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A Tripartite Evolutionary Game of Green Agricultural Technology Diffusion: Conservative Oscillation, Critical Thresholds, and State-Dependent Policy

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Abstract

Understanding when coordinated cooperation emerges in multi-agent systems, and when it fails, is a central question in the study of complex socio-economic dynamics. This paper develops a tripartite evolutionary game among three boundedly rational populations—local governments, agribusinesses, and smallholder farmers—and applies it to the diffusion of green agricultural technology, using conservation tillage in Northeast China’s black soil region as a concrete setting. The model incorporates a performance-based subsidy that is disbursed only upon realized adoption, thereby foreclosing subsidy capture. We derive the replicator dynamics, analyze the asymptotic stability of all eight pure-strategy equilibria, and, for the regime in which the system fails to converge, construct a first integral analytically and verify its conservation numerically to machine precision. Four findings emerge. First, the intuitively ideal fully coordinated state is dynamically unstable; the stable desirable outcome is one in which the government withdraws while the market sustains adoption. Second, under low initial willingness the system does not converge to any evolutionarily stable strategy but enters a sustained, conservative (center-type) oscillation—a policy-reversal trap that transient interventions cannot extinguish, placing the dynamics within the class of Hamiltonian-like evolutionary systems. Third, a sharp critical threshold in initial willingness partitions the state space into distinct basins of attraction, rendering policy effectiveness state-dependent. Fourth, within the modeled trap, credible penalties and enhanced agribusiness service capacity can engineer escape, whereas untargeted farmer subsidies are markedly less effective and may even deepen the oscillation. These results recommend treating public intervention as a transitional, regime-aware catalyst with a built-in exit. Beyond the agricultural setting, the analysis illustrates how conservative oscillations and multiple basins shape the controllability of multi-agent cooperation systems.



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1. Introduction

1.1. Background

Northeast China’s black soil region, producing about a quarter of national grain output and half of its japonica rice, is regarded as the “ballast stone” of national food security [1]. Yet decades of over-cultivation have cut its organic-matter content by 50 to 60 percent and

thinned the topsoil to about 30 cm. In response, China enacted the Black Soil Protection Law, the world's first national statute dedicated to a single soil type, effective 1 August 2022, framing black soil as the “giant panda of cultivated land” [2].

The principal remedy is conservation tillage, epitomized by the “Lishu Model” of no-till straw-mulching, which curbs erosion, rebuilds fertility, and in demonstration fields raises maize yields by 8 to 10 percent while cutting input costs by CNY 1000 to 2920 per hectare [3]. The Northeast Black Soil Conservation Tillage Action Plan (2020–2025) targeted 1.4×10^8 mu, about 70 percent of suitable cropland [4]; implementation exceeded 1.12×10^8 mu in 2024 [5]. The Plan rests on the same three-actor structure studied here, with business and extension entities as carriers and farmers kept at the center to join voluntarily [4].

1.2. The Coordination Problem

This stress on voluntary participation points to the crux of the challenge: diffusion is fundamentally a coordination problem among several decision-makers, not a matter of technology alone. Conservation tillage is scale-sensitive and equipment-intensive, and its short-run private return is often negative even though its long-run return is positive, so a farmer's choice turns on both government incentives and whether socialized-service organizations make the technology practicably available, while the government weighs the costs of regulating, subsidizing, and penalizing against food-security and accountability pressures.

The outcome thus emerges from the strategic interaction of three boundedly rational populations, namely, local governments, agribusinesses, and smallholder farmers, none of which can secure the desirable result alone. Evolutionary game theory suits this setting, since it traces how the proportions adopting each strategy co-evolve through learning and imitation rather than assuming perfectly rational optimizers [6], and capturing when diffusion succeeds or fails requires modeling all three actors in one dynamic framework.

