ the corresponding collapse probability contribution. Thus, $p = 0$ if the other actor conserves, and $p = q_c/2$ if the other actor intensifies. It follows that

$$V_{\mathrm{C}X} > V_{\mathrm{I}X} \iff (1-\Delta r)(1+\gamma(1-p)) < \gamma \frac{q_c}{2}. \tag{1}$$

Depending on whether the condition holds for neither, both, or only one value of $p$, three outcomes are possible. If the condition holds for both values of $p$ ($F$ and $G$ are false), conservation is dominant, and the Conservation Harmony regime emerges. If it holds for neither ($F$ and $G$ are true), intensification is dominant, yielding either the Prisoner's Dilemma (when conservation remains collectively optimal, i.e., $C$ holds) or Intensification Harmony (when it does not). For $C$ to hold, it is easy to show that $(1-\Delta r)(1+\gamma) < \gamma q_c$. If the condition (Eq. (1)) holds only when the other actor intensifies ($F$ is false), but not when the other actor conserves ($G$ is true), the Chicken game emerges.

The fourth logical possibility, where the condition holds only when the other actor conserves ($G$ false and $F$ true), would correspond to the Stag-Hunt game. This case is ruled out by monotonicity: since increasing $p$ always relaxes the condition, it cannot hold for $p = 0$ while failing for $p = q_c/2$. Stag-Hunt, therefore, cannot emerge in the two-period model. In the full multi-period model, an additional mechanism

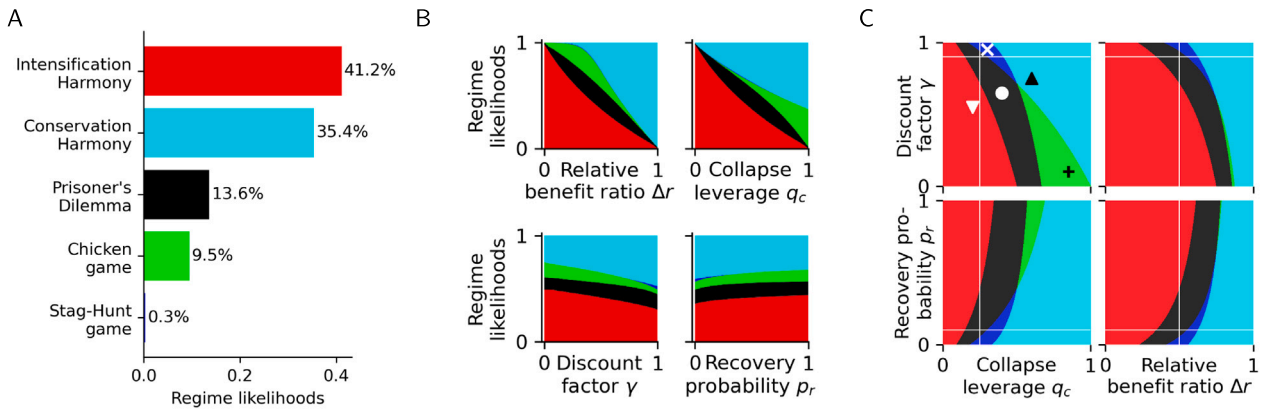



**Fig. 2. Emerging collective-action regimes** under great uncertainty. **A: Overall likelihoods.** All three social dilemma types emerge from the four-dimensional parameter space of the model — but not equally likely for uniformly sampled parameters. In these regimes, conservation is collectively optimal, but individuals may not be incentivized to choose the conservation action. There are also two Harmony game regimes, one for conservation, one for intensification, without a conflict-of-interest between individual and collective action. **B: Likelihood dependencies.** The likelihoods of the five collective-action regimes versus each model parameter. The other three parameters are sampled uniformly. **C: Parameter spaces.** Collective-action regimes in two-dimensional parameter space sections. The four plots are spanned around the point: short-term conservation incentive $\Delta r = 0.5$, collapse leverage $q_c = 0.25$, discount factor $\gamma = 0.9$, and recovery probability $p_r = 0.1$.

enables it: the stationary distribution of the Markov chain depends on the *joint* strategy profile, so the long-run probability of degradation is substantially lower when both actors conserve than when one defects. This endogenous feedback makes conservation self-reinforcing when the other actor also conserves, generating the Fear condition ($V_{\mathrm{CI}} < V_{\mathrm{II}}$) that defines the Stag-Hunt regime.

Thus, we find that long-term interactions are required for the Stag-Hunt coordination regime to emerge in our model.

