Mitigating Ecological Tipping Points via Game-environment Feedback

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Mitigating Ecological Tipping Points via Game-environment Feedback[1]

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Abstract

Widespread exploitation of biological resources raises concerns about the emergence of tipping points characterizing abrupt ecosystem collapse. Mitigating these tipping points is crucial for the sustainability of our being. However, our understanding of how the feedback loop between human exploitation strategies and the environment influences the mechanisms governing these tipping points remains elusive. This study employs an eco-evolutionary game-theoretic framework to explore the coupled dynamics of a renewable resource undergoing a sudden collapse. We investigate the co-evolution of strategic interactions and environmental dynamics using six possible game combinations representing diverse social dilemmas. We find that, depending on the choice of environment-dependent payoff structure, the tipping point can be shifted or even completely eluded. Additionally, this study emphasizes the impact of monitoring and punishment mechanisms against high-effort exploitation strategists on the system's resilience. Our results unveil a rich spectrum of dynamics, spanning from multistability to oscillation, thereby presenting formidable challenges to resource management. While addressing the tragedy of the commons resulting from heightened harvesting efforts, targeted penalties for high-effort strategists emerge as a mitigating factor. Overall, our study highlights the interplay between ecological tipping points, individual decision-making, and external control mechanisms within the realm of resource management.

Keywords: Tipping points, feedback-evolving games, diverse social dilemmas, tragedy of the commons, targeted punishment

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1. Introduction

The likelihood of catastrophic shifts in common resources due to slight alterations in internal or external stressors is an alarming aspect of complex ecosystems [14, 36]. This phenomenon encapsulates sudden and large deviations in the structure and functionality of the system, frequently associated with the existence of alternative stable states [22, 47]. A gradual change in the stressor/driver pushes the system towards a critical threshold or a tipping point beyond which significant and often irreversible changes occur [9, 41]. Several studies have investigated tipping points and their impacts on a wide range of dynamic ecological systems, such as savanna ecosystems [22], coral reefs [32], Iceland vegetation [42], and fisheries [10, 40]. Understanding a sudden transition/tipping to an alternative state is crucial for the resilience of a system [30]. Moreover, the management and conservation of alternative stable states in complex systems are becoming significant and have received much attention in recent years in response to fisheries [24, 39] and vegetation changes [7]. Therefore, elucidating the mechanisms that trigger tipping points [34], along with developing avoidance policies, should be a scientific and societal endeavor.

Humanity's growing impact on the planet triggers environmental responses, which, in turn, influence public opinions on sustainability and conservation efforts. This establishes a dynamic feedback loop in which individual behaviors and environmental states continuously influence and adapt to each other [3, 44, 46, 49]. Furthermore, the actions of individuals or groups on shared resources may alter the incentives for behavioral adaptations driven by changes in the environment [8, 11, 20, 31]. This interplay between human behavior and the environment can lead to *coupled human-environmental systems* (CHES) exhibiting richer dynamics [17, 24, 27, 28]. CHES are ubiquitous and appear in various systems, e.g., global climate systems [23] and water research [26]. Similar feedback loops are apparent in epidemic scenarios, where the control measures - ranging from vaccination to mask-wearing and social distancing - are intricately tied to the severity of the contagious disease outbreak [2, 4, 37]. Previous studies [5, 15, 40] have explored how human strategic evolution can aid in delaying or eluding ecological tipping points by defining utility functions. However, the influence of varying feedback mechanisms between human exploitation strategies and the environment on tipping dynamics remains unexplored, particularly across a range of possible environment-dependent payoff structures.

Weitz et al. [49] provided a framework for analyzing feedback-evolving games in the realm of pairwise interactions between cooperators and defectors. By building upon replicator dynamics to incorporate the evolvability of payoffs based on the environmental state, the authors found that incentivizing cooperation when others defect in a resource-limited situation is crucial to prevent the tragedy of the commons (TOC). The phenomenon of the tragedy of the commons illustrates a significant dilemma where individuals, lured by the prospect of seeking advantages over others, unwittingly contribute to the exhaustion of shared resources [19]. This, in turn, leads to a decline in the collective well-being of the entire community. However, the tragedy can be effectively averted in numerous common scenarios [35], often through intricate sets of regulations that control access to resources. Later, Tilman et al. [46] investigated the harvesting of a common resource with intrinsic growth dynamics, where the resource exhibits a smooth transition to depletion under over-harvesting conditions. They showed that introducing an incentive structure for harvesters leads to complex dynamics, including bistability and oscillation, in the coupled human-environment system. However, the impact of different payoff structures on the co-evolution of harvesting strategies and the environment, particularly in situations where exploitation poses a risk of sudden resource collapse, remains an open question.

Ensuring sustainability of the common-pool resource at the desired level may necessitate the implementation of a robust system of punishment for individuals engaged in over-harvesting [13, 16, 18, 21, 25, 48]. A well-structured punishment strategy could encompass penalties such as fines, restrictions on resource access, or even legal consequences for repeated violations. Alongside this, other control measures such as voluntary enforcement or ostracism are explored as viable solutions to tackle the core issue [33, 43]. However, recent studies have shown that relying solely on punishment may not be sufficient to sustain a thriving environment for the well-being of future generations [12, 39]. Therefore, a key challenge lies in designing a punishment structure that can effectively deter over-harvesting by modifying the payoffs associated with it, thereby altering the behavior of harvesters.

Here, we study the coupled dynamics of a renewable resource influenced by individual exploitation strategies. Individuals can choose between two distinct harvesting strategies characterized by varying levels of harvesting efforts, e.g., high-effort and low-effort exploitation strategies. A dynamic payoff structure is defined for pairwise interactions between these strategies. Importantly, the structure of the game itself adapts to the environmental state, reflecting the changing social dilemmas encountered by players. This flexibility allows us to capture the nonlinear and context-dependent nature of real-world resource management scenarios. Given that the replete environmental state fosters a more competitive game environment compared to the depleted state, we explore the evolutionary outcomes by combining two distinct games at these states chosen from four games: the Trivial game, the Chicken game, the Stag-hunt game, and the Prisoner's dilemma. This approach yields six possible game combinations for investigation. These combinations encompass various dilemmas arising in both replete and depleted environmental states. Furthermore, we introduce the mechanisms of inspection and punishment, specifically targeting individuals employing the high-effort exploitation approach. This governance mechanism influences the competition between strategies and the overall state of the environment. By analyzing this eco-evolutionary framework, we gain a deeper understanding of how resource dynamics, individual decision-making, and external interventions interact to affect the environmental tipping points and eventually shape the resilience of ecological systems. Our study reveals that the choice of the game combination can shift or even avert the tipping point. Increasing the degree of effort from the high-effort strategy or implementing effective monitoring can trigger a collective shift in population opinion towards the low-effort strategy, with outcomes ranging from sudden transition to smooth transition. The study also reports that targeted punishment steers the coupled system away from the complexities of multistability, promoting a consistently rich environment.

2. Models and methods

To begin with, we consider a model of a renewable resource. The resource growth is assumed to be logistic. The resource stock is diminished by harvesting activities. The dynamics of the resource (m) are subsequently governed by:

$$\frac{dm}{dt} = rm\left(1 - \frac{m}{K}\right) - qe\psi_i(m), \tag{2.1}$$

where r represents the resource intrinsic growth rate, and K is the carrying capacity. The functional response $\psi_i(m)$ captures resource deterioration due to harvesting. The parameter q maps the applied harvesting effort e into the rate of resource degradation.

In the context of renewable resource management, the type of functional response to harvesting activity has significant implications for the long-term sustainability of the resource. As harvesting effort (e) increases, both Holling Type-I ($\psi_1(m) = m$) and Type-II ($\psi_2(m) = \dfrac{m}{h+m}$) functional responses lead to complete depletion of the resource, where h is the half-saturation constant. However, the depletion mechanism differs: For Holling type-I functional response, increasing effort leads to a smooth decrease in resource biomass until a threshold $e = e_{F_1}$, where the resource undergoes extinction through a transcritical bifurcation (see Fig. 1(a)). In contrast, for Holling type-II functional response, the trivial equilibrium gains stability at $e = e_{F_2}$, and the resource biomass undergoes a sudden transition to extinction at a critical effort level $e = e_{F_3}$ (see Fig. 1(b)). However, type-III functional response ($\psi_3(m) = \dfrac{m^2}{h^2+m^2}$) exhibits different dynamics, and complete extinction is avoided, but the resource collapses to a low abundance state. Notably, for the type-III functional response, the trivial equilibrium is unstable irrespective of the effort level. The phenomenon of bistability is observed between two positive steady states within the range (e_{F_4}, e_{F_5}) (Fig. 1(c)). Here, we focus on investigating the impact of harvesting activities on resource dynamics prone to *sudden extinction*; hence, we consider the Type-II functional response of resource degradation.