More specifically, conservation-tillage diffusion is a coordination game with endogenous feedback rather than a one-shot adoption decision: farmers' willingness depends on government incentives and agribusiness service availability; agribusiness promotion becomes profitable only when adoption is sufficiently likely; and local governments face both accountability pressure and a free-riding incentive once adoption generates public ecological benefits. A tripartite evolutionary-game framework is therefore necessary because it captures interdependent, boundedly rational strategy adjustment, possible free-riding, and path-dependent transitions among coordination success, withdrawal, and persistent oscillation.

1.3. Research Gaps and Contributions

Tripartite evolutionary-game studies of green agriculture have clarified how governments, intermediaries, and producers interact. Zuo (2023) examines environmental regulation and green credit in farmers' adoption of green production technology [7]; Chen et al. (2024) model promotion among heterogeneous actors and find initial willingness decisive [8]; and, closest to our setting, a study of cultivated-land quality protection finds hybrid upfront-plus-performance incentives more effective than single instruments [9]. Outside agriculture, Xie and Jin (2019) show the method's relevance to land policy [10].

These contributions are valuable, yet four gaps remain. First, the literature analyzes convergence to evolutionarily stable strategies but leaves behavior under non-convergence uncharacterized. Second, policy effectiveness is treated as independent of the starting point, overlooking that the starting point may itself select among multiple equilibria, as documented by Carter and Barrett (2006) for adoption traps [11]. Third, the comparative effectiveness of instruments, and its dependence on the system's regime, is rarely isolated.

Fourth, quantitative analyses tailored to the black-soil setting, guarding against subsidy capture, remain scarce.

To address these gaps, this paper develops a tripartite evolutionary game of green-technology adoption among local governments, agribusinesses, and smallholder farmers, calibrated to the black-soil setting. Its contributions are fourfold. First, the model is free-riding-proof: its payoffs encode adoption subsidies and penalties, a performance-based agribusiness subsidy, bidirectional technology spillover, and governmental free-riding, with the agribusiness subsidy paid only upon realized adoption, foreclosing subsidy capture. Second, we characterize a policy-reversal trap: under low initial willingness, the system reaches no stable strategy but enters a sustained, conservative oscillation, for which we construct a first integral and verify its conservation to machine precision, placing agricultural diffusion within the Hamiltonian-like dynamics identified by Hofbauer (1996) [12]. Third, a sharp initial-willingness threshold splits the state space into a basin converging to the market-sustained equilibrium and one trapped in oscillation, an instance of the multiple-equilibria logic of adoption traps [13], so the same instrument can act in opposite directions across regimes. Fourth, the intuitively ideal fully coordinated state proves unstable; the stable ideal is market-sustained adoption after the government withdraws, and within the trap credible penalties and added agribusiness capacity can engineer escape, whereas untargeted farmer subsidies are less effective and can even deepen the oscillation. Public intervention is thus best understood as a transitional catalyst with a built-in exit, not a permanent fixture.

2. Literature Review

This study draws on, and contributes to, four strands of literature: the use of evolutionary game theory in environmental and resource governance, tripartite evolutionary-game models of green agricultural technology, the empirical determinants of farmers' adoption of conservation practices, and the role of agricultural socialized-service organizations.

2.1. Evolutionary Game Theory and Its Use in Resource Governance

Classical game theory presumes fully rational agents with complete information, an assumption ill-suited to the diffuse, repeated, and information-poor interactions that characterize environmental governance. Evolutionary game theory relaxes this assumption by modeling boundedly rational populations whose strategy frequencies co-evolve through learning and imitation, with the replicator dynamic describing how successful strategies spread. The conceptual cornerstone of the field is the evolutionarily stable strategy introduced by Maynard Smith and Price (1973) [14], and the replicator equation that operationalizes the dynamic was formulated by Taylor and Jonker (1978) [15]. The subsequent development of the theory, including its application to bimatrix and asymmetric conflicts, was synthesized by Hofbauer and Sigmund (2003) in an authoritative review whose framework this paper follows [6].