*Parameter uncertainty analyses.* Analyzing the consequences of decisions in global change issues requires accounting for great uncertainty (Polasky et al., 2011). Thus, we investigate which collective-action regimes can emerge and how likely they are, based solely on the structural features of our model. These are the causal mechanisms and the four parameters, each in the range between zero and one, as described above. To avoid introducing additional assumptions, we sample each parameter independently from a maximum-entropy distribution (Jaynes and Bretthorst, 2003). That is, in our case, the uniform distribution over the interval $[0, 1]$. Fig. 2A shows how likely each of the five collective-action regimes (game types) is to emerge over this parameter space. To study the effects of each parameter individually, we compute the regime likelihoods when a single parameter is fixed to a specific value (Fig. 2B). Finally, we illustrate four specific sections of the parameter space (Fig. 2C).

## 3. Results

### 3.1. Emerging collective-action regimes

We find that actors' ecological embeddedness in commons with tipping elements can give rise to five collective-action regimes, some of which are beneficial for collective conservation, while others are detrimental (2A-C). In all three social dilemma types, conservation is collectively optimal. Here, it is appropriate to think of conservation as cooperation and intensification as defection.

The most detrimental regime for collective conservation is the Prisoner's Dilemma (black in Fig. 2). Both greed and fear ($G$ and $F$) incentivize individuals to intensify, making intensification a dominant strategy and leading to the famous and still ubiquitous tragedy-of-the-commons narrative (Hardin, 1968). The unique equilibrium (II) is Pareto-dominated by mutual conservation (CC), yet neither agent can unilaterally improve their outcome by deviating. Here, only central outside authorities or bottom-up arrangements and social reciprocity have been shown to facilitate cooperation (Ostrom, 1990; Rand and Nowak, 2013). Interestingly, it only occurs with an overall likelihood of approx. 14% in our model. It requires intermediate values of the short-term conservation incentive, $\Delta r$, and the collapse leverage, $q_c$. It is slightly more pronounced when agents care little about future rewards (small discount factor $\gamma$), and recovery is frequent (high recovery probability $p_r$) (Fig. 2B,C).

The second-most-detrimental regime for conservation is the Chicken game (green in Fig. 2). When only greed, not fear ($G$ holds, $F$ does not), incentivizes individuals to intensify, neither (CC) nor (II) is a Nash equilibrium, and conservation action remains divided. One agent will employ intensification and be better off than the other agent, who has no incentive to deviate from conservation. Strategically, this regime induces a motivation to act quickly, if possible, before the other agent and ensure the preferable position as the intensification actor – a situation often seen in negotiation settings (Bodansky, 2001; Barrett, 2005). The Chicken game regime is also interesting because it leads to the spontaneous emergence of inequality among the agents. Even though both agents have identical characteristics, they end up in a situation where one agent is better off than the other. Full conservation requires outside mechanisms, as in a Prisoner's Dilemma. The Chicken game regime occurs with an overall likelihood of approx. 10% of (Fig. 2A). It is more pronounced for a low short-term incentive to conserve, $\Delta r$, frequent collapse (high collapse leverage $q_c$), little care for future rewards (small discount factor $\gamma$), and frequent recovery (high recovery probability $p_r$) (Fig. 2B,C).

The second most beneficial regime for collective conservation is the Stag-hunt game (blue in Fig. 2). When only fear drives agents to intensification ($F$ holds, $G$ does not), mutual conservation and mutual intensification are both strategic equilibria. Fear means that a unilateral conserving agent risks ending up in the worst position ($V_{\mathrm{CI}} < V_{\mathrm{II}}$), making intensification a defensible "safe" choice. The absence of greed means there is no incentive to defect from mutual conservation ($V_{\mathrm{IC}} \leq V_{\mathrm{CC}}$), so the cooperative equilibrium is self-sustaining once reached. Crucially, these two equilibria are Pareto-ranked (John and Selten, 1988): mutual conservation (CC) strictly dominates mutual intensification (II) in terms of collective welfare (condition $C$). The collective challenge is therefore one of coordination (reaching the Pareto-superior equilibrium) rather than one of incentive misalignment, which requires an additional social mechanism. The Stag-hunt game occurs relatively rarely, with an overall likelihood of approx. 0.3% (Fig. 2A). It is more pronounced when the care for future rewards, $\gamma$, is