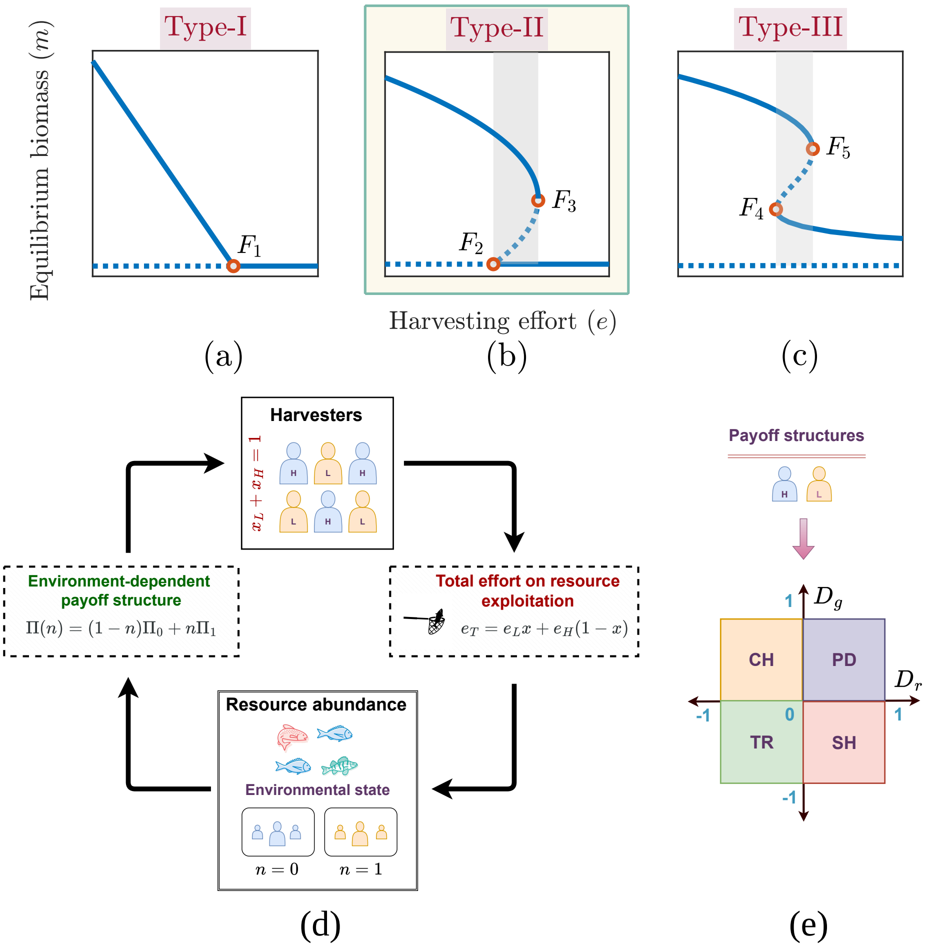

Figure 1. (a)-(c) Changes in the resource equilibrium biomass of the uncoupled system (2.1) as a function of harvesting effort, e. (a) Gradual changes in the resource biomass, and (b, c) sudden changes in the resource biomass, where the coexistence of alternative stable-steady states is marked with the shaded region. F_1 and F_2 represent transcritical bifurcation points, and F_3, F_4, and F_5 represent saddle-node bifurcation points. (d) Schematic diagram of a coupled human-environment system. The composition of harvesters with different strategies (low-effort and high-effort) reshapes the environmental state (n), which in turn alters the payoffs associated with each harvesting strategy. These modified payoffs influence the strategic evolution of the harvesters. x_L and x_H are the frequencies of low- and high-effort harvesters, respectively ($x_L = x$, $x_H = 1-x$). The effort levels for these strategists are e_L and e_H, resulting in a total effort of $e_T = e_L x + e_H(1-x)$. The payoffs for pairwise interactions between these strategies vary depending on the environmental state, represented by the matrices Π_0 and Π_1 for depleted and replete states, respectively. These matrices capture different social dilemmas. (e) The categorization of four game classes on the $D_r - D_g$ plane within the range $-1 \leq D_r, D_g \leq 1$. The first, second, third, and fourth quadrants respectively represent the prisoner's dilemma (PD) $(D_r > 0, D_g > 0)$, the chicken (CH) game $(D_r < 0, D_g > 0)$, the trivial (TR) game $(D_r < 0, D_g < 0)$, and the stag-hunt (SH) game $(D_r > 0, D_g < 0)$.

From Eqn. (2.1) with $\psi_i(m)=\psi_2(m)=\dfrac{m}{h+m}$, we find the following non-zero equilibrium solutions:

$$m_{1,2}=\frac{1}{2}\left[(K-h)\pm\sqrt{(K+h)^2-\frac{4qeK}{r}}\right], \tag{2.2}$$

together with the trivial solution $m=0$ (the extinction equilibrium). Simple calculations with non-zero equilibrium solutions (2.2) provide us two tipping points at $e=e_{F_2}=\dfrac{rh}{q}$ and at $e=e_{F_3}=\dfrac{r(K+h)^2}{4qK}$. Within the range (e_{F_2},e_{F_3}), the system exhibits bistability between two stable equilibria (one representing the stable equilibrium state $m=m_1$ and the other representing the state of extinction $m=0$, separated by the unstable equilibrium state $m=m_2$). When the harvesting effort exceeds the threshold $e=e_{F_3}$, the resource biomass suddenly tips to the alternative extinction state.

The strategic composition of the population can reshape the prevailing environmental landscape, which, in turn, reconfigures the underlying payoff structures within the game [45, 49]. We assume that individuals opt for one of two strategies that differ in the level of effort they put into harvesting. We consider x as the fraction of the population adopting the low-effort strategy, reflecting the utilization of a low effort (e_L) in the process of resource harvesting, while the remaining population employs a more intensive effort, e_H. This realistic scenario can be mathematically represented by the inequality $e_L<e_H$. In the context of harvesting efforts, individuals employing the low-effort and high-effort strategies can be labeled "cooperators" and "defectors", respectively. After incorporating population behaviors, Eqn. (2.1) (with $\psi_i=\psi_2$) modifies into:

$$\frac{dm}{dt}=rm\left(1-\frac{m}{K}\right)-\frac{q(e_Lx+e_H(1-x))m}{h+m}. \tag{2.3}$$

Now, we consider a scenario where all individuals in the population adopt the low-effort harvesting strategy, i.e., when $x=1$. In this case, the resource stock at the stable equilibrium is given by

$$m=a\equiv\frac{1}{2}\left[(K-h)+\sqrt{(K+h)^2-\frac{4qe_LK}{r}}\right], \tag{2.4}$$

and a stands for the maximum sustainable level of the resource m. This optimal outcome motivates us to transform the resource stock m into the state of the environment n employing the linear map: $n=\dfrac{m}{a}$ [3]. Applying this transformation, Eqn. (2.3) is converted into the following equation governing the state of the environment:

$$\frac{dn}{dt}=rn\left(1-\frac{an}{K}\right)-\frac{q(e_Lx+e_H(1-x))n}{h+an}, \tag{2.5}$$

where the normalized environmental state n is confined in the range $[0,1]$, which is forward invariant.

Now, we define a payoff structure for pairwise interactions between these two strategies, where the payoff matrix is environment-dependent [49], as presented in the following equation:

$$\Pi(n)=(1-n)\Pi_0+n\Pi_1=(1-n)\begin{bmatrix}R_0 & S_0\\ T_0 & P_0\end{bmatrix}+n\begin{bmatrix}R_1 & S_1\\ T_1 & P_1\end{bmatrix}. \tag{2.6}$$

The matrices Π_0 and Π_1 represent the payoff structures in depleted $(n=0)$ and replete $(n=1)$ environmental states, respectively. In this context, R and P represent the reward for mutual cooperation and punishment for mutual defection, respectively. S (sucker's payoff) and T (temptation) denote the payoffs for cooperating against defection and defecting against cooperation, respectively. Typically, in a state of depletion, harvesters tend to engage in efforts to restore the environment. Consequently, this inclination leads to payoffs that encourage cooperation or favor a lesser social dilemma. Conversely, in the replete state, there is a potential for the over-exploitation of resources, resulting in payoffs that favor defection or a more pronounced dilemma [1]. Therefore, the first payoff matrix (Π_0) in Eqn. (2.6) entails either no dilemma or a milder dilemma compared to the second one (Π_1).

In order to reduce the parameter count in the payoff matrices, we make use of a commonly employed parametrization [1] in terms of greed D_g $(=T-R)$ and fear D_r $(=P-S)$. Without loss of generality, we can assume $R=1$ and $P=0$. This normalization establishes the advantage of mutual cooperation over mutual defection as unity across all game scenarios [38]. This leads to $T=1+D_g$ and $S=-D_r$, where $-1<D_g, D_r<1$. Applying these, Eqn. (2.6) can be rewritten as:

$$\Pi(n)=(1-n)\begin{bmatrix}1 & -D_{r_0}\\ 1+D_{g_0} & 0\end{bmatrix}+n\begin{bmatrix}1 & -D_{r_1}\\ 1+D_{g_1} & 0\end{bmatrix}. \tag{2.7}$$

Depending on the ranges of D_r and D_g, four different game scenarios are possible: the Trivial game, Chicken game, Stag-hunt game, and Prisoner's dilemma (for details, see Fig. 1(e)). Additionally, variations in the intensity of social dilemmas at different environmental states allow us to consider six distinct game combinations between Π_0 and Π_1.

