Behavioral and Ecological Dynamics in Voluntary Conservation: A Case Study of TurtleWatch

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Abstract

Biodiversity is essential to ecosystem stability and human well-being, yet it is increasingly threatened by habitat destruction, climate change, and overexploitation. This paper examines TurtleWatch, a conservation tool designed to reduce the accidental bycatch of endangered loggerhead turtles by informing fishers of turtle locations. We develop a mathematical model that couples ecological population dynamics with economic decision-making and social incentives to study when voluntary conservation can emerge and persist. Our analysis shows that long-run outcomes depend on three nested conditions: ecological feasibility, existence of a mixed-adoption equilibrium, and stability of that equilibrium. We find that partial compliance is possible only within a wedge-shaped parameter region defined by the balance between ecological signal strength, scaled social enforcement, and fishing profitability. Within the stable portion of this region, equilibrium adoption rises smoothly from low compliance to near-universal adoption as ecological signals and enforcement strengthen. Outside this region, the system polarizes toward full compliance or widespread defection, even when an interior equilibrium exists mathematically. We also find that when harvest pressure exceeds ecological growth capacity, no level of adoption can prevent ecological collapse. These results show that successful voluntary conservation programs must do more than create incentives to cooperate; they must also generate feedbacks that stabilize cooperation over time. Although motivated by TurtleWatch, this framework applies broadly to conservation, public health, and other collective-action problems.

1 Introduction

Biodiversity is the variety of all forms of life and is essential to the proper functioning of all ecosystems. Biodiversity, shaped over 4.5 billion years of evolution and increasingly influenced by human activities, plays a critical role in creating and supporting the habitats where species thrive. It has greatly contributed to modern advancements in human health research. Protecting biodiversity is crucial, not only for its inherent worth but also for the essential benefits it provides, such as clean air, fresh water, fertile soil, and crop pollination[1]. Yet despite its immense value, biodiversity is under constant threat due to human activities and environmental changes.

Primary drivers of biodiversity loss include habitat destruction, climate change, pollution, over-exploitation, and invasive species[2]. Deforestation and urbanization is detrimental to the various species living within these critical habitats. Forests are essential to life, acting as an array of different trees and species. However, without the proper shelter and life necessities a forest provides them, the many species coexisting within the habitat will also vanish. Beyond habitat destruction, another major threat to biodiversity is climate change. Unfortunately, global average surface temperature has risen at an average rate of 0.17°F per decade since 1901[3]. However, in recent years, the United States has experienced warming at a rate faster than the global average. With each degree of warming, the risk of species extinction rises significantly. Studies indicate that a 1.5°C increase in global temperatures could elevate extinction risks by 4%, while a 3°C rise may increase the risk to 26%[4]. Under a 2°C warming scenario, approximately 5% of species are projected to face extinction, escalating to 16% with a 4.3°C increase[5]. These projections underscore the critical importance of mitigating climate change to preserve biodiversity. Regrettably, climate change has already caused significant destruction resulting in the first climate-driven extinctions. In the ocean, rising temperatures can cause irreversible damage to marine and coastal ecosystems. Over the past 150 years, nearly 50% of live coral reefs have been lost and continued warming poses a threat to the survival of the remaining reefs[6]. However, climate change is not just about rising temperatures; it can also lead to an increase in extreme events, such as hurricanes, droughts, wildfires, and floods[7]. These extreme events can have devastating impacts on biodiversity. For example, the frequency of intense hurricanes in the Caribbean has increased in the past decade, with Hurricane Maria in 2017 causing severe damage to a variety of ecosystems. The storm destroyed several forests, reefs, and even pushed endangered species such as the Puerto Rican parrot closer to extinction[8]. This highlights how these extreme events can directly accelerate biodiversity loss.

Another devastating factor is pollution. From plastic to industrial chemicals, pollution is one of the most harmful threats to biodiversity: it depletes wildlife, ruins habitats, and disrupts ecosystems[9]. Furthermore, overfishing, hunting, and unsustainable resource extraction reduce populations, while invasive species outcompete native organisms, further disrupting ecosystems. As a result, conservation efforts are crucially important.

A remarkable example of successful conservation efforts is the recovery of the California condor[10]. In 1982, only 21 remained in the wild and by 1985, the last wild condors were captured to start a captive breeding program.[11] Slowly, reintroduction efforts began, sending condors back out into the wild. As of 2023, the population has grown to over 560 individuals across California, Arizona, Utah, and Baja California, Mexico[12].

Another successful conservation effort was the recovery of the Bald Eagle. After a prolonged decline linked to a decrease in prey-species, the introduction of the egg-thinning pesticide DDT nearly wiped out bald eagles from the lower 48 states. Wanting to save the birds, in 1962, Rachel Carson's book, Silent Spring, demonstrated to the public the harm DDT has on birds, and with pressure, the EPA largely banned the use of DDT in 1972[13]. Slowly, reintroduction efforts began and they helped reverse the bald eagle's decline. In 2007, the Interior Department officially declared the bald eagle fully recovered and removed it from the endangered species list.[14]

Unfortunately, there have been several failed conservation efforts, and one such example is the Baiji.[15] The Baiji (Lipotes vexillifer) is a freshwater dolphin species in China's Yangtze

River. These species suffered a drastic population decline due to industrialization, pollution, habitat destruction, and unsustainable fishing practices[16]. Though many conservation efforts were taken, many failed for a variety of reasons. One reason was delayed action: by the time serious conservation efforts began, the population was already critically low. Furthermore, despite the laws protecting these species, the rapid industrial development in China continued to degrade the Baiji's habitat. Another effort was made to protect these species by establishing a captive breeding population however this failed due to the Baiji's sensitivity of captivity and difficulty finding viable breeding individuals. Illegal fishing methods like electrofishing harmed the remaining population of these species. Now these species are declared "functionally extinct" and it is one of the first cetacean species to go extinct due to human activity showing how crucial it is for conservation efforts to be preemptive.

Another example of a failed conservation effort is TurtleWatch. TurtleWatch is a fisheries and turtle management tool developed by the National Oceanic and Atmospheric Administration to help reduce accidental bycatch of loggerhead turtles (Caretta caretta), which are already endangered under the US Endangered Species Act, and to prevent overfishing. Turtle movement patterns and ocean temperature data are used to create maps that identify where turtles are located.[17][18] This helps fishing vessels reduce the number of interactions with turtles as well as allow sustainable fishing practices. While the tool has potential, it has not achieved its intended results, primarily due to issues with policy implementation and fishers' compliance.

In this paper, we will explore the reasons behind the failure of TurtleWatch, focusing on 3 areas: the lack of strong incentives, insufficient enforcement of guidelines, and the disconnect between conservation goals and the economic realities faced by local fishers. Furthermore, we will discuss potential solutions, such as stronger regulations, improved outreach programs for fishers, and integration of economic incentives to ensure the success of conservation efforts like TurtleWatch.