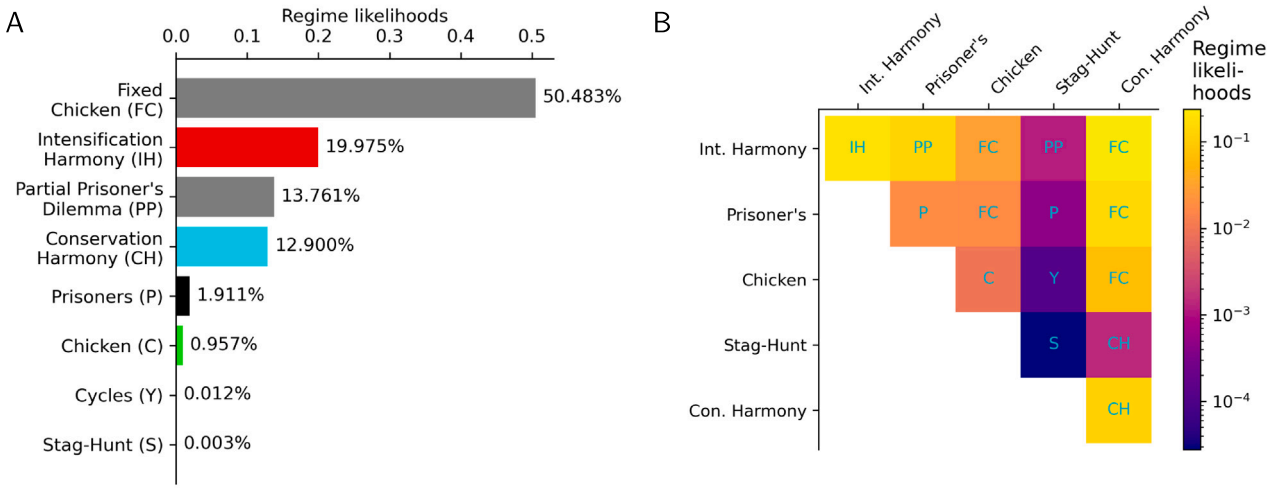



**Fig. 3. Emerging collective-action regimes for heterogeneous agents.** For diverse agents (determined by four parameters each), three additional qualitatively distinct incentive regimes emerge. **A: Overall likelihoods** for eight qualitativly destinct outcome regimes. **B: Likelihoods for all regime combinations.** Letters indicate to which outcome regime a regime combination belongs.

high and recovery occurs rarely (small $p_r$). Short-term incentives and collapse leverage have less influence on its occurrence (Fig. 2B,C).

We also find two Harmony game regimes. The most beneficial regime for collective conservation is the Conservation Harmony game (cyan in Fig. 2). Here, neither greed nor fear drives agents to intensification (neither $G$, nor $F$ hold). Without any conflict of interest, both agents will cooperate and employ conservation. Regardless of what the other agent is doing, both individuals are incentivized to conserve. Thus, a Conservation Harmony game regime fully resolves the social dilemma toward self-enforcing and self-sustaining cooperation, without requiring any additional mechanism. Interestingly, it occurs with a large overall likelihood of approx. 35%. (Fig. 2A). It is more pronounced for high short-term incentives to conserve, $\Delta r$, and large collapse leverages $q_c$ — and to a lesser extent, for high caring for future rewards, $\gamma$, and rare recoveries (small $p_r$).

We also find a Intensification Harmony regime (red in Fig. 2). Here, intensification is the optimal choice, both individually and collectively ($F$ and $G$ hold, but $C$ does not). The environment transitions between prosperous and degraded states. With over 40%, it is the most likely regime to occur (Fig. 2C).

So far, we have assumed that agents are identical for simplicity. The following section will show how our model can be extended to agents with heterogeneous characteristics.

### 3.2. Heterogeneous actors

Environmental degradation and inequality are two defining challenges of the twenty-first century (Hamann et al., 2018; Drupp et al., 2025). Actors impact the environment to a different degree. Ecological damages affect actors differently, and they have different preferences for immediate or future outcomes. To include this diversity into our model, we refine our model such that each agent has an individual short-term conservation incentive $\Delta r^i$, individual discount factor $\gamma^i$, and personal beliefs about the collapse leverage $q_c^i$ and the recovery probability $p_r^i$, for $i = \{1, 2\}$.

We find that for diverse agents (determined by four parameters each), three additional qualitatively distinct incentive regimes emerge (Fig. 3A). These additional regimes from diverse actors arise because, for one actor, the situation falls within one of the five core regimes. In contrast, for the other actor, it seems to fall within another (Fig. 3 B). By mere combinatorial and symmetry arguments, this would yield 10 additional social incentive regimes. However, when we focus primarily on the outcome of a regime combination, we can combine several regime combinations into different classes. For example, when one agent believes the situation is an Intensification Harmony, it is irrelevant whether the other agent thinks it is a Conservation Harmony or Chicken game. The Conservation Harmony and Chicken game differ only in the incentive an agent has when the other agent opts for conservation. Since, in our example, the focal agent will always choose intensification, this difference between the regimes is negligible. In the end, a Fixed Chicken regime emerges. Considering this logic, we summarize these heterogeneous regime combinations into three additional regimes.