The average payoffs associated with implementing strategies of low or high effort can be expressed in terms of greed D_g and fear D_r as follows:

$$\left.\begin{aligned}\pi_L(x,n) &= x-(1-x)\left[(1-n)D_{r_0}+nD_{r_1}\right],\\ \pi_H(x,n) &= x\left[1+(1-n)D_{g_0}+nD_{g_1}\right].\end{aligned}\right\} \tag{2.8}$$

The notion of greed and fear associated with the game can be interpreted through the lens of the incentive to either follow or lead strategy changes, whether in a depleted or a replete environmental state as [46]:

$$\begin{aligned}\Delta_L^1 &= \pi_H(1,1)-\pi_L(1,1)=D_{g_1},\\ \Delta_H^1 &= \pi_H(0,1)-\pi_L(0,1)=D_{r_1},\\ \delta_L^0 &= \pi_L(1,0)-\pi_H(1,0)=-D_{g_0},\\ \delta_H^0 &= \pi_L(0,0)-\pi_H(0,0)=-D_{r_0}.\end{aligned}$$

Here, Δ_L^1 measures the incentive to be the first to adopt the high-effort strategy in the replete environment. It is like starting a gold rush, reaping the initial benefits before others catch on and the resource dwindles. By contrast, Δ_H^1 represents the incentive of joining an existing rush. The parameter δ_H^0 represents the incentive to be the pioneer in adopting the low-effort approach in the depleted environment. It is like starting an environmental movement, reducing the impact even when others have not. Finally, δ_L^0 captures the incentive to join an existing movement.

To curb over-exploitation of the resource, we implement a centrally organized system for inspection and penalties, a strategy often applied in real-world resource management systems [12, 16, 31]. Specifically, we assume that defection is detected with a probability p. If an individual is identified for employing the high-effort approach, they will incur a fine β (>0), which will be deducted from their accumulated payoffs. In this context, the parameter p signifies the efficacy of the monitoring, while β encapsulates the severity of the punishment. In practical terms, the authority's response in terms of punishment intensifies as the environmental state deteriorates. With this consideration, the payoff matrix takes the following form:

$$\widehat{\Pi}(n)=(1-n)\begin{bmatrix}1 & -D_{r_0}\\ 1+D_{g_0}-p\beta_0 & -p\beta_0\end{bmatrix}+n\begin{bmatrix}1 & -D_{r_1}\\ 1+D_{g_1}-p\beta_1 & -p\beta_1\end{bmatrix}, \tag{2.9}$$

where β_0 and β_1 represent the penalties corresponding to depleted and replete environmental states, respectively ($\beta_0>\beta_1$).

Integrating potential inspection and punitive measures into the evolutionary process results in a modification of the average payoffs (2.8), as expressed below

$$\begin{aligned}\widehat{\pi}_L(x,n) &= x-(1-x)\left[(1-n)D_{r_0}+nD_{r_1}\right],\\ \widehat{\pi}_H(x,n) &= x\left[1+(1-n)D_{g_0}+nD_{g_1}\right]-p\left[(1-n)\beta_0+n\beta_1\right].\end{aligned} \tag{2.10}$$

With the above considerations, the governing equations of the coupled human-environment system with punishment are given by:

$$\begin{aligned}\frac{dx}{dt} &= x(1-x)(\widehat{\pi}_L(x,n) - \widehat{\pi}_H(x,n)),\\ \frac{dn}{dt} &= rn\left(1-\frac{an}{K}\right) - \frac{q(e_L x + e_H(1-x))n}{h+an}.\end{aligned} \tag{2.11}$$

Fig. 1(d) provides a schematic representation of this dynamical system. The coupled system (2.11) possesses the below six feasible equilibria $E_i = (x, n)$; $i = 0, \ldots, 5$:

(i) The depleted environmental state $E_0 = (0, 0)$, which supports the high-effort strategy only.

(ii) The depleted environmental state $E_1 = (1, 0)$, which supports the low-effort strategy only.

(iii) The replete environmental state $E_2 = (1, 1)$, which supports the low-effort strategy only.

(iv) An intermediate environmental state $E_3 = (0, \widehat{n})$, which supports the high-effort strategy only. The state of the environment $\widehat{n}$ is given by:

$$\widehat{n} = \frac{1}{2a}\left[(K-h) + \sqrt{(K+h)^2 - \frac{4qe_H K}{r}}\right].$$

The feasibility of this equilibrium requires that $e_H < e_{F_3}$.

(v) The depleted environmental state $E_4 = (\overline{x}, 0)$, which supports the coexistence of both strategies in the population. Here, the frequency of cooperators is given by $\overline{x} = \dfrac{D_{r_0} - p\beta_0}{D_{r_0} - D_{g_0}}$. The equilibrium E_4 is feasible if $D_{r_0} < p\beta_0 < D_{g_0}$ or $D_{r_0} > p\beta_0 > D_{g_0}$. The equilibrium $(\overline{x}, 0)$ represents a scenario in which the long-term coexistence of both strategies results in the complete exploitation of the environment.

(vi) An intermediate environmental state $E_5 = (x^*, n^*)$, which also supports the coexistence of both strategies. The frequency of cooperators is given by:

$$x^* = \frac{1}{e_H - e_L}\left[e_H - \frac{r}{q}(h + an^*)\left(1 - \frac{an^*}{K}\right)\right] \equiv f(n^*),$$

where the environmental state n^* is the positive solution of the following equation:

$$\widehat{\pi}_L(f(n), n) - \widehat{\pi}_H(f(n), n) = 0.$$

With variations in the combination of games (i.e., the choice of the payoff matrices Π_0 and Π_1) and the effort level e, there will be dissimilarity in the existence, cessation, and creation of these equilibrium points. This paper offers a detailed analysis of these variations, exploring how different configurations affect the evolutionary outcomes of the coupled system (2.11). For a detailed analysis, please refer to the *SI Appendix*, Section 1.

3. Results

(a) Increased harvesting effort with different game combinations has variable effects on environmental tipping points

Unrestricted harvesting efforts, without strategic interactions, can result in catastrophic ecological collapse. This raises an important concern: What happens when players adjust their levels of effort within a game-theoretic framework? Does this adjustment influence the players' strategy profile, ultimately impacting the environmental state? While prior research on feedback-evolving games primarily focused on scenarios where players maintain a constant level of effort while harvesting resources [46], this study aims to address this question by investigating how variations in the effort levels of harvesters affect the tipping point for ecological collapse across different game scenarios. To achieve this, we hold the cooperators' effort level (e_L) constant while varying the effort level of defectors (e_H). Notably, the replete environmental state ($n=1$) can foster a more competitive game compared to the depleted state ($n=0$). We explore the evolutionary outcomes of the coupled system (2.11) by considering six distinct game combinations, i.e., SH and PD, TR and SH, TR and PD, CH and PD, TR and CH, and CH and SH (for abbreviations, see the Fig. 1 caption), which capture the *variations in dilemmas* that arise in these two contrasting states.

Combination of SH and PD: The prisoner's dilemma (PD) illustrates the temptation for individuals to prioritize short-term gains by defecting and exploiting the environment despite the potential long-term consequences. In contrast, the stag-hunt (SH) game highlights the importance of coordination among individuals to achieve a higher payoff through cooperation and sustainable practices rather than continuing to exploit the environment. Notably, the PD captures a more pronounced social dilemma compared to the SH game. Motivated by this, we investigate the dynamic behavior of the coupled system (2.11), where pairwise interactions between harvesters in depleted and replete environmental states can be modeled by the SH and PD games, respectively.

In the SH and PD game combination, there is no incentive to switch to the low-effort strategy in the depleted environmental state, given that all other participants adhere to defect ($\delta_H^0 < 0$). Consequently, the depleted environmental state remains consistently stable, provided the harvesting effort of defectors (e_H) exceeds the tipping threshold $e_{F_2} = 0.25$ (Fig. 2(a)). With further increase in e_H, upon reaching the threshold $e_{F_3} = 0.525$, there is a sudden transition to extinction in the environment state (n). Therefore, within the bistability region $e_H \in (e_{F_2}, e_{F_3})$, the environment may either settle into a depleted state or an intermediate state. Consequently, within this range, the resource dynamics resemble those of the uncoupled system, where an intensified harvesting pressure triggers tipping. For this game combination, we observe that the high-effort strategy may prevail throughout the entire population across all effort levels, depending on initial conditions.