However, it is essential to consider not only the conservation efforts but also the economic viability. Many communities depend on fishing for their livelihood - thus, conservation strategies must balance protecting species with supporting incomes. Programs like TurtleWatch aim to reduce bycatch of turtles while allowing fishers to continue their work, ensuring both marine biodiversity and economic stability for local communities. The feedback loop between conservation and the economy is crucial for long-term sustainability.

The economic importance of biodiversity cannot be underestimated. For example, global fisheries are valued at $276.5 billion annually, allowing several job opportunities for millions worldwide. Similarly, the global tourism industry is valued at $1.9 trillion a year with several tourist attractions dependent on the local biodiversity found there to attract visitors.

In this sense, biodiversity is also economically important as it supports key industries that contribute to the well being of millions of people in the world. To address the complex challenges of biodiversity conservation, various efforts have been carried out, often driven by either top-down policies or bottom-up organizational initiatives, each with varying degrees of success. We schematically represent the feedback loops between biodiversity and human activity.

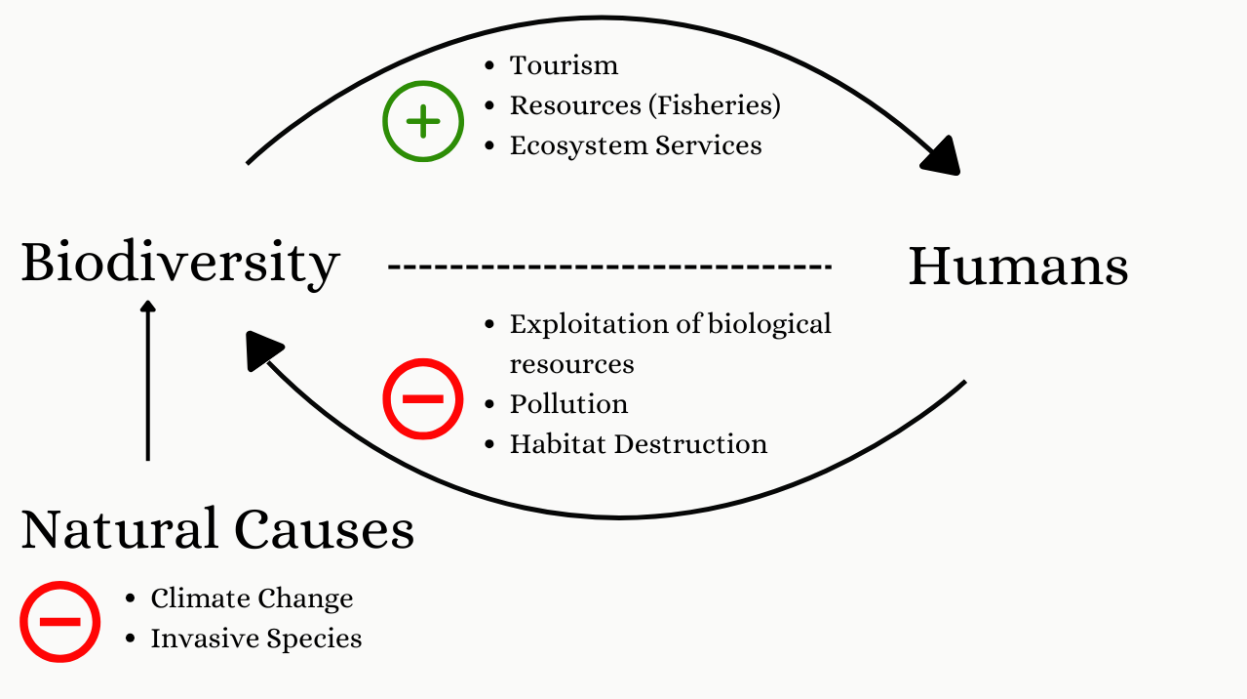


Figure 1: Schematic representation of reciprocal feedback loops between Biodiversity and Humans.

To investigate the challenges and dynamics surrounding voluntary conservation efforts like TurtleWatch, we developed a mathematical model that combines ecological population growth, economic incentives, and social influences. This modeling approach allows us to systematically explore how different factors, such as enforcement strategies, economic trade-offs, and ecological feedback, affect the adoption of conservation practices over time. By simulating various scenarios, the model provides valuable insights into why some conservation programs succeed while others struggle, offering guidance to design more effective and resilient environmental policies. In the next section, we introduce the structure of the model and the key assumptions underlying our analysis.

2 Model

We couple ecological dynamics (fish $R(t)$ and turtle $T(t)$) with the behavioral dynamics of the fishing community via the fraction of TurtleWatch adopters $f(t) \in [0,1]$. Following Gordon–Schaefer, harvest is linear in effort and stock. Two fisher types coexist: adopters (C) and non-adopters (I), with per-type catchabilities and efforts.

State variables.

$$R(t) \quad \text{(fish)}, \qquad T(t) \quad \text{(turtles)}, \qquad f(t) \quad \text{(fraction of adopters)}.$$

Ecological dynamics

With intrinsic growth rates r_R, r_T, carrying capacities K_R, K_T, fisher density n, efforts e_C, e_I, and catchabilities q_C^R, q_I^R (fish) and q_C^T, q_I^T (turtles), stocks evolve as

$$\frac{dR}{dt} = R\left[r_R\left(1 - \frac{R}{K_R}\right) - \left(q_C^R\, n\, f\, e_C + q_I^R\, n\,(1-f)\, e_I\right)\right],$$
$$\frac{dT}{dt} = T\left[r_T\left(1 - \frac{T}{K_T}\right) - \left(q_C^T\, n\, f\, e_C + q_I^T\, n\,(1-f)\, e_I\right)\right].$$

Economic payoffs and penalties

Let p be price per fish and w cost per unit effort. Profits (ignoring penalties) are

$$\pi_C = p\, q_C^R\, R\, e_C - w\, e_C, \qquad \pi_I = p\, q_I^R\, R\, e_I - w\, e_I.$$

We model two penalty channels in a single expression: (i) a top-down (government) penalty on non-adopters proportional to turtle harm, and (ii) an *ostracism* (social) penalty on adopters when others defect.

$$U_C \;=\; \pi_C \;-\; \underbrace{\gamma\, n\,(1-f)}_{\text{ostracism on cooperators}}, \qquad U_I \;=\; \pi_I \;-\; \underbrace{\frac{\left(q_I^T e_I - q_C^T e_C\right) T}{q_C^T e_C}}_{\text{top-down penalty on non-adopters}}.$$

Here $\gamma \geq 0$ measures the strength of social costs. Setting $\gamma = 0$ recovers the "no ostracism" case.