*Fixed Chicken.* This regime describes a situation in which one agent (determined by agent heterogeneity) chooses intensification, and the other chooses conservation. As in the Chicken game regime, the intensification agent is better off than the conservation agent. However, inequality does not emerge spontaneously; it is predetermined by agent heterogeneity. The Fixed Chicken regime consists of the following regime combinations: Intensification Harmony-Conservation Harmony game, Intensification Harmony-Chicken game, Prisoner's Dilemma-Chicken game, Prisoner's Dilemma-Conservation Harmony game, and Chicken-Conservation Harmony game. With over 50% of all cases, it is by far the most likely outcome, given a uniformly sampled parameter space, i.e., without additional assumptions or information about the model parameter values (Fig. 3A).

*Partial tragedy.* The regime combinations Intensification Harmony-Prisoner's Dilemma and Intensification Harmony-Stag-Hunt game lead both agents to choose intensification, but only one agent is happy with that choice. The other would prefer both agents to select conservation. We call this regime a Partial Prisoner's game. It occurs with approx. 14%, given a uniformly sampled parameter space (Fig. 3A).

*Cycles.* In the regime combination Chicken-Stag-Hunt game, there is no equilibrium in pure strategies. Instead, the individual incentives have a cyclic relationship. When the Stag-Hunt agent conserves, the Chicken agent wants to intensify, which the Stag-Hunt agent responds to with intensification. However, when the Stag-Hunt agent intensifies, the Chicken agent wants to conserve, prompting the Stag-Hunt agent to conserve as well. And the cycle begins anew. However, the regime occurs very rarely, with only approximately 0.01% given a uniformly sampled parameter space (Fig. 3A).

Overall, it is interesting to observe that the likelihood of the Prisoner's Dilemma game regime occurring decreased to below 2%. Assuming heterogeneous agents, the outcome is dominated by inequality.

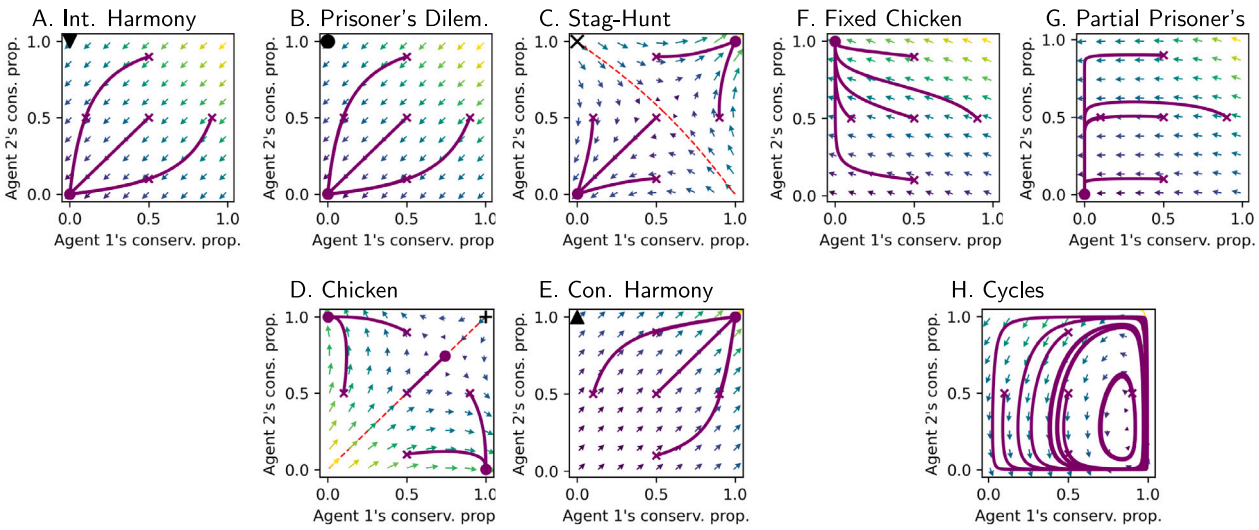



**Fig. 4. Collective Reinforcement Learning Dynamics.** Dynamic and boundedly rational micro-foundations for each of the five collective-action regimes for homogeneous agents (A–E) and the three additional regimes for heterogeneous agents (F–H). The points in parameter space for each of the regimes are portrayed in Fig. 2C. These dynamics allow for an explicit representation of the transient, non-linear dynamics in a transparent and understandable way. At the same time, they are coherent with the equilibrium perspective.

The Fixed Chicken and the Partial Prisoner's Dilemma game regimes occur together in almost two-thirds of cases, given a uniformly sampled parameter space (Fig. 3A). For the occurrence likelihoods for all eight heterogeneous regimes (Fig. 3A), we include the Prisoner's Dilemma-Stag-Hunt game combination within the core Prisoner's Dilemma game regime, and the Harmony-Stag-Hunt game combination within the core Harmony game regime.