When harvesting effort surpasses the threshold $e_H = 0.338$, a shift occurs, but the resulting positive environmental state is unstable. At $e_H = 0.846$, a Hopf bifurcation stabilizes the coexistence equilibrium. As defectors intensify effort levels, individuals increasingly adopt the low-effort strategy, contributing to environmental improvement, as reflected in the rising environmental equilibrium curve. At $e_H = 0.845$, a pair of coexistence steady states emerge with contrasting stability properties. Advancing to $e_H = 0.857$, another tipping event emerges: the unstable branch of the coexistence steady state collides with the lower equilibrium curve, resulting in their mutual annihilation. Within the narrow range $e_H \in (0.846, 0.857)$, the coupled system demonstrates tri-stability. It entails an attraction towards a population predominantly adopting either the low-effort strategy ($x^* > 0.5$) or the high-effort strategy ($x^* < 0.5$), or alternatively, being composed entirely of the high-effort strategy. Consequently, the environment may settle into a high or low intermediate state or undergo complete depletion depending upon the initial condition. As defectors dedicate more effort to harvesting, the degree of dominance of the low-effort strategy initially surges before plateauing. That results in a positive correlation between the environmental state and the harvesting effort of defectors. Overall, this game combination unveils the possibility of environmental recovery from depletion. While increased efforts by defectors initially exacerbate environmental degradation, and some moderate effort levels result in total collapse, high exploitation efforts can trigger environmental restoration. This happens due to an increase in the frequency of cooperators (see the upper panel of Fig. 2(a)).

Combination of TR and SH: Now, we investigate the dynamic behavior of the coupled system (2.11) where trivial and stag-hunt games represent decision-making frameworks in depleted and replete environmental states, respectively (Fig. 2(b)). For any harvesting effort e_H, individuals are incentivized to lead the environmental movement, further inducing instability in the equilibrium state $(0,0)$. This implies that complete resource extinction, resulting from the high-effort strategy only, is unlikely. Furthermore, in the replete state, the lack of incentive to adopt the high-effort strategy when others cooperate ensures the stability of the desired state $(1,1)$.

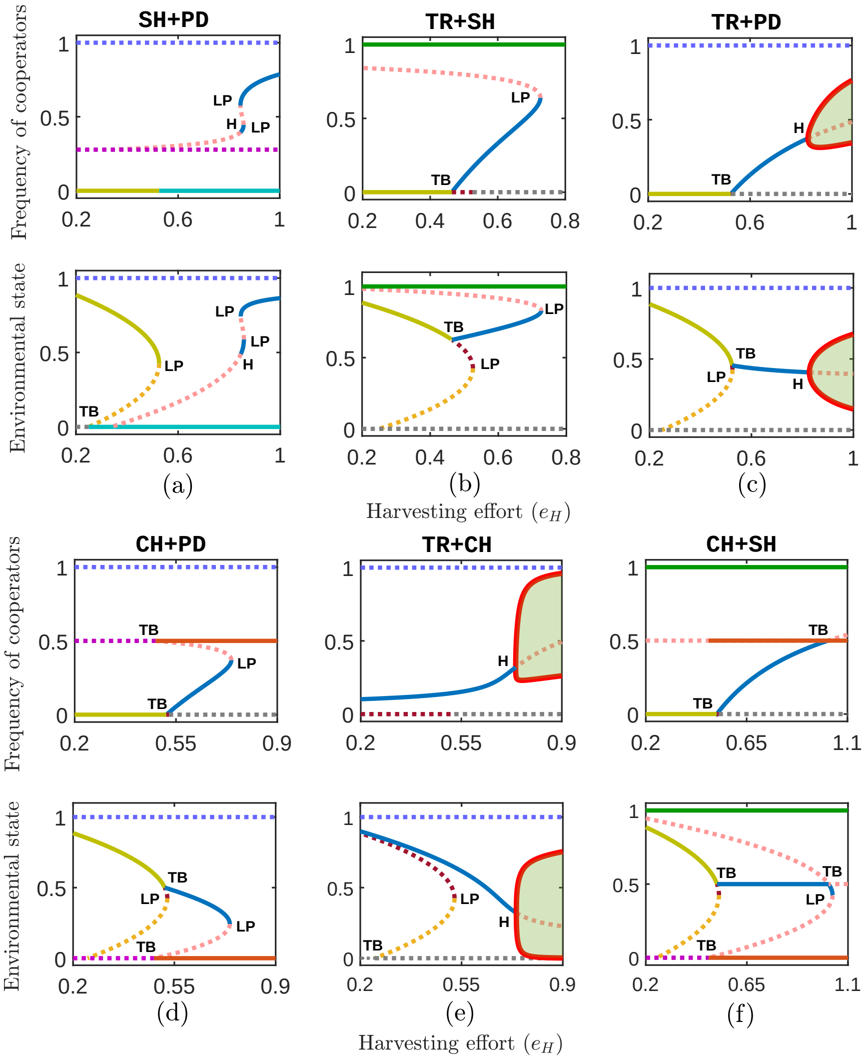

Figure 2. Without monitoring system ($p=0$), dynamics of stationary states of x (frequency of operators) and n (environmental state) with variations in e_H for all possible game combinations. Parameter values are: $r=0.25$, $K=5$, $q=0.8$, $e_L=0.02$, and $h=0.8$. Payoff matrix parameters are (a) $D_{g_0}=-0.13$, $D_{r_0}=0.05$, $D_{g_1}=0.01$, $D_{r_1}=0.03$; (b) $D_{g_0}=-0.12$, $D_{r_0}=-0.2$, $D_{g_1}=-0.02$, $D_{r_1}=0.12$; (c) $D_{g_0}=-0.12$, $D_{r_0}=-0.1$, $D_{g_1}=0.22$, $D_{r_1}=0.12$; (d) $D_{g_0}=0.2$, $D_{r_0}=-0.2$, $D_{g_1}=0.1$, $D_{r_1}=0.2$; (e) $D_{g_0}=-0.08$, $D_{r_0}=-0.05$, $D_{g_1}=0.5$, $D_{r_1}=-0.05$; and (f) $D_{g_0}=0.2$, $D_{r_0}=-0.2$, $D_{g_1}=-0.2$, $D_{r_1}=0.2$. Stable and unstable equilibria are marked with solid and dashed curves, respectively. Coexistence equilibrium $E^*=(x^*,n^*)$: Blue (stable) and dashed pink (unstable) curves; $E_1=(1,1)$: Green (stable) and dashed blue (unstable) curves; $E_0=(0,0)$: Cyan (stable) and dashed black (unstable) curves; $\widehat{E}=(0,\widehat{n})$: Light green (upper stable), dashed yellow (lower unstable), and dashed maroon (upper unstable) curves; $\overline{E}=(\overline{x},0)$: Red (stable) and dashed magenta (unstable) curves. The system (2.11) undergoes various bifurcations marked as LP: Saddle-node, TB: Transcritical, and H: Hopf. In (a), the system exhibits bistability between depleted and intermediate states. In (b) and (d), it undergoes tipping, transitioning to replete and depleted states, respectively. In (c) and (e), the system experiences instability and exhibits oscillatory dynamics. In (f), the environment tips either to a depleted or replete state, depending upon initial conditions.

Specifically, when $e_H < 0.464$, population behavior becomes polarized: it is either a unanimous adoption of the low-effort strategy or the high-effort strategy (upper panel of Fig. 2(b)). Consequently, the environment stabilizes in either the replete state or an intermediate state. In the parameter window, $e_H \in (e_L, 0.464)$, elevated harvesting effort by a population composed entirely of defectors results in a decline in the equilibrium state of the environment (lower panel of Fig. 2(b)). As the effort exceeds the threshold $e_H = 0.464$, the relative degradation of the intermediate environmental state from its replete state, i.e., the quantity $\left(\dfrac{1-\widehat{n}}{\widehat{n}}\right)$ exceeds the incentive ratio for gold rush participation versus environmental leadership. This leads to a significant change in population behavior through the emergence of a transcritical bifurcation: a fraction of the population embraces the low-effort strategy. The frequency of cooperators rises with increased effort, subsequently contributing to environmental enrichment. This trend ceases at the threshold $e_H = 0.726$, where the stable equilibrium branch, characterizing the progression of the environmental state in the presence of both strategies, collides with the unstable branch of the coexistence equilibrium through a saddle-node bifurcation. For $e_H > 0.726$, every individual adopts the low-effort strategy (i.e., $x = 1$) irrespective of any initial conditions. Consequently, the environment settles into the desired replete state. Therefore, mirroring the combination of the SH and PD scenario, defector effort initially contributes to environmental degradation. Yet, exceeding a threshold flips the effect: effort fosters cooperation and enriches the environment. Notably, high effort induces a tipping point, leading to a sudden environmental improvement towards the replete state.