Strategy dynamics

Adoption evolves via a replicator dynamic:

$$\frac{df}{dt} \;=\; f(1-f)\left(U_C - U_I\right).$$

Scaled-α simplification (closed forms)

To obtain transparent expressions we impose

$$e_C = e_I = e, \qquad q_C^R = \alpha\, q_I^R, \qquad q_C^T = \alpha\, q_I^T, \qquad 0 < \alpha < 1,$$

so TurtleWatch scales catchability by α for both species. With H_R, H_T denoting total per-capita harvest rates:

$$H_R = ne\, q_I^R\big[1 + (\alpha - 1)f\big], \qquad H_T = ne\, q_I^T\big[1 + (\alpha - 1)f\big].$$

Positive steady states (R^*, T^*) given f^* satisfy

$$R^* = K_R\left[1 - \frac{neq_I^R\left(1 + (\alpha - 1)f^*\right)}{r_R}\right], \qquad T^* = K_T\left[1 - \frac{neq_I^T\left(1 + (\alpha - 1)f^*\right)}{r_T}\right].$$

Indifference (replicator) condition. Using $p = 1$ for clarity and substituting the penalties above,

$$U_C - U_I = \underbrace{\alpha q_I^R R^* e - q_I^R R^* e + \frac{1-\alpha}{\alpha} T^*}_{\text{top-down part}} \; - \; \underbrace{\gamma n(1 - f^*)}_{\text{ostracism}}.$$

An interior equilibrium ($0 < f^* < 1$) requires $U_C = U_I$, i.e.

$$-\,(1-\alpha)\, q_I^R R^* e + \frac{1-\alpha}{\alpha}\, T^* - \gamma n(1 - f^*) \;=\; 0,$$

which rearranges to the *unified* indifference line

$$\boxed{T^* \;=\; \alpha\, q_I^R e\, R^* \;+\; \frac{\alpha}{1-\alpha}\,\gamma\, n\,\big(1 - f^*\big)}$$

that collapses to $T^* = \alpha q_I^R e R^*$ when $\gamma = 0$ (no ostracism).

Solving for f^*. Substitute R^*, T^* from the ecological steady states into the boxed relation to obtain one scalar equation in f^*:

$$K_T\left[1 - \frac{neq_I^T(1 + (\alpha - 1)f^*)}{r_T}\right] = \alpha q_I^R e\, K_R\left[1 - \frac{neq_I^R(1 + (\alpha - 1)f^*)}{r_R}\right] + \frac{\alpha}{1-\alpha}\,\gamma\, n\,\big(1 - f^*\big).$$

Any root with $0 < f^* < 1$ that also yields $R^* > 0$ and $T^* > 0$ is a biologically and behaviorally feasible interior equilibrium.

2.1 Why we care about an interior equilibrium

An *interior equilibrium* is a steady state with $0 < f^* < 1$ in which both strategies (cooperators/adopters and non-adopters) persist alongside positive fish and turtle stocks. It matters for three reasons:

1. **Policy-relevance.** Interior outcomes represent realistic mixed communities where some fishers adopt TurtleWatch while others do not.

2. **Trade-offs and welfare.** Mixed adoption creates nontrivial trade-offs between fish harvest and turtle protection; it is exactly in the interior where compliance instruments affect outcomes *at the margin*.

3. **Comparative statics.** Only with a nondegenerate (interior) f^* can we meaningfully compare how changes in effectiveness (α), sanctions (γ), or fishing pressure (n, e, q) shift behavior and stocks.

By contrast, boundary equilibria ($f = 0$ or $f = 1$) are corner cases.

2.2 Units of the Original Parameters

Before nondimensionalizing, we recall the units of each original quantity (one consistent choice):

- $R(t), T(t)$: population (individuals).
- t: time.
- r_R, r_T: 1/time.
- K_R, K_T: individuals.
- e_C, e_I: effort (e.g., boat-days per unit time).
- q: catchability, such that $q\,e$ (stock) has units 1/time.
- n: number (or density) of fishers (dimensionless scaling of total effort).
- α: dimensionless effectiveness factor.
- γ: penalty strength (chosen so that γn has payoff units in the replicator equation).

2.3 Nondimensionalization of the Model

We now reduce the number of parameters by rewriting the system in dimensionless form.

Original system (scaled-α).

$$\frac{dR}{dt} = R\left[r_R\left(1 - \frac{R}{K_R}\right) - neq_I^R\big(1 + (\alpha - 1)f\big)\right], \tag{1}$$

$$\frac{dT}{dt} = T\left[r_T\left(1 - \frac{T}{K_T}\right) - neq_I^T\big(1 + (\alpha - 1)f\big)\right], \tag{2}$$

$$\frac{df}{dt} = f(1-f)\Big(-(1-\alpha)q_I^R eR + \frac{1-\alpha}{\alpha}T - \gamma n(1-f)\Big). \tag{3}$$

Scaling of variables. Let $x = R/K_R$, $y = T/K_T$, and $\tau = r_R t$, so $\frac{d}{dt} = r_R \frac{d}{d\tau}$.

Dimensionless ecological dynamics. Define

$$A_R := \frac{neq_I^R}{r_R}, \qquad A_T := \frac{neq_I^T}{r_T}, \qquad \rho := \frac{r_T}{r_R}.$$

Then

$$\frac{dx}{d\tau} = x\Big[1 - x - A_R\big(1 + (\alpha - 1)f\big)\Big], \tag{4}$$

$$\frac{dy}{d\tau} = \rho\, y\Big[1 - y - A_T\big(1 + (\alpha - 1)f\big)\Big]. \tag{5}$$

Dimensionless behavioral dynamics. Dividing Eq. (3) by r_R and substituting $R = K_R x$, $T = K_T y$ gives

$$\frac{df}{d\tau} = (1 - \alpha)\, f(1 - f)\Big[-\Lambda x + \frac{\Theta}{\alpha} y - \Gamma(1 - f)\Big],$$

where

$$\Lambda := \frac{q_I^R e K_R}{r_R}, \qquad \Theta := \frac{K_T}{r_R}, \qquad \Gamma := \frac{\gamma n}{r_R}.$$

Parameter reduction. In the scaled-α model, the original dynamics depend on ten primitive parameters $r_R, r_T, K_R, K_T, n, e, q_I^R, q_I^T, \alpha, \gamma$. After nondimensionalization, the system is governed by the dimensionless combinations $A_R, A_T, \rho, \Lambda, \Theta, \Gamma$ together with α.