These equilibrium-regime analyses revealed a plurality of collective and individual incentive configurations, some beneficial for conservation cooperation and others favoring intensification. However, it cannot fully capture which option the actors ultimately choose. In the next section, we resolve this issue by providing a dynamic, boundedly rational foundation for these collective-action regimes.

### 3.3. Boundedly-rational learning dynamics

We complement the equilibrium analyses with a dynamic account of our model. By letting the agency of our actors originate from an established neuro-cognitive learning paradigm, reinforcement learning (Schultz et al., 1997; Dayan and Niv, 2008), we obtain an explicit model of the transient, non-linear dynamics while maintaining a connection to the equilibrium perspective (Barfuss, 2022). Specifically, we use a deterministic model of reinforcement learning (Barfuss et al., 2019; Barfuss and Mann, 2022; Barfuss, 2020), which provides a lightweight and robust tool for understanding how such cognitive and psychological factors lead to behavior (McNamara, 2013; Schill et al., 2019; Constantino et al., 2021). This learning model is consistent with the decision model of the equilibrium analysis (Barfuss, 2022). However, instead of using individual incentives to determine the final regimes, they are used to update the agents' current strategies during learning (see Supplementary Information for details).

When the underlying collective-action regime has only one equilibrium (Intensification Harmony, Prisoner's Dilemma, Conservation Harmony, Fixed Chicken, and Partial Prisoner's Dilemma game), the learning dynamics evolve to this equilibrium from all points in the strategy space; mutual intensification for Intensification Harmony, Prisoner's Dilemma, and Partial Prisoner's Dilemma game regimes (Fig. 4AB&G), mutual conservation for the Harmony game regime (Fig. 4E), and unilateral intensification/conservation for the Fixed Chicken game regime (Fig. 4F).

Interestingly, the learning timescales differ between the homogeneous-actor and heterogeneous-actor cases. In the homogeneous-actor case, both agents change their strategies on the same timescale, as the approximately diagonal learning trajectories in Fig. 4AB&E show. In the heterogeneous-actor cases, however, one agent learns faster than the other. In Fig. 4F&G, the learning trajectories cross the strategy space almost horizontally, indicating that Agent 1 learns much faster than Agent 2.

When the collective-action regime is either the Chicken or the Stag-Hunt game, the optimal strategy for one agent depends on the other agent's strategy. The equilibrium to which the learning dynamics converge depends on the agents' initial strategy profiles. The dynamics are in a multi-stable regime (Fig. 4C&D).

In the Chicken game regime, one agent sacrifices its own welfare to mitigate the negative consequences for the other agent. The question is, which agent will do so? Fig. 4D shows that it is the agent that initially has a smaller disposition for intensification. If both agents initially choose intensification with equal probability, the dynamics evolve to a mixed equilibrium, which, however, would cease to exist given a tiny error in the agents' learning process. Notably, the learning dynamics perspective reveals that the inequality between agents in the Chicken regime arises from differences in their initial strategies. It is not due to differences in agent characteristics. These are identical.

In the Stag-Hunt game regime, agents must coordinate on mutually beneficial conservation. The question is, under what conditions do they manage to do so? Fig. 4C suggests that the combined initial predisposition for conservation must exceed a critical threshold. This critical separatrix separates the basins of attraction for the mutual conservation and intensification equilibrium and depends on the model's parameter values. Interestingly, the Stag-Hunt game regime is the only one in which parameter values influence the size of the basins of attraction. In all other regimes, the basin sizes are unaffected.

Lastly, the learning dynamics perspective even resolves the cyclic incentive structure of the Cycles regime. It consists of one agent in a Chicken game regime and one agent in a Stag-Hunt game regime. Here, cyclic learning dynamics emerge, which do not converge to a single fixed point in strategy space (Fig. 4H).

So far, we have focused on the structural features of our idealized model, either by studying the entire parameter space or by examining representative parameter combinations. In the following section, we juxtapose our theoretical results with empirical data.