Combination of TR and PD: Replacing the stag-hunt game with the prisoner's dilemma as a decision-making framework in the replete state alters the dynamical behavior of the coupled system (2.11). Analogous to the previous case, increased effort triggers a transcritical bifurcation at $e_H = 0.524$, paving the way for the low-effort strategy (upper panel of Fig. 2(c)). While the frequency of cooperators increases with rising e_H, it fails to enrich the environment as expected (lower panel of Fig. 2(c)). When reaching the threshold $e_H = 0.827$, the stability of the coexistence equilibrium is disrupted via a Hopf bifurcation, resulting in the manifestation of oscillatory dynamics. This prompts the emergence of cyclic behavior between low and high-effort strategies. Such behavior highlights the notion that a guaranteed winner is elusive in the long run. Instead, one strategy may prevail over the other within a specific time frame, only to be surpassed by the other in a different time window. Therefore, in this game scenario, despite the environment continually deteriorating as effort level increases, it can be prevented from tipping into complete collapse. However, with a high level of effort, the emergence of cyclic dynamics showcases the complexities of achieving long-term sustainability.

Combination of CH and PD: In this case, we observe that at the threshold $e_H = 0.517$, cooperators begin to emerge via a transcritical bifurcation (upper panel of Fig. 2(d)). Similar to the previous game combination, as defectors increase their efforts, the frequency of cooperators also rises, but the heightened harvesting pressure leads to a continuous degradation of the environmental state. At $e_H = 0.741$, the population behavior undergoes a sudden transition (lower panel of Fig. 2(d)). Both strategists coexist with equal frequency ($\overline{x} = 0.5$), accompanied by an abrupt environmental collapse. Therefore, this game combination demonstrates the possibility of shifting the tipping point, which arises from a counterintuitive feedback loop: defectors' actions inadvertently foster cooperation, allowing the resource to withstand a greater degree of exploitation.

Combination of TR and CH: The CH game in the replete state presents a scenario where individuals are incentivized to either initiate an environmental movement or lead a gold rush. but simply joining an existing gold rush is not. These ensure the instability of equilibria $(0,0)$, $(1,1)$, and $(0,\widehat{n})$ (Fig. 2(e)). Therefore, at any effort level e_H, this game combination does not allow a stable environmental state – whether depleted, replete, or intermediate – through a single strategy. What is intriguing is the sustained coexistence of both strategies, resulting in the existence of a stable positive environmental state. Similar to the preceding game scenarios, the frequency of cooperators increases with increasing e_H. Further, the increase in e_H results in the destabilization of the coexistence equilibrium E_5 at $e_H = 0.739$ via a Hopf bifurcation. The co-evolutionary system undergoes persistent oscillations in both strategies and the environmental state. While total environmental collapse can be prevented, the environment continues to fluctuate between extinction and intermediate states, driven by cyclic dominance between strategies (Fig. 3(a,b)). This illustrates the oscillatory tragedy of the commons under intensified harvesting pressure. Unlike the combination of TR and PD, where a single strategy might dominate the population at moderate effort levels from defectors, the introduction of the CH game in the replete state drives players to adopt a coexisting strategy, irrespective of the effort level.

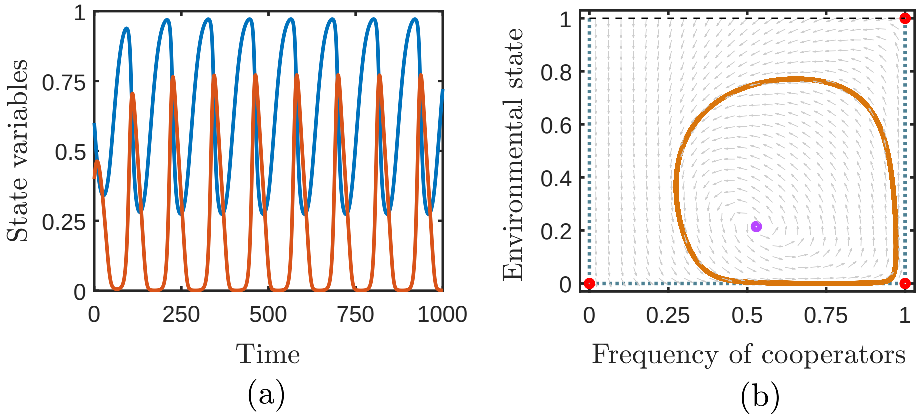

Figure 3. (a) Oscillatory behaviors of both strategies and the environment. In the combination of TR and CH, time evolutions of the frequency of the low-effort strategy (blue) and the environmental state (red) with the harvesting effort $e_H = 0.95$. (b) Phase plane dynamics of the coupled system (2.11). Red-filled circles represent unstable equilibria; the orange closed trajectory captures the limit cycle around the unstable coexistence equilibrium (violet-filled circle). The arrows represent the direction of dynamics with time. The other parameters are same as in Fig. 2(e)

Combination of CH and SH: Playing the SH game at the replete state offers no incentive to spearhead the gold rush. This helps to maintain the stability of the desired state $(1, 1)$, regardless of the effort exerted by defectors (Fig. 2(f)). The intermediate environmental state, characterized by coexisting strategies, emerges via a transcritical bifurcation at $e_H = 0.517$. At $e_H = 0.48$, an additional unstable coexistence equilibrium emerges as the equilibrium $(\overline{x}, 0)$ undergoes stability restoration. Notably, the unstable branch of the coexistence equilibrium meets the stable equilibrium at the threshold $e_H = 1.014$, triggering a swap in their stability through another transcritical bifurcation. At $e_H = 1.016$, two branches of the coexistence equilibrium collide and disappear, eliminating the possibility of an intermediate environmental state. Overall, in the context of the CH game scenario at the depleted state, switching from the PD to the SH game at the replete state also results in a similar phenomenon of shifting the environmental tipping point toward complete collapse. However, the key distinction is that, depending on initial conditions, there remains always a possibility for the environment to recover to the replete state.

The *SI Appendix*, Section 2.1 presents time evolution results for system (2.11), illustrating the impact of varying effort levels of defectors on tipping points across different game structures. Also, the impact of e_H on environmental tipping points and the potential emergence of the tragedy of the commons (TOC) are summarized in Table 1. We would like to bring it to the fore that although IC-TOC (Initial condition dependent TOC) and O-TOC (Oscillatory TOC) have apparent negative connotations, they can actually be interpreted positively for resource sustainability. The former evades TOC ($n = 0$) for a finite measure of initial conditions, while the latter evades TOC for a finite fraction of the oscillation time period.

Table 1: Without system monitoring ($p=0$), outcomes of the coupled human-environment system (2.11) for different game combinations with increasing defector harvesting effort e_H, where IC-TOC: Initial condition dependent TOC, and O-TOC: Oscillatory TOC.

Game combination		Effect of e_H on tipping	Effect of e_H on TOC
At $n=0$	At $n=1$		
SH	PD	Eluded	IC-TOC
TR	SH	Eluded	No TOC
TR	PD	Eluded	No TOC
CH	PD	Shifted	IC-TOC
TR	CH	Eluded	O-TOC
CH	SH	Shifted	IC-TOC

(b) Eco-evolutionary dynamics for different incentive structures

In the combination of the CH and PD games, we observe that the emergence of the tipping point characterizing complete resource collapse is shifted, though it cannot be completely prevented (Fig. 2(d)). We consider this specific game combination to investigate how incentives for behavioral change influence the occurrence of this delayed collapse. In particular, we investigate how variations in the incentive of joining an existing gold rush (Δ_H^1) and that to lead an environmental movement (δ_H^0) shape the evolutionary outcomes of the coupled system (2.11). The introduction of PD at the replete state ($n=1$) leads to a strictly dominant strategy of defection, resulting in over-harvesting and depletion of the abundant resource. On the other hand, the invocation of the CH game at the depleted state ($n=0$) leads to a mixed strategy of cooperation and defection. This, in turn, fosters more sustainable harvesting practices.

We observe that the frequencies of the strategies at the stable equilibrium $(\overline{x}, 0)$ remain unaffected despite the lure of the gold rush (Δ_H^1) (Fig. 4(a)). With a low incentive to follow the gold rush, both strategies coexist in a positive environmental state. However, as the motivation to follow the high-effort approach at the replete state increases, both the frequency of cooperators and the environmental states show a declining trend. At the threshold $\Delta_H^1=0.284$, the stability of the coexisting equilibrium is disrupted, leading to a phase of oscillatory coexistence. These cycles rapidly increase in amplitude until they encounter an unstable coexistence state. The cyclical behavior then vanishes abruptly through a homoclinic bifurcation. A further increase in incentive level triggers a fold bifurcation, causing the branches of the coexisting equilibria to disappear abruptly, leading to monostability at the depleted state. Therefore, under the same incentive level Δ_H^1, the environment either settles into the depleted state or an intermediate state, depending upon initial conditions. Additionally, in the intermediate environmental state, the incentive level determines the population behavior: it can either settle into a fixed cooperation level or oscillate between two different levels of cooperation.

When the incentive to lead an environmental movement (δ_H^0) is low, the environment remains in the depleted state (Fig. 4(b)). As the incentive increases, cooperators become dominant. In the range $\delta_H^0 \in (0.1521, 0.1527)$, the system exhibits bistability between the depleted state and periodic cycles. A further incentive hike causes the cycles to disappear at $\delta_H^0=0.1527$ through a Hopf bifurcation. For $\delta_H^0 \in (0.1527, 0.304)$, another bistability zone emerges between depleted and positive steady states. At $\delta_H^0=0.304$, the depleted state loses stability through a transcritical bifurcation, leaving the system monostable at an intermediate state. Therefore, high incentives for environmental leadership ensure recovery to a positive state, irrespective of initial conditions. This highlights the contrasting effects of incentives for environmental leadership and participation in gold rush activities on environmental improvements.