Parameter	Definition	Interpretation
A_R	$A_R = \frac{neq_I^R}{r_R}$	Fish harvest pressure relative to fish growth
A_T	$A_T = \frac{neq_I^T}{r_T}$	Turtle harvest pressure relative to turtle growth
ρ	$\rho = \frac{r_T}{r_R}$	Relative ecological timescale (turtles vs. fish)
Λ	$\Lambda = \frac{q_I^R e K_R}{r_R}$	Economic leverage of fish stock on payoffs
Θ	$\Theta = \frac{K_T}{r_R}$	Ecological signal scale of turtles
Γ	$\Gamma = \frac{\gamma n}{r_R}$	Strength of social pressure relative to ecological dynamics
α	$\alpha \in (0, 1)$	Effectiveness of rule-following fishers (dimensionless)

Table 1: Dimensionless parameters obtained through nondimensionalization of the model. Each parameter represents a ratio of ecological, economic, or social processes, highlighting the reduced set of mechanisms governing system behavior.

3 Analytical Results

3.1 Feasibility Conditions in Dimensionless Form

In the dimensionless framework, ecological feasibility depends only on (A_R, A_T, α), while the existence and value of an interior adoption equilibrium depend on two reduced behavioral ratios obtained by scaling all behavioral terms by the same reference scale Λ (see Figure 2).

Ecological steady states at fixed f. For a given adoption fraction f, the dimensionless steady-state stocks are

$$x^*(f) = 1 - A_R\big(1 + (\alpha - 1)f\big), \qquad y^*(f) = 1 - A_T\big(1 + (\alpha - 1)f\big),$$

where $A_R = \frac{neq_I^R}{r_R}$ and $A_T = \frac{neq_I^T}{r_T}$.

Feasibility (positive stocks). A biologically meaningful equilibrium requires $x^*(f) > 0$ and $y^*(f) > 0$ for some $f \in [0, 1]$. This yields a lower bound $f \in [f^{\min}, 1]$, with

$$f^{\min} = \max\left\{0,\ \frac{1 - A_R}{A_R(\alpha - 1)},\ \frac{1 - A_T}{A_T(\alpha - 1)}\right\}.$$

If $f^{\min} \geq 1$, then no positive ecological steady state exists for any adoption level, and we classify the regime as ecologically infeasible.

Interior equilibrium condition. The nondimensional behavioral dynamics admit an interior equilibrium $f^* \in (0, 1)$ when the behavioral bracket vanishes,

$$-\Lambda x^* + \frac{\Theta}{\alpha} y^* - \Gamma(1 - f^*) = 0.$$

Because this condition is linear in $(\Lambda, \Theta, \Gamma)$, only their ratios matter. Dividing through by Λ yields the canonical reduced form

$$-x^*(f) + \frac{\Xi}{\alpha}\, y^*(f) - \hat{\Gamma}(1 - f) = 0,$$

where we define the two independent behavioral ratios

$$\Xi := \frac{\Theta}{\Lambda}, \qquad \hat{\Gamma} := \frac{\Gamma}{\Lambda}.$$

Equivalently, the interior equilibrium condition can be written as the *behavioral indifference line*

$$y^*(f) \;=\; \frac{\alpha}{\Xi}\, x^*(f) \;+\; \frac{\alpha}{\Xi}\, \hat{\Gamma}(1 - f).$$

Existence and uniqueness. Define

$$\Phi(f) \;\equiv\; -x^*(f) + \frac{\Xi}{\alpha}\, y^*(f) - \hat{\Gamma}(1-f).$$

Since $x^*(f)$ and $y^*(f)$ are linear in f, the function $\Phi(f)$ is also linear in f. Therefore:

Interior-existence test. An interior equilibrium exists *iff*

$$\Phi(f^{\min})\,\Phi(1) \le 0.$$

In that case, the interior equilibrium $f^* \in (f^{\min}, 1)$ is unique.

Thus, ecological feasibility depends only on (A_R, A_T, α), and conditional on feasibility the existence and value of an interior adoption equilibrium depend only on the two behavioral ratios $(\Xi, \hat{\Gamma})$.

Interpretation of the reduced behavioral parameters. The nondimensionalization reveals that behavioral outcomes depend on the original economic, ecological, and social parameters only through two simple ratios. Specifically, the ecological–economic signal ratio

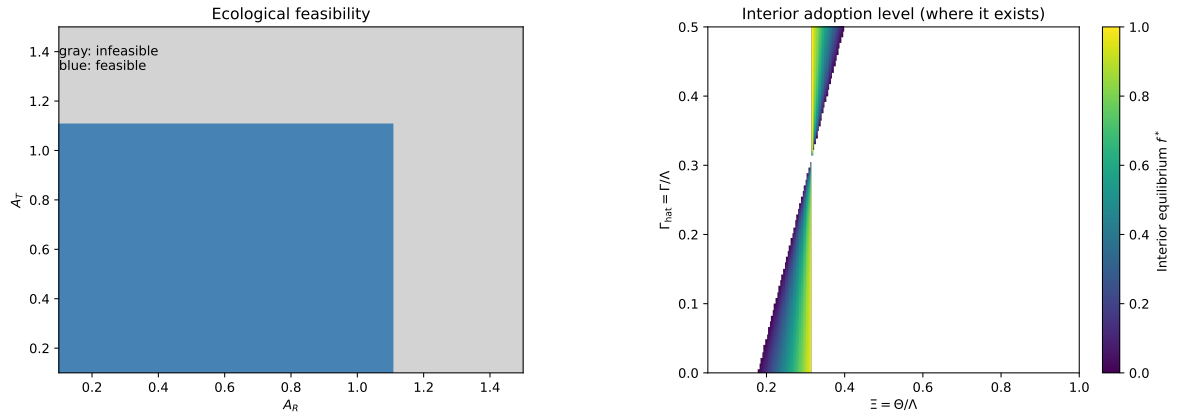
$$\Xi = \frac{\Theta}{\Lambda} = \frac{K_T}{q_I^R e K_R}$$

compares the size of the turtle population, which generates the ecological signal relevant for compliance, to the economic pressure from fishing, measured by fish catchability, effort, and fish carrying capacity. Large values of Ξ correspond to situations in which turtles are abundant or highly visible relative to the profitability of fishing, making conservation behavior more attractive. Similarly, the scaled enforcement parameter

$$\hat{\Gamma} = \frac{\Gamma}{\Lambda} = \frac{\gamma n}{q_I^R e K_R}$$

measures the strength of social or institutional penalties relative to the same economic pressure from fishing profits. Stronger penalties or larger fishing communities increase $\hat{\Gamma}$, while higher effort, catchability, or fish productivity reduce its effectiveness.

Importantly, both Ξ and $\hat{\Gamma}$ share the same denominator, $q_I^R e K_R$, highlighting that ecological signals and social enforcement compete against the same underlying economic incentive to fish. As a result, policies that reduce fishing effort or profitability (e.g., effort caps or gear restrictions) can have effects on behavior similar to increasing enforcement or enhancing the visibility of ecological impacts. This common scaling explains why equilibrium adoption outcomes are naturally organized in the $(\Xi, \hat{\Gamma})$ parameter plane.