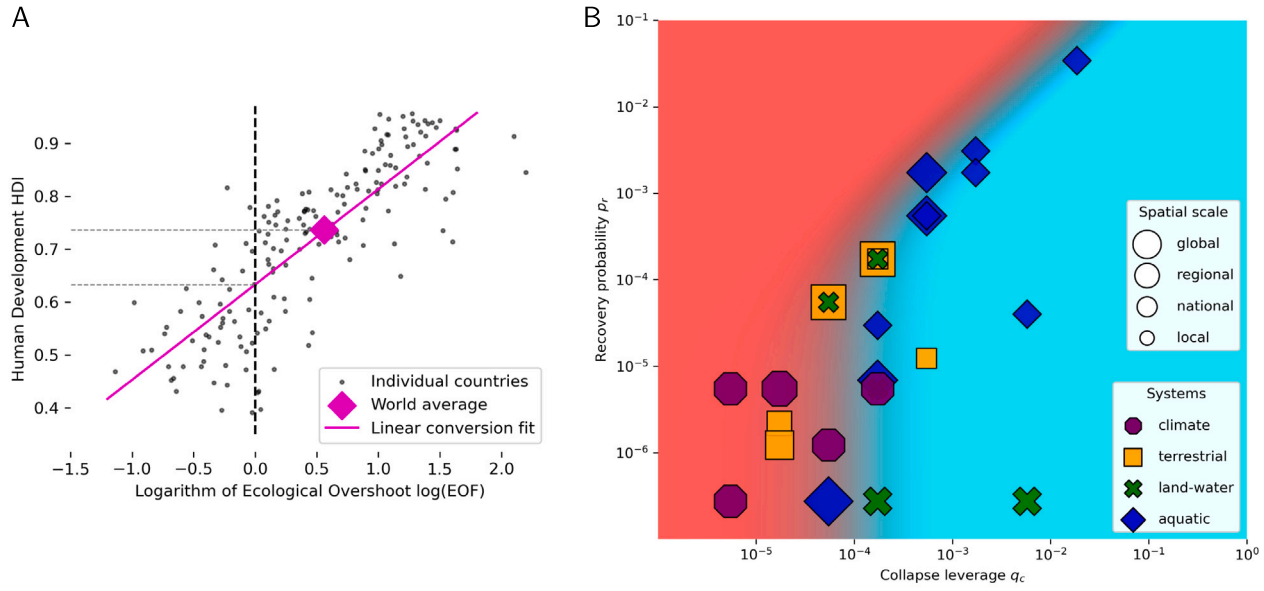



**Fig. 5. Empirical illustration** of our model. **A:Estimating the short-term conservation incentive** using the relationship between human development and ecological overshoot. The data year is 2018. Small dots represent individual country values. The large square denotes the world average. The straight pink line is the best linear fit representing the current mode of converting Nature use into human development. The short-term conservation incentive, $\Delta r = 0.862$, results from the ratio between a sustainable achievable level of human development (at $\log(\text{EOF}) = 0$) and the current level (at $\text{EOF} = 1.75$). **B: collective-action regimes for 27 natural tipping elements** across spatial scales and systems, taken from the Regime Shifts Database. A $\pm 10\%$ uncertainty interval around the estimated $\Delta r$ and yearly discount rates between 1% and 30% were assumed. The resulting regime uncertainty is represented by interpolting within the three-dimensional color space.

### 3.4. Empirical illustration

In this section, we apply our model to the tipping elements and regime shifts of the Regime Shifts Database (Biggs et al., 2018). We aim to constrain the model parameters to plausible values for this case and explore the consequences of these constraints. For simplicity, we reduce the number of model parameters we need to estimate, assuming the fate of Nature's supporting and regulating services lies in the hands of two identical representative decision-makers (Fig. 2A). These agents represent two abstract social planners who take into account the game-theoretic collective-action regime in addition to optimizing the discounted future net benefits. Thus, we are left with estimating the four parameters of our model: $(q_c, p_r, \gamma, \Delta r)$.

The Regime Shifts Database contains information on 27 natural regime shifts or tipping elements across the climate, terrestrial, land-water, and aquatic systems and spatial scales. We convert the typical time scale and reversibility attributes of the Regime Shifts Database to the collapse leverage $q_c$ and the recovery probability $p_r$, assuming one timestep in our model corresponds to one day on Earth. We convert these attributes into numeric values $T_c$ and $T_r$ in units of days. These are mapped into probability space by $p = 1/T$ (See Supplementary Information for details).

To estimate a plausible range for the agents' discount factor applicable to the tipping elements across systems and scales, we consider two bounds. The highest care for future utility assumes a social discount rate of 1% yearly, which a large group of experts finds acceptable, despite substantial disagreement (Drupp et al., 2018). For the lowest level of care for future rewards, we consider a yearly discount rate of up to 30%, which is in the order of magnitude of the upper bound on time discounting found empirically (Cohen et al., 2020). Thus, we use a range of 1%–30% for the yearly discount rate and convert these into daily discount factors usable within our model (See Supplementary Information for details).