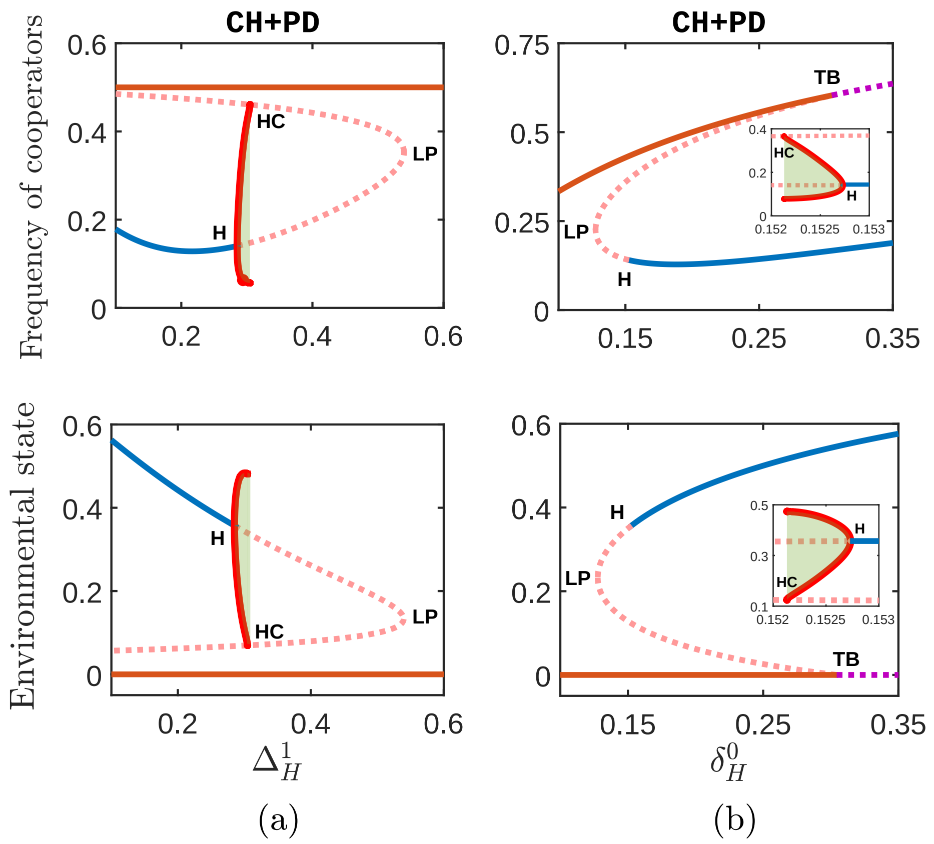

Figure 4. Possible evolutionary outcomes of the coupled system (2.11) with respect to hikes in the incentive level (a) Δ_H^1 and (b) δ_H^0 for defector harvesting effort $e_H = 0.6$. The other parameters are the same as in Fig. 2(d). In (a), periodic oscillations produced due to the loss of equilibrium stability die out through a homoclinic bifurcation (HC). At high incentive levels, the environment collapses, with both harvesting strategies coexisting at equal frequencies. (b) Increasing the incentive level δ_H^0 leads to a sudden and significant improvement in the environmental state.

The emergence of bistable dynamics between depleted and oscillatory environments for variations in the levels of incentives is illustrated through time-series solutions of the coupled system (Fig. 5). For example, when the incentive to follow the gold rush is fixed at $\Delta_H^1 = 0.3$, an initial condition of $(0.6, 0.15)$ leads to complete environmental collapse in the presence of both strategies. In contrast, when the initial frequency of cooperators reduces to half of its previous value (setting the initial condition to $(0.3, 0.15)$), the environmental state remains positive over time. However, it continues to exhibit an oscillatory pattern in conjunction with the strategies (Fig. 5(a)).

A similar phenomenon of bistable dynamics is also captured when the incentive to lead the environmental movement is fixed at $\delta_H^0 = 0.1525$. However, a notable distinction from the previous incentive structure is the pattern of periodic cycles. Here, the peak of a typical oscillatory pattern alternates among four distinct values over time, demonstrating a 4-cycle periodic solution within a coupled human-environment system (Fig. 5(b)).

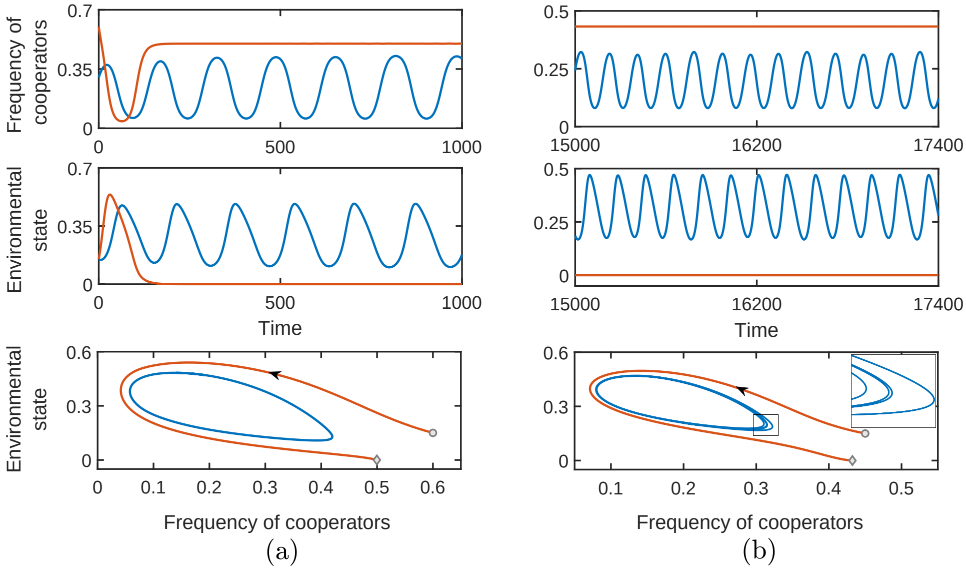

Figure 5. Time evolutions of the coupled system for the CH and PD game combination. The incentives are set as (a) $\Delta_H^1 = 0.3$, and (b) $\delta_H^0 = 0.1525$. The other parameters are the same as in Fig. 4. Variations in the initial population opinion and environmental state influence the evolutionary outcomes of the coupled system. Panel (a) illustrates periodic oscillations in both strategies and the environment, while (b) reveals a 4-cycle periodic solution. Initial conditions and equilibrium positions are marked with gray circles and diamond shapes, respectively.

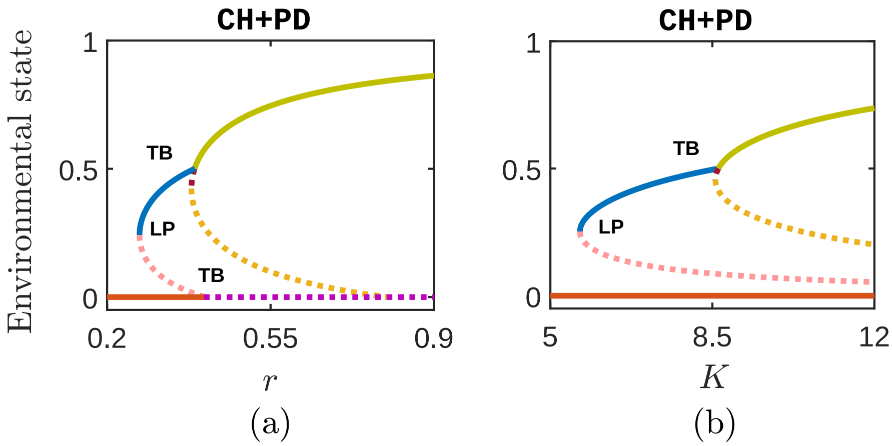

Figure 6. For varying intrinsic resource growth rate (r) and carrying capacity (K), evolutionary outcomes of the environmental state correspond to the CH and PD game combination under a punishment-free scenario. The other parameters are the same as in Fig. 2(d) with $e_H = 0.8$. An increase in both parameters leads to the sudden emergence of an intermediate environmental state, followed by significant improvement. While varying growth rate transitions the system from bistability to monostability, varying carrying capacity maintains the dependence of evolutionary outcomes on initial conditions.