(a) Ecological feasibility in the (A_R, A_T) plane for fixed $\alpha = 0.9$. Blue regions indicate parameter combinations for which there exists at least one adoption level $f \in [0, 1]$ such that both fish and turtle steady-state abundances are positive. Gray regions indicate infeasibility, where no adoption level can prevent ecological collapse. Increasing either harvest-to-growth ratio (A_R or A_T) shrinks the feasible region.

(b) Interior equilibrium adoption level f^* as a function of the social enforcement parameter $\hat{\Gamma}$ and the ecological–economic signal ratio $\Xi = \Theta/\Lambda$, conditional on ecological feasibility $(A_R, A_T, \alpha = 0.6, 0.4, 0.1)$. Colors indicate the value of the unique interior equilibrium f^* where it exists. Blank regions correspond to parameter values for which only boundary equilibria ($f = 0$ or $f = 1$) are possible. Stronger social enforcement and larger ecological signal strength relative to economic incentives increase the equilibrium adoption level.

Figure 2: Equilibrium structure of the nondimensionalized model. (**Left**) Ecological feasibility depends only on the harvest-to-growth ratios A_R and A_T. (**Right**) Conditional on feasibility, the equilibrium adoption level is governed by the balance between social enforcement (Γ) and ecological signal strength relative to economic incentives (Ξ).

3.2 Stability of the Interior Adoption Equilibrium

Finding an interior equilibrium f^* means that there is a value of f between 0 and 1 for which the equations predict no change in adoption. However, this does not guarantee that such a state will actually be observed. To understand what happens in simulations, we also need to check whether this interior equilibrium is stable: that is, whether the system returns to f^* after a small disturbance.

Behavioral dynamics near an interior equilibrium. At an interior equilibrium, the fish and turtle populations take their steady values $x^*(f)$ and $y^*(f)$, which depend linearly on the adoption level f. Substituting these steady-state expressions into the dimensionless behavioral equation gives

$$\frac{df}{d\tau} = (1 - \alpha)\, f(1 - f)\, \Phi(f),$$

where

$$\Phi(f) = -x^*(f) + \frac{\Xi}{\alpha}\, y^*(f) - \hat{\Gamma}(1-f), \qquad \hat{\Gamma} = \frac{\Gamma}{\Lambda}.$$

An interior equilibrium $f^* \in (0,1)$ satisfies $\Phi(f^*) = 0$, meaning that the positive and negative incentives to adopt exactly balance.

How to test stability. To determine stability, we ask the following question: if f is changed slightly above or below f^*, does it move back toward f^*, or does it move away?

Because the factor $(1-\alpha)f(1-f)$ is always positive for $0 < f < 1$, the direction of change is determined by how $\Phi(f)$ varies with f. If $\Phi(f)$ decreases as f increases, then a small increase in f makes $\frac{df}{d\tau}$ negative and pushes f back down, which is stabilizing. Conversely, if $\Phi(f)$ increases with f, then small deviations grow and the interior equilibrium is unstable.

This means that the interior equilibrium is stable if and only if

$$\Phi'(f^*) < 0.$$

Explicit stability condition. Since both $x^*(f)$ and $y^*(f)$ are linear functions of f, the function $\Phi(f)$ is also linear, and its derivative is constant:

$$\Phi'(f) = -\frac{dx^*}{df} + \frac{\Xi}{\alpha}\frac{dy^*}{df} + \hat{\Gamma}.$$

Using

$$\frac{dx^*}{df} = A_R(1-\alpha), \qquad \frac{dy^*}{df} = A_T(1-\alpha),$$

we obtain the stability condition

$$\boxed{(1-\alpha)\Big[-A_R + \frac{\Xi}{\alpha}A_T\Big] + \hat{\Gamma} < 0.}$$

Combining existence and stability. An interior equilibrium exists (when ecological feasibility holds) if

$$\Phi(f^{\min})\,\Phi(1) \le 0,$$

which, in the common case $f^{\min} = 0$, implies

$$\boxed{\alpha\,\frac{x^*(1)}{y^*(1)} \;\le\; \Xi \;\le\; \alpha\,\frac{x^*(0)+\hat{\Gamma}}{y^*(0)}.}$$

Putting these conditions together, a *stable* interior equilibrium exists only if all of the following hold:

$$\boxed{\begin{aligned} &f^{\min} < 1, \\ &\alpha\,\frac{x^*(1)}{y^*(1)} \;\le\; \Xi \;\le\; \alpha\,\frac{x^*(0)+\hat{\Gamma}}{y^*(0)}, \\ &\Xi < \alpha\left(\frac{A_R}{A_T} - \frac{\hat{\Gamma}}{(1-\alpha)A_T}\right). \end{aligned}}$$

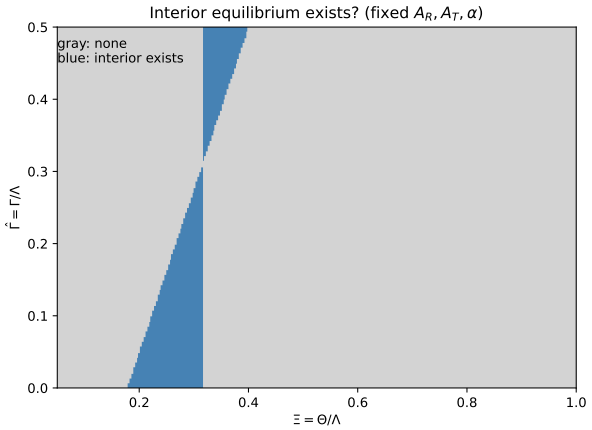
Implication. These inequalities show that interior adoption equilibria can exist but still be unstable. In particular, if fish and turtle populations respond in the same way to reduced fishing effort ($A_R = A_T$), then the existence condition requires $\Xi \geq \alpha$, while the stability condition requires $\Xi < \alpha$ whenever $\hat{\Gamma} \geq 0$. As a result, no stable interior equilibrium is possible in this symmetric case. In simulations, the system therefore moves toward boundary outcomes with either full adoption ($f \to 1$) or no adoption ($f \to 0$), even though an interior equilibrium exists mathematically.

Intuition for stability of the interior equilibrium. The stability condition describes what happens after a small change in the adoption level around an interior equilibrium. Suppose that the fraction of adopters f increases slightly. This reduces fishing pressure, which allows both fish and turtle populations to increase. Higher fish abundance makes fishing more profitable and therefore reduces the incentive to adopt the conservation technology, while higher turtle abundance strengthens the ecological signal that encourages adoption. Whether the system returns to the interior equilibrium or moves away from it depends on which of these two effects is stronger.