To estimate a plausible range for the short-term conservation incentive, $\Delta r$, we assume the ultimate purpose of using the biosphere to produce provisioning goods is human development (Raworth, 2017). As a proxy for that, we use the Human Development Index, $\text{HDI} \in [0, 1]$, the geometric mean of life expectancy, education, and per capita income indicators. To assess the HDI value humanity can currently achieve on a sustainable basis and under the current ecological overshoot (i.e., $b_C$ and $b_I$ of our model), we contrast the achieved HDI value versus the ecological overshoot factor EOF. This is the ratio of our demand for supporting and regulating services to Nature's ability to meet that demand sustainably (Dasgupta and Levin, 2023). Fig. 5A (gray points) shows the HDI value vs. a proxy of the (logarithm of the) ecological overshoot factor for each country if everyone on Earth would adopt the average lifestyle of that country (Wackernagel and Beyers, 2019). The straight pink line shows the best linear fit to these data points, and the large pink square represents the world average. With the help of this linear model, we can read the respective HDI values, $b_{\text{C}} \approx 0.632$ for the conservation action (at $\log(\text{EOF}) = 0$) and $b_{\text{I}} \approx 0.736$ for the intensification action. In the degraded state without the biosphere's regulating and maintenance services, we assume the extreme of zero human development, $b_{\text{D}} = 0$. Together, this yields a short-term incentive to conserve, $\Delta r = (b_{\text{C}} - b_{\text{D}})/(b_{\text{I}} - b_{\text{D}}) \approx 0.862$. To account for the different scales and systems of the regime shifts and uncertainty in the estimate itself, we use $\Delta r$-values in the range from $-10\%$ of 0.862 to $+10\%$ of 0.862, i.e., $\Delta r \in [0.776, 0.949]$.

Applying these parameter constraints, we find the resulting parameter space section spanned by the recovery probability $p_r$ vs. the collapse leverage $q_c$ dominated by Intensification and Conservation Harmony game regimes (Fig. 5B). Given the significant parameter uncertainty we considered, it is interesting to observe that this uncertainty affects only a comparably minor part of the parameter space shown. Because the regime colors result from the three-dimensional color space, we can visualize regime uncertainty by interpolating between them.[1] The

[1] The three (color) dimensions indicate whether the collective, greed, and fear benefit comparisons are positive or negative (Fig. 2B).

uncertainty region concerns the edge between the Intensification and Conservation Harmony game regimes. Here, dark colors indicate the presence of a Prisoner's Dilemma game regime. For larger values of the transition rates, $p_r$ and $q_c$, one observes a slight hint of the blue Stag-Hunt game regime between the Prisoner's Dilemma and Harmony game regimes. Thus, we can state that our finding that social dilemma traps, such as a Prisoner's Dilemma, Chicken or Stag-Hunt game, occur relatively rarely is robust under these regime shifts dynamics and significant uncertainty around the discount factor and short-term conservation incentive.

Interestingly, we find most tipping elements and regime shifts within or around the dark, uncertain Prisoner's Dilemma region. Notably — and perhaps consistently with our current experience — many climate and ecological tipping elements fall within or are close to this Prisoner's Dilemma belt. According to our model, collective action in these tipping elements is most likely prone to a tragedy of the commons.

## 4. Discussion

Collective conservation efforts are essential to sustain the commons safely away from dangerous tipping points. The established practice is to address environmental collective action problems through explicit social interactions, such as reciprocity, communication, agreements, and norms. We have shown that natural tipping dynamics alone — without any explicit social interactions — can serve as catalysts for human cooperation by giving rise to a plurality of collective-action regimes. Some of these are beneficial for collective conservation, while others are detrimental. In our theoretical model, two representative decision-makers must trade off the immediate benefits of intensification against the long-term benefits of conservation. In contrast to performing the conservation action, intensification risks triggering a shared ecological tipping element with detrimental consequences for the actors' well-being. The model parameter space comprises the probabilities of collapse and recovery of the tipping element, the degree to which actors value future benefits, and the relative short-term incentive to opt for conservation. Without additional assumptions, all four parameters are equally likely to have values between 0 and 1.

We conducted a comprehensive uncertainty analysis of our model, underscoring the need to account for great uncertainty when analyzing the consequences of decisions in global change issues (Polasky et al., 2011). Even for two identical actors, we find that all three two-by-two social dilemma types (Prisoner's Dilemma, Chicken, Stag-Hunt) emerge consistently across the parameter space of our model. We also find two Harmony regimes where individual and collective incentives are aligned, one for conservation, the other for intensification.