(c) Resource growth rate and carrying capacity can affect evolutionary outcomes of the coupled system

The interplay between resource growth rate (r) and harvesting strategies strongly determines the evolutionary outcomes of the coupled system (2.11). When the resource growth rate is low

($r < 0.2694$), the environment struggles to sustain itself in the long run under intense harvesting pressures from both strategists (Fig. 6(a)). At $r = 0.2694$, the environment experiences a sudden recovery, transitioning to a positive state. As the resource grows at a faster rate, more individuals adopt the high-effort approach, yet rapid growth contributes to environmental improvement. At the threshold, $r = 0.3857$, evolution reaches a state of full defection. In the parameter window $r \in (0.2694, 0.4097)$, the system exhibits bistability, in which, depending upon the initial strategy profile and the prevailing environmental conditions, it could either tip towards complete resource depletion or stabilize at an intermediate level. Overall, the environmental state exhibits a positive trend, even without any external monitoring.

With a fixed resource growth rate, we observe a nearly identical phenomenon of sudden resource enhancement and subsequent environmental progress as the carrying capacity increases (Fig. 6(b)). However, unlike the previous scenario, the stability of the depleted state (represented by the equilibrium $(\overline{x}, 0)$) remains unaffected by changes in carrying capacity. This suggests that while an increased carrying capacity can enhance the environmental state, there remains an inherent risk of complete depletion, even under identical environmental conditions and game rules. This highlights a potential limitation to the benefits of nutrient enrichment in the context of strategy-environment interactions.

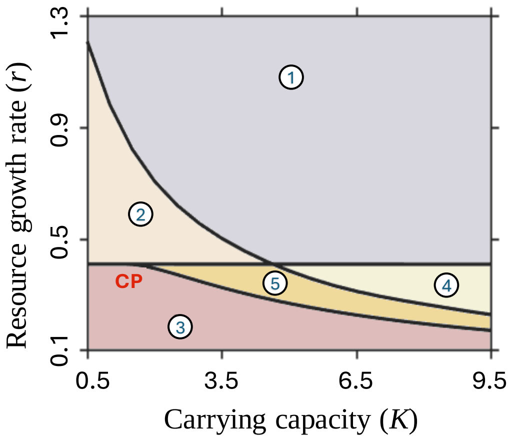

Figure 7. Diverse dynamics of the human-environment system with variations in the parameters r and K. Stability regions include: monostability at $E_3(0, \widehat{n})$ (region 1), $E_4(\overline{x}, 0)$ (region 3), and $E_5(x^*, n^*)$ (region 2); bistability between E_3 and E_4 (region 4), and between E_4 and E_5 (region 5). CP: Cusp point. The other parameters are the same as in Fig. 6.

To better understand the combined effects of resource growth rate and carrying capacity on the evolutionary dynamics of the coupled system, we construct a two-parameter bifurcation diagram in the $r - K$ plane (Fig. 7). We observe that when the carrying capacity is low, the environment transitions smoothly to a positive state as the resource growth rate increases, driven by a transcritical bifurcation. However, once K exceeds a certain threshold, increasing r leads to a tipping point that triggers abrupt environmental recovery. The saddle-node curve and transcritical bifurcation curve intersect at the cusp point at coordinates $(r, K) = (0.4097, 1.379)$. For any level of K, the high-effort strategy alone drives the environment to a monostable positive state as r increases. The r- threshold for this transition decreases with higher K. Notably, when the resource grows at a very low or very high rate, variations in carrying capacity do not affect the qualitative behavior of the coupled system. Within a specific intermediate range of r, an increase in K can shift population opinion towards the high-effort strategy exclusively, moving the system from a state of coexistence to a positive environmental state dominated by the high-effort strategy. For high values of K, within a specific range of r, the coupled system exhibits two types of bistable dynamics: bistability between the coexistence equilibrium (x^*, n^*) and the depleted state $(\overline{x}, 0)$, both with coexisting strategies, and bistability between $(\overline{x},0)$ and the positive state $(0,\widehat{n})$, which supports the high-effort strategy only.

(d) Monitoring defectors can mitigate environmental collapse

Until now, we have studied the coupled model (2.11) without considering monitoring and enforcement (i.e., $p=0$). However, catching defectors and imposing fines are crucial components of sustainable policies that can significantly alter the qualitative behavior of the model. The severity of punishment can create a more pronounced dilemma in the depleted state compared to the replete state, especially with strong monitoring. This is because the potential negative consequences of defection become more prominent, potentially outweighing the initial temptation to defect. In this context, we explore how inclusion and variation of monitoring efficacy (p) affect defection and influence the evolutionary outcomes of the coupled system across various game combinations.

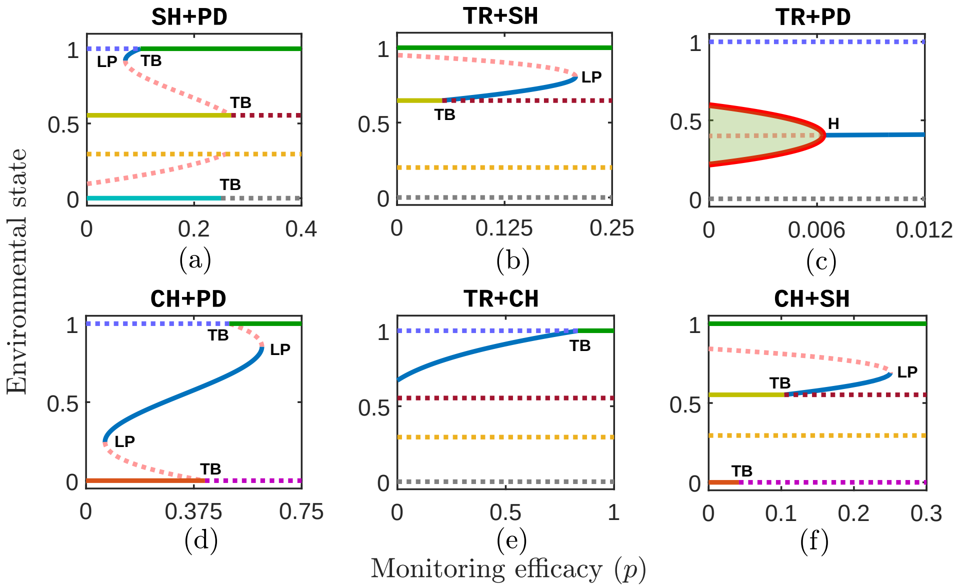

Figure 8. Governance of the monitoring efficacy p on the evolutionary dynamics of the environmental state for different game combinations. We consider (a) $e_H=0.5$, $\beta_0=0.2$, $\beta_1=0.1$; (b) $e_H=0.45$, $\beta_0=0.2$, $\beta_1=0.1$; (c) $e_H=0.9$, $\beta_0=\beta_1=0.2$; (d) $e_H=0.8$, $\beta_0=\beta_1=0.2$; (e) $e_H=0.5$, $\beta_0=\beta_1=0.6$; (f) $e_H=0.5$, $\beta_0=0.2$, $\beta_1=0.1$, and the other parameters are same as in Fig. 2. In all scenarios, an improvement in system monitoring contributes to environmental enrichment. However, the mode of transition to the desired replete state varies: In (a) and (e), the environment undergoes smooth transitions to the replete state, while in (b), (d), and (f), it is non-smooth. High monitoring efficacy can also mitigate system instability caused by intense efforts, as seen in (c).

Combination of SH and PD: In the absence of any governing mechanisms ($p=0$), we first consider the stag-hunt game and prisoner's dilemma as decision-making frameworks in depleted and replete environmental states, respectively. We observe that, without monitoring, if defectors invest 25 times more effort in harvesting compared to cooperators ($e_L=0.02$, $e_H=0.5$), the entire population ends up adopting the high-effort strategy (Fig. 8(a)). However, the environmental outcome depends on initial conditions: inadequate resources lead to extinction, while high initial resource biomass enables a shift to a sustainable equilibrium, preventing depletion. This bistability persists until monitoring efficacy (p) exceeds 0.072. Beyond this threshold, population behavior changes significantly, with many individuals favoring the low-effort strategy over the high-effort one.

As the monitoring system improves, more individuals opt for the low-effort strategy due to the reduced average payoff for defection. When $p \in (0.072, 0.098)$, the system exhibits tristability, where both strategies can coexist, or everyone chooses the high-effort strategy. At $p = 0.098$, there is a collective shift towards the low-effort strategy, resulting in a non-critical transition of the environment to the replete state. In the range $p \in (0.098, 0.23)$, tristability re-emerges, with outcomes ranging from sustainable cooperation to high-effort exploitation, which may lead to resource depletion or stabilization at some sustainable level.

A subsequent increase in the monitoring efficacy results in the destabilization of the equilibria $(0, \widehat{n})$ and $(0, 0)$ via transcritical bifurcations at the thresholds $p = 0.23$ and $p = 0.25$, respectively. In the narrow window $(0.23, 0.25)$, the system exhibits bistability between the depleted and replete environmental states. Beyond the threshold $p = 0.25$, each individual embraces the low-effort strategy, resulting in the environment settling into the replete state, irrespective of the initial population opinions and environmental conditions (For a detailed assessment of system resilience under varying monitoring efficacy, please refer to the *SI Appendix*, Section 2.2).