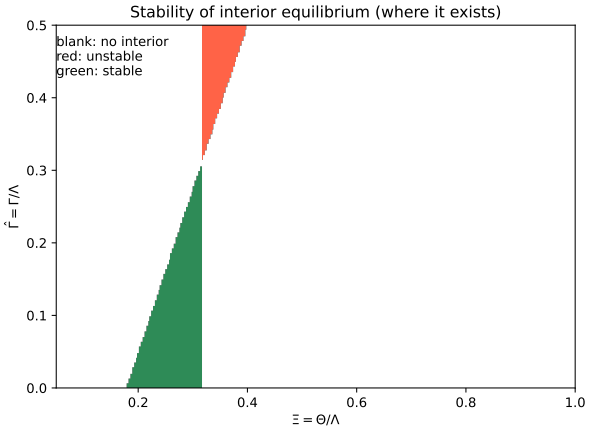
A stable interior equilibrium is more likely when fish profits respond more strongly to reduced fishing pressure than turtle recovery does ($A_R > A_T$), when the conservation technology is effective (small α), and when social or institutional penalties are weak (small $\hat{\Gamma}$). In this situation, a small increase in adoption raises fish profits enough to counteract further adoption, pushing the system back toward the interior and creating a self-correcting balance between economic incentives and ecological benefits.

By contrast, strong enforcement tends to destabilize interior equilibria. Because penalties become weaker as more fishers adopt the technology, an increase in f reduces enforcement and can amplify deviations instead of correcting them. Similarly, when fish and turtle stocks respond in similar ways to reduced fishing effort, the ecological feedbacks do not balance each other. In these cases, the system tends to move toward boundary outcomes with either full adoption or no adoption. As a result, interior equilibria may exist in theory but still be unstable in simulations.

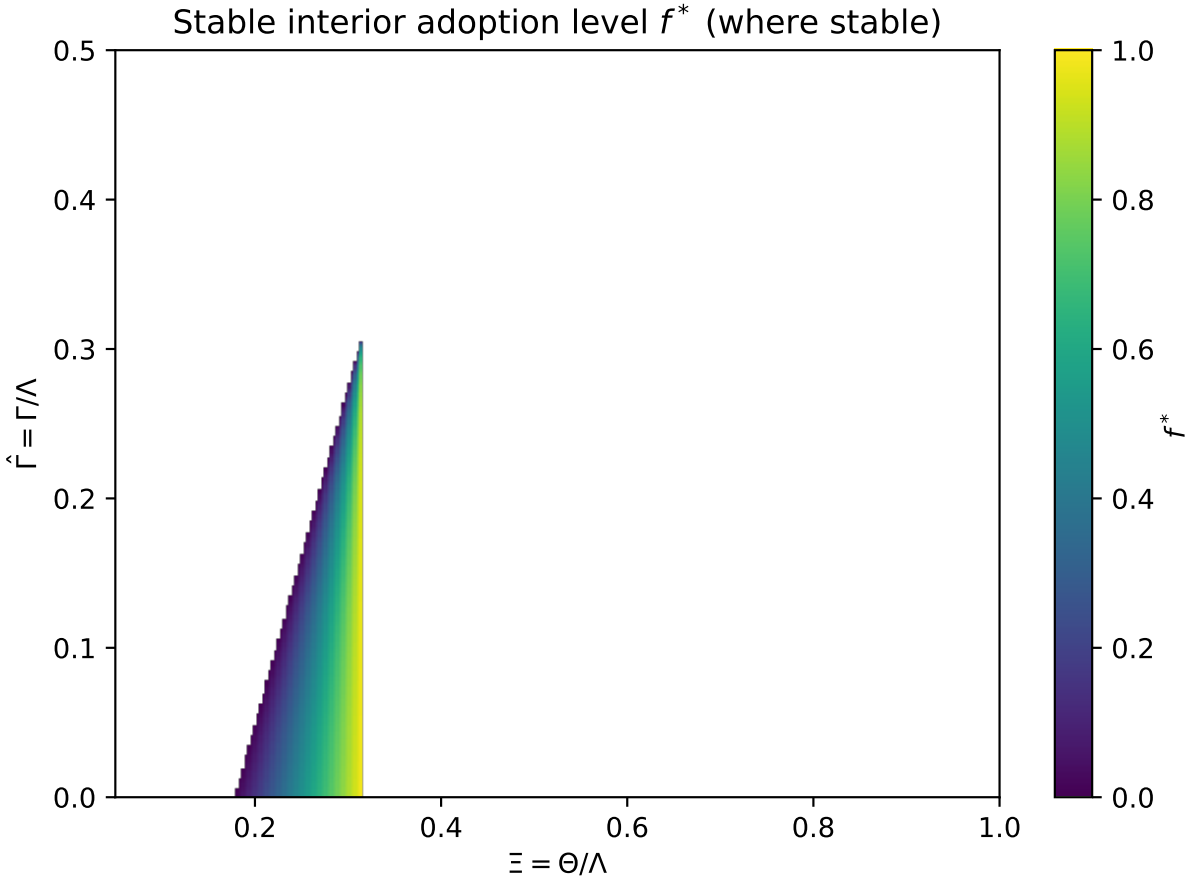
Results: existence versus stability. Figure 3 separates two different questions. First, does an interior equilibrium $f^* \in (0, 1)$ exist at all? Second, if it exists, will the ODE simulation actually converge to it?



(a) **Existence.** Blue means an interior equilibrium $f^* \in (0, 1)$ exists (for the fixed A_R, A_T, α values used), while gray means no interior equilibrium exists.



(b) **Stability.** Among points where an interior equilibrium exists, green indicates it is stable and red indicates it is unstable. Blank regions correspond to no interior equilibrium.



(c) **Stable interior level.** The value of f^* is shown only where the interior equilibrium is stable; darker colors correspond to smaller f^* and lighter colors to larger f^*.

Figure 3: Existence and stability of interior adoption equilibria in the reduced $(\Xi, \hat{\Gamma})$ parameter plane (with A_R, A_T, α fixed). The first panel shows where an interior equilibrium exists, the second panel shows whether that interior equilibrium is stable, and the third panel shows the stable interior adoption level f^* where stability holds.

Panel 3a shows the *existence* region in the $(\Xi, \hat{\Gamma})$ plane. This region has a wedge-like shape because the equilibrium condition is linear in f, so the root can only lie inside $(0, 1)$ for a limited range of parameter values. Increasing Ξ (a stronger turtle signal relative to fishing profits) and increasing $\hat{\Gamma}$ (stronger enforcement relative to fishing profits) both make it easier for the model to have a mixed-adoption fixed point.

However, existence does not imply stability. Panel 3b shows that some parameter combinations produce an interior equilibrium that is *unstable* (red). In those cases, simulations do not settle at f^*; instead, $f(\tau)$ moves away from the interior value and ends up at one of the boundary outcomes ($f \to 0$ or $f \to 1$). This happens because the incentives change when f changes: increasing adoption can make fishing more profitable (by letting fish recover) and can also weaken penalties (because fewer fishers are non-adopters). These feedbacks can push the system away from the interior equilibrium.