Overall, our findings are at odds with the classical narrative of the tragedy of the commons. The narrative of the tragedy of the commons is still widespread. Our model of the commons, however, suggests that there is no conflict of interest between the individual and the collective in more than three out of four cases. In contrast, the Prisoner's Dilemma regime occurs in less than 15%, given a uniformly sampled parameter space. Even when considering empirical regime shift dynamics under significant uncertainty around the discount factor and short-term conservation incentive, social dilemma regimes occur relatively rarely. Thus, commons with ecological tipping points are not necessarily doomed to tragedy, even without explicit social interaction. Ostrom and colleagues have also documented that commons do not always end up in a tragedy (Ostrom et al., 2002). Commons are more like a drama, sometimes a tragedy, sometimes a comedy, and often something in between. However, the obtained institutional design principles for sustainable commons stewardship (Ostrom, 1990) are based on explicit social interactions, such as monitoring, sanctions, and conflict-resolution mechanisms. Likewise, Nowak (2006)'s famous summary about the field posits five rules for the evolution of cooperation, all of which stem from an explicitly social mechanism, such as direct or indirect reciprocity. With this work, we add a sixth rule: ecological reciprocity. Our model provides an ecological microfoundation for the drama of the commons. It explains the plurality of collective-action regimes from the actors' ecological embeddedness into a shared ecological tipping element.

A systematic analysis of agents with heterogeneous traits reveals that, in one out of two cases, the outcome is inequality among agents, driven by their differences. Given the critical role that social inequality plays in environmental policy (Drupp et al., 2025; Hamann et al., 2018), the high likelihood of this collective-action regime suggests that the structural features of human–environment interactions, as depicted by our idealized model, are especially susceptible to creating divided actions and severe inequality among diverse actors.

We showed the robustness of our game-theoretic equilibrium analyses by grounding all collective-action regimes in collective reinforcement learning dynamics (Barfuss et al., 2025). Underscoring the need for a more dynamic understanding of human behavior (Schill et al., 2019), these dynamics provide a bounded-rational account of strategic interactions. We have shown instances of complex, transient behavior and evolution on different learning time scales. The critical parameter values at which the underlying collective-action regimes change constitute social tipping points. Thus, by extending these analyses of learning dynamics, our model framework could be applied to develop an integrated account of coupled social-ecological tipping elements.

Despite the high degree of abstraction of our model, its empirical illustration underscores two hypotheses: First, game-theoretic considerations are relevant to the analysis of decision-making in ecological tipping elements. Typically, integrated assessment models consider only a single representative-agent approach, which must optimize the social welfare function (Farmer et al., 2015). Our result suggests that such an approach would fall short of accounting for relevant strategic factors when determining an optimal policy. Second, ecological dynamics of collapse and recovery are critical to optimal collective decision-making. Thus, our model provides a formal account for exploring the consequences, opportunities, and challenges of reconnecting to the biosphere (Folke et al., 2011), i.e, a fundamental shift in perspectives and worldviews, recognizing that human societies and economies are not separate from Nature, but deeply embedded within and dependent on the biosphere's life-supporting systems.

Our work serves as a starting point for exploring the cooperation-promoting potential of the actor's ecological embeddedness. Further work is needed to address some significant limitations of this starting point. The fate of the biosphere lies in the hands of more than just two representative decision-makers, who are certainly not identical. Ecological dynamics are more complex than our model represents and have irreducible uncertainties. And even if we can get into an ecologically-mediated Harmony game regime, the question of whether the actor can adapt in time to avoid tipping remains open. In addition to systematically investigating the potential of ecological reciprocity, it will be of vital importance to analyze how to combine the cooperation-promoting mechanisms from ecological with social reciprocity in the most effective way. Many works already implicitly use a combined approach. We hope that conceptual clarity about the mechanism of ecological reciprocity can shed new light on the quest for rapid and large-scale collective action.

In conclusion, our work provides ecological microfoundations of social dilemma traps. We have shown that natural tipping dynamics alone can give rise to a plurality of collective-action regimes, some of which are beneficial for collective conservation, while others are detrimental. Our model, thus, suggests that transitions into cooperation-promoting regimes do not necessarily require explicit social mechanisms. In the Harmony game regime, collective conservation is both self-enforcing and self-sustaining. This discovery reframes the relationship between ecosystems and societies: the environment is not a passive backdrop for human cooperation, but an essential catalyst for its formation.

## CRediT authorship contribution statement

**Wolfram Barfuss:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jonathan F. Donges:** Writing – review & editing, Conceptualization. **Matthias Bethge:** Writing – review & editing, Supervision. **Simon A. Levin:** Writing – review & editing, Supervision, Conceptualization.

## Declaration of competing interest

The authors declare no conflict of interest.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ecolecon.2026.109082.

## Data availability

All mathematical details, Python computer code, and data are publicly available at https://github.com/wbarfuss/Tipping-Catalysts-Cooperation/ and archived safely at Zenodo https://doi.org/10.5281/zenodo.20276553.

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