Combination of TR and SH: When TR and SH games align with depleted and replete states, the replete state remains consistently stable regardless of the efficacy level of system monitoring (Fig. 8(b)). However, below $p = 0.058$, the system's transition to the desired state depends on initial conditions, leading to possible bistability where the collective high-effort strategy may stabilize the environment at an intermediate level. At $p = 0.058$, destabilization of the "all defector" scenario allows both strategies to coexist. Further increase in efficacy level triggers an abrupt shift in the collective opinion of the population, transitioning from a co-existing strategy to the low-effort strategy only. Beyond $p = 0.208$, each individual embraces the low-effort strategy, irrespective of their initial choices or the prevailing environmental conditions. This unified shift leads to the environment settling into the desired prosperous state $n = 1$.

Combination of TR and PD: In this game combination, without any governing mechanism, strategic dominance oscillates in a fluctuating environment (Fig. 8(c)). Introducing a monitoring system dampens these oscillations, and at $p = 0.006$, a Hopf bifurcation occurs. At this efficacy level, the instability caused by excessive harvesting efforts wipes out, allowing the environment to settle into a sustainable equilibrium point.

Combination of CH and PD: In the context of CH and PD game combination, in the presence of both strategies, heavy exploitation by defectors results in complete environmental depletion (Fig. 8(d)). However, with active monitoring, the environment can experience an abrupt recovery at the point $p = 0.065$. The system experiences another tipping event at the monitoring effectiveness of 61.4%. Beyond this threshold, evolution reaches a full state of cooperation, and the environment settles into the replete state irrespective of any initial conditions.

Combination of TR and CH: Now, let us consider a situation where, amidst a backdrop of weak governance, the environment settles into an intermediate state (Fig. 8(e)). Enhancing monitoring leads to an improved environment, with a growing majority adopting the low-effort strategy. However, at the monitoring effectiveness of 83%, the environment undergoes a transcritical bifurcation, leading to a smooth transition to the replete state.

Combination of CH and SH: Similar to the combination of TR and SH games, the environment undergoes a sudden transition to the replete state from an intermediate state with growing monitoring efficacy. However, unlike the TR and SH game structure, there is a risk of complete environmental depletion at low monitoring levels, even with both strategies present (see Fig. 8(f)).

Overall, these results highlight that, across all possible game combinations considered here (with the exception of the TR and PD combination), adjusting monitoring efficacy encourages each individual to adopt the low-effort exploitation strategy, ultimately leading to the replete environmental state. Notably, achieving this outcome does not require a fully effective monitoring system ($p \approx 1$), and even a lower level of monitoring efficacy can promote sustainability. Therefore, to achieve the replete environment, it is not necessary to detect and penalize every high-effort strategist. The efficacy threshold required to reach the replete state varies depending on the specific game combination, reflecting the different dynamics and challenges each game structure presents in managing collective behavior and resource sustainability. These results are summarized in Table 2.

Table 2: For fixed effort levels (e_L and e_H), outcomes of the coupled human-environment system (2.11) for different game combinations with increasing monitoring efficacy p.

Game combination		TOC without monitoring	Effect of p on tipping	Effect of p on TOC
At $n=0$	At $n=1$			
SH	PD	IC-TOC	Eluded	Eluded
TR	SH	No TOC	Eluded	No TOC
TR	PD	No TOC	No effect	No TOC
CH	PD	TOC	Eluded	Eluded
TR	CH	No TOC	Eluded	No TOC
CH	SH	IC-TOC	Eluded	Eluded

4. Discussion

Intensified exploitation of common resources can lead to degradation and abrupt collapse of many natural systems [29, 41]. This heightens the question of preventing or managing sudden transitions and creating a sustainable ecosystem. Throughout this paper, in the considered uncoupled model of resource dynamics, the resource biomass experiences a catastrophic collapse to an alternative contrasting state in response to increased harvesting pressure. Here, we propose a game-theoretic framework that allows individuals to choose varying levels of effort in their harvesting practices. Within this framework, a dynamic game structure is established, offering a strategic choice between low- and high-effort strategies. Individuals can either maintain their current approach or switch strategies based on incentives, which are directly influenced by resource abundance. By analyzing the feedback-evolving mechanisms between human exploitation strategies and the underlying environment across different environment-dependent payoff structures, we investigate how these interactions influence tipping points and encourage behavioral shifts toward sustainable practices.

We find that, unlike the combination of TR and PD, which presents the greatest disparity between individual self-interest and collective welfare, all other game scenarios exhibit a lack of cooperative behavior when defectors exert moderate efforts. However, increased efforts trigger a shift in population behavior, leading to the emergence of cooperators essential for environmental restoration. In certain exceptions, such as the combination of CH and PD or CH and SH, increased cooperation to counter intense defection can paradoxically worsen environmental conditions compared to less cooperative scenarios. This emphasizes the complex nature of a coupled system, where positive actions can yield unintended consequences. The study reveals that the invocation of SH game at the replete environment can maintain stability in that state, even without system monitoring. However, in the context of the PD or CH game, individuals settling into the replete environment become challenging. In contrast, the TR or CH game consistently yields an unstable environment in the depleted state. This instability arises from the positive incentives that encourage a shift to the low-effort strategy when dealing with a poor environmental state. Furthermore, with low incentives and no monitoring system in place, individuals may eventually adopt the high-effort strategy, leading the environment into a depleted state. This dilemma emerges when SH and PD games, respectively, characterize the game classes associated with the depleted and replete states.

We also show that in games combining TR and CH or TR and PD, intensified efforts from defectors affect the system's stable configuration. While Tilman et al. [46] found that the existence of limit cycles depends critically on the degree of timescale separation between environmental and strategy dynamics, our findings reveal that independent of timescale separation, TR and CH or TR and PD game combination gives rise to cyclic patterns for high harvesting efforts from defectors. Interestingly, in the CH and PD combination, increasing effort significantly shifts the tipping of ecological collapse. However, depending on initial conditions, the CH and SH game combination results in tipping towards either the replete or depleted state. Recently, Sarkar et al. [40] demonstrated that incorporating social norms into fishery management strategies through imitation dynamics could help maintain moderate fish density levels even under intense harvesting pressure. This suggested a potential avenue to mitigate tipping. In the TR and SH or SH and PD scenarios, we observe counterintuitive outcomes where increased efforts from defectors contribute to the improvement of the environmental state. In the former case, the system tips to the replete state at a specific effort threshold, while in the latter, the environment experiences continuous enrichment towards sustainability. Therefore, the invocation of game structures between exploitation strategies potentially affects the tipping point, either by shifting or completely preventing it, depending on the specific payoffs involved. Previously, Bauch et al. [5] investigated an environment prone to catastrophic collapse due to harvesting and found that the risk of these impending tipping events can be alleviated by modulating the intensity of social norms and the costs associated with conservation efforts. Recently, Black et al. [6] conducted an experiment on a microbial ecological community under controlled conditions and revealed that evolution can shift tipping points to higher stress levels, ultimately improving ecological resilience.

The mechanism of detecting high-effort strategists and imposing fines based on environmental conditions [12] can play a crucial role in eluding ecological tipping points. Under conditions of low monitoring efficacy, we find multistable dynamics where the replete environmental state can coexist with depleted or intermediate states, presenting formidable obstacles to effective resource management. As the monitoring efficacy improves, we identify transitions in population opinions, with outcomes ranging from catastrophic to non-catastrophic, contingent upon the specific game scenarios. The transition from a mixed strategy to a low-effort dominance, influenced by monitoring efficacy thresholds, demonstrates that heightened monitoring effectiveness steers the coupled system away from the multistability, directing it towards the desired prosperous state. In the case of the TR and PD combination, the emergence of Hopf bifurcation in terms of monitoring efficacy marks a significant transition wherein the destabilizing influence of unregulated dynamics is subdued, allowing for the establishment of a balanced and enduring environmental equilibrium. Our study also reports that the tragedy of the commons, resulting from defectors' intensified harvesting efforts — which may present as oscillations or be influenced by initial conditions — can be mitigated through targeted punishment. Overall, by influencing exploitation strategies through targeted penalties, it becomes possible to mitigate the tipping point of ecological collapse. However, a fully effective monitoring system ($p = 1$) is not required to achieve this outcome.

Future research in this direction could explore the introduction of a distinct player type, such as the institution. This entity would be responsible for implementing a tiered tax system that differentiates between low- and high-effort strategies. Through the development of such a framework, one may investigate how the strategic actions of this regulatory institution can influence ecological tipping points and promote sustainability across various game structures. Furthermore, investigating eco-evolutionary systems within the context of critical transitions in higher dimensions, such as in temporal networks, is a promising research area.

Data accessibility.

The article has no additional data.

Declaration of AI use.

We have not used AI-assisted technologies in creating this article.

Authors' contributions.

A.M.: conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, writing—original draft, writing—review and editing; S.S.: formal analysis, investigation, writing—review and editing; S.C.: formal analysis, investigation, writing—original draft, writing—review and editing; P.S.D.: conceptualization, funding acquisition, methodology, resources, supervision, validation, visualization, writing—original draft, writing—review and editing

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration.

We declare we have no competing interests.

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