Finally, panel 3c shows the *value* of the stable interior equilibrium f^*, but only in the region where it is stable. In this stable region, higher Ξ generally corresponds to larger equilibrium adoption, because turtles are more important relative to profits. The three panels together explain why our earlier feasibility test and ODE simulations can disagree: the feasibility test identifies where an interior fixed point exists, while the simulations converge only when that fixed point is also stable.

4 Results (simulations)

To validate the analytical equilibrium classification, we numerically integrate the nondimensionalized ODE system for representative parameter choices (Fig. 4)

$$\frac{dx}{d\tau} = x\Big[1 - x - A_R\big(1 + (\alpha - 1)f\big)\Big], \tag{6}$$

$$\frac{dy}{d\tau} = \rho\, y\Big[1 - y - A_T\big(1 + (\alpha - 1)f\big)\Big], \tag{7}$$

$$\frac{df}{d\tau} = (1 - \alpha)\, f(1 - f)\Big[-\Lambda x + \frac{\Theta}{\alpha} y - \Gamma(1 - f)\Big], \tag{8}$$

where $x = R/K_R$ and $y = T/K_T$ are normalized stocks, $\tau = r_R t$ is dimensionless time, and the dimensionless parameters are defined in Section 2.3. We integrate the ODEs using a standard adaptive solver (Runge–Kutta). Initial conditions are chosen with $x(0), y(0) \in (0, 1)$ and $f(0) \in (0, 1)$. For each run we record the time series $(x(\tau), y(\tau), f(\tau))$ and the long-run outcome (approach to an interior equilibrium versus convergence to a boundary). We report representative trajectories illustrating: (i) ecological collapse, (ii) an interior adoption equilibrium, and (iii) the two boundary regimes ($f \to 0$ and $f \to 1$).

The first panel of Figure 4 shows an ecological collapse case, where fishing pressure is so high that even the best possible adoption level cannot keep both species positive. In this regime both x and y decrease toward zero, and the adoption dynamics become irrelevant because the ecological system fails.

The remaining panels show regimes where ecology is feasible, but the long-run behavior of f differs. When incentives to adopt are weak (small Ξ and weak enforcement), the adoption fraction decreases and the system approaches the boundary outcome $f \to 0$. When

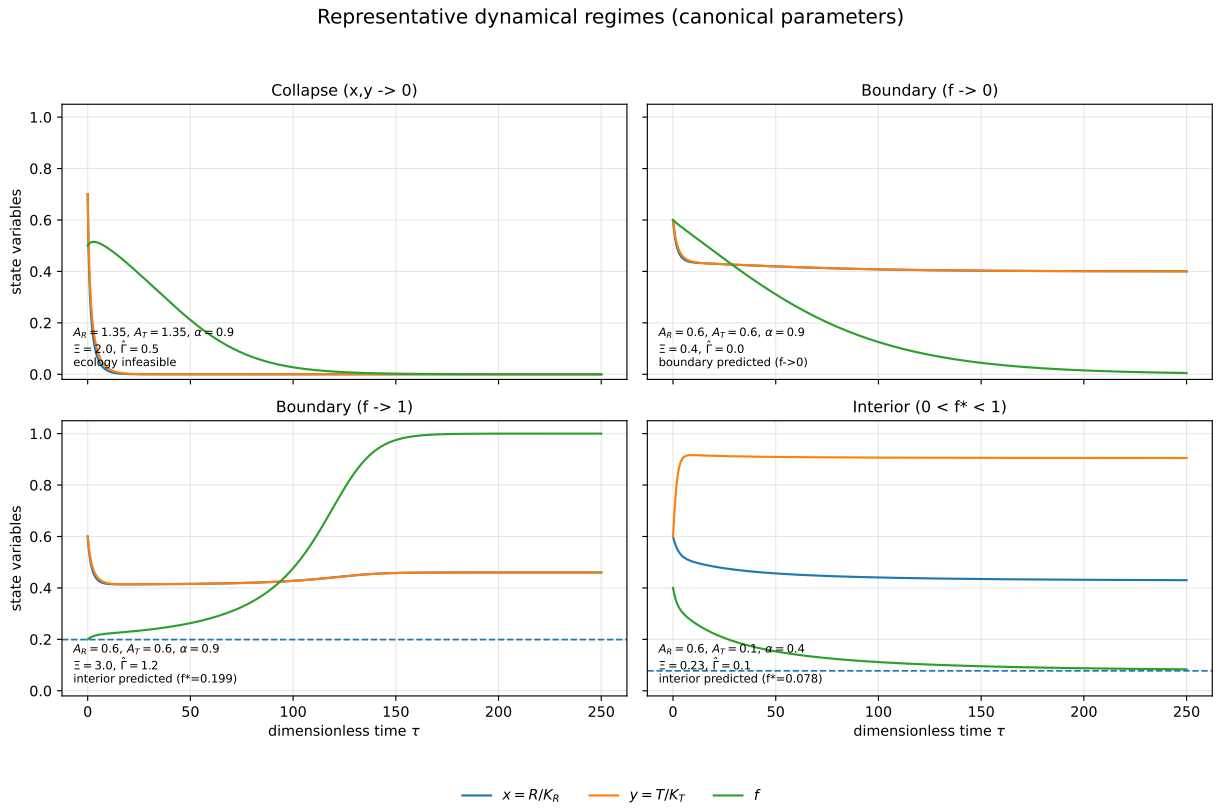


Figure 4: Representative time trajectories of the dimensionless model in four qualitatively different regimes. Each panel shows fish ($x = R/K_R$), turtles ($y = T/K_T$), and adoption (f) over dimensionless time τ. The regimes are: ecological collapse (both x and y approach zero), two boundary outcomes ($f \to 0$ and $f \to 1$), and a case where the dynamics converge to a stable interior adoption level. When an interior equilibrium is predicted analytically, the dashed line indicates the predicted value f^*.

incentives are strong (large Ξ and/or large $\hat{\Gamma}$), the adoption fraction increases and the system approaches $f \to 1$.

Finally, we also show a case where the system converges to a stable interior adoption level. In this case $f(\tau)$ approaches a value strictly between 0 and 1, and the dashed line (the analytically predicted f^*) matches the simulation. Together, these examples show why it is important to check stability: an interior equilibrium can exist mathematically, but only stable interior equilibria are actually observed as long-run outcomes of the ODE.

5 Discussion

In this section, we interpret the analytical and simulation results together, emphasizing how the existence, stability, and magnitude of interior adoption equilibria depend on the balance between ecological signals, economic incentives, and social enforcement.

A central insight from our analysis is the distinction between existence and stability of interior adoption equilibria. As shown in Figure 3, there is a wedge-shaped region in the

reduced parameter plane (Ξ, $\hat{\Gamma}$) where an interior equilibrium $f^* \in (0, 1)$ mathematically exists. However, only a subset of this region yields a stable interior equilibrium. In the unstable portion, the model predicts a mixed-adoption fixed point, but the ODE simulations do not converge to it. Instead, the dynamics move toward boundary outcomes $f \to 0$ or $f \to 1$.

This distinction helps explain why feasibility conditions alone are insufficient to predict long-run behavior. An interior equilibrium may satisfy the indifference condition, yet still be dynamically unattainable. Figure 4 confirms this: only when the analytical stability condition holds does the time trajectory converge to the predicted dashed interior level f^* otherwise, adoption moves toward full compliance or complete defection.

Gradual Structure of Interior Adoption

Within the stable region (Figure 3c), the equilibrium adoption level f^* varies smoothly across parameters. Importantly, the stable interior region has a clear gradient structure

- On the left side of the shaded region (lower Ξ and weaker $\hat{\Gamma}$), the equilibrium adoption level is low.
- On the right side of the shaded region (higher Ξ and/or stronger $\hat{\Gamma}$), the equilibrium adoption level is low.

This reveals that adoption is not binary but continuously structured by the balance between ecological signal strength and enforcement relative to economic pressure. The parameter $\Xi = \Theta/\Lambda$ measures the ecological signal of turtles relative to fishing profitability. Larger Ξ means turtles are more visible or ecologically significant relative to profits. As Ξ increases, the interior equilibrium shifts upward, meaning more fishers voluntarily adopt TurtleWatch.

Similarly, $\hat{\Gamma}$ represents social or institutional enforcement scaled relative to fishing profits. Increasing $\hat{\Gamma}$ also shifts the system toward higher equilibrium adoption but only within the region where stability holds. Thus, the model predicts a structured continuum:

- Weak ecological signals and weak enforcement $\to$ low interior adoption (if stable)
- Moderate signals and enforcement $\to$ mixed communities
- Strong signals and enforcement $\to$ near-universal adoption
- Extremely strong enforcement can destabilize interior equilibria and push the system toward full adoption as a boundary outcome.

Why Stability Fails in Some Regions

The instability of some interior equilibria reflects feedback effects between ecology and behavior.

When adoption increases:

- Fishing pressure declines
- Fish stocks recover

- Profits increase
- Enforcement weakens (because fewer fishers defect)

If the profit rebound or enforcement weakening is strong enough, it can push the system away from the interior equilibrium. In those cases, mixed adoption cannot be sustained. The community instead polarizes toward either full compliance or widespread defection.

This explains why the existence region in Figure 3a is larger than the stable region in Figure 3b. Mixed adoption is mathematically possible over a wide range of parameters, but dynamically sustainable only under stricter conditions.

Implications for TurtleWatch and Voluntary Conservation

These results refine our earlier qualitative insights.

- **Early Adopters Matter But Relative to Economic Pressure.** The effectiveness of rule-followers (captured by $\alpha$and embedded in Ξ shapes whether interior adoption is even possible. When ecological signals are weak relative to profits, voluntary adoption cannot be sustained. This means that conservation programs like TurtleWatch must ensure that ecological feedbacks are visible and meaningful compared to economic incentives.

- **Social Enforcement Has a Nonlinear Role.** Moderate enforcement increases interior adoption smoothly. However, very strong enforcement can eliminate mixed outcomes entirely, pushing the system to full compliance. At the same time, some enforcement levels can destabilize interior equilibria. Thus, policy design must consider not only how much enforcement is applied, but how it interacts dynamically with ecological and economic feedbacks.

- **Mixed Communities Are Structured, Not Arbitrary.** A major conceptual contribution of the updated results is that mixed adoption is not accidental or random. It occupies a clearly defined wedge-shaped region in parameter space. Within that region, adoption levels vary continuously from low to high. This suggests that real-world conservation programs may naturally produce:

  - Partial compliance in moderate incentive regimes
  - Polarization in unstable regimes
  - Near-universal adoption when ecological signals or enforcement dominate profits

- **Collapse Remains a Distinct Regime.** Figure 4 also illustrates that when ecological feasibility fails (large A_R and A_T), no adoption level can prevent collapse. In these regimes, behavioral dynamics become irrelevant because both species decline toward zero. This reinforces a key policy message: voluntary compliance cannot compensate for excessive harvest pressure relative to ecological growth. Ecological feasibility is a prerequisite for behavioral solutions.

The Broader View

Taken together, the updated results show that voluntary conservation outcomes are governed by three nested conditions:

1. Ecological feasibility: Can positive stocks exist at all?
2. Existence of interior adoption: Does a mixed equilibrium solve the indifference condition?
3. Stability of that equilibrium: Will the system actually converge to it?

Only when all three hold do we observe sustained partial compliance. This layered structure provides a clearer conceptual framework for understanding why some voluntary conservation programs stabilize at moderate adoption levels, while others either fail completely or shift toward near-universal compliance.

6 Conclusion

Biodiversity conservation increasingly depends on voluntary cooperation in settings where ecological and economic incentives are tightly intertwined. In this paper, we studied TurtleWatch as a case study of how ecological dynamics, economic payoffs, and social enforcement jointly determine whether sustainable behavior can emerge and persist.

By coupling population dynamics with replicator behavior, we showed that voluntary conservation outcomes are governed by three nested conditions. First, ecological feasibility must hold: fish and turtle populations must be able to remain positive under some adoption level. Second, an interior adoption equilibrium must exist, meaning that adopters and non-adopters can be indifferent at some mixed level of compliance. Third, and most importantly, that equilibrium must be dynamically stable. Only when all three conditions are satisfied does the system converge to sustained partial compliance.

Our results reveal that mixed adoption is neither arbitrary nor guaranteed. In the reduced parameter space, interior equilibria exist only within a wedge-shaped region defined by the balance between ecological signal strength (relative to fishing profits) and scaled social enforcement. Within the stable portion of this region, equilibrium adoption levels vary continuously. Low compliance when ecological signals and enforcement are weak relative to economic incentives, to near-universal adoption when they are strong. Outside the stability region, even when a mixed equilibrium exists mathematically, the system polarizes toward boundary outcomes with either full compliance or widespread defection.

These findings refine the interpretation of voluntary conservation programs such as TurtleWatch. Early adopters can shift collective behavior, but only when ecological feedback is strong relative to the profitability of fishing. Social enforcement raises adoption, yet its effects are nonlinear and can change whether mixed outcomes are stable or unstable. Most importantly, behavioral incentives alone cannot prevent collapse when harvest pressure exceeds ecological growth capacity.

Although this study focuses on TurtleWatch, the framework applies broadly to conservation, climate mitigation, public health, and other collective-action problems. Our results show that sustainable cooperation requires more than a balance of incentives at a single point;

it requires feedback mechanisms that stabilize that balance. Understanding the distinction between equilibrium existence and stability provides a clearer foundation for designing policies that promote durable, long-term collective action.

7 Acknowledgements

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