The use of evolutionary game theory in economic and policy analysis was placed on a rigorous footing by Friedman (1991), who established the connection between evolutionarily stable strategies and the local stability properties of the Jacobian at the corresponding equilibrium [16]. That connection is the methodological foundation for the eight-vertex stability analysis undertaken in Section 4. Within the broader field, this study engages most directly with two threads. The first concerns the dynamics of asymmetric games whose interior fixed points are neutrally stable rather than asymptotically stable and therefore exhibit closed orbits around centers, a class that Hofbauer (1996) argues may be viewed as Hamiltonian-like [12]. The second concerns the deployment of evolutionary game theory in collaborative environmental governance, and particularly in studies of green-technology

incentives, where penalty design and the inclusion of multiple stakeholders consistently emerge as decisive, as Wang and Shang (2024) illustrate for pollution control [17].

2.2. Tripartite Evolutionary Games of Green Agricultural Technology

The application of tripartite evolutionary game theory to green agriculture has grown rapidly. A representative line of work, exemplified by Zuo (2023), models government, banks, and farmers under environmental regulation and green credit, and finds that farmers adopt green production technology only when the technical subsidy exceeds a critical value [7]. A more recent and methodologically close study by Chen et al. (2024) examines green-technology promotion among smallholders, family farms, and agricultural service providers, and identifies initial willingness as a decisive condition for diffusion [8]. This last finding directly motivates the central role that initial willingness plays in this analysis.

Other tripartite agricultural models examine adjacent settings. Wang and Shang (2024) develop a framework for non-point source pollution control involving government, village collectives, and farmers, illustrating how supervision and the choice between structural and non-structural measures combine to shape outcomes [17]. Closer to the institutional setting of this paper, a study of cultivated-land quality protection designs incentives through interactions among governments, agricultural production outsourcing service organizations, and farmers, concluding that hybrid incentives combining upfront subsidies with performance-based rewards sustain cooperation more effectively than either instrument alone [9]. That conclusion is the empirical referent for the performance-based subsidy design introduced in Section 3.

Two shared limitations of this strand motivate the analysis. The models typically focus on convergence to evolutionarily stable strategies and stop short of characterizing the dynamics when convergence fails, and they generally analyze policy effectiveness as if it were independent of the system's initial state. Both omissions matter, because the system can fail to converge altogether, and the same instrument can have opposite effects depending on where the system starts.

2.3. Determinants of Farmers' Adoption of Conservation Practices

A substantial empirical literature identifies the micro-level determinants of conservation-technology adoption and provides the behavioral foundation for the model's parameters. For the black-soil region specifically, the household-survey study by Jilin Province by Guo et al. (2022) shows that knowledge of government subsidies, access to socialized technical services, and use of agricultural machinery are decisive influences on whether farmers adopt conservation tillage [18]. This evidence directly underpins the specification that farmer adoption depends jointly on government incentives, through the subsidy and penalty channels, and on agribusiness-mediated technology spillover.

Two features of the evidence are particularly salient for the model. The first is that conservation tillage entails substantial upfront costs and a transitional risk of yield reduction, meaning that its short-run private return is often negative even though its long-run and ecological returns are positive, which is exactly the configuration encoded in the sign condition of Assumption 6 in Section 3. The second is that adoption is strongly conditioned on the availability of external technical services, which implies that the smallholder's payoff cannot be specified independently of the service provider's behavior. This interdependence is the rationale for the bidirectional linkage between agribusiness promotion and farmer adoption in the payoff matrix.

2.4. The Role of Agricultural Socialized-Service Organizations

The fourth strand explains why a distinct agribusiness population is essential to the model rather than incidental to it. Because conservation tillage is scale-sensitive and

equipment-intensive, requiring no-till seeders, straw-mulching machinery, and technical know-how that fragmented smallholders cannot efficiently acquire alone, the gap between what a smallholder needs and what a smallholder can provide must be bridged by an intermediary. Agricultural socialized-service organizations, including cooperatives, specialized service firms, and machinery-service providers, perform this role by integrating green technologies into the production process on smallholders' behalf. Qing et al. (2023) show empirically that outsourced machinery services significantly raise farmers' adoption of green practices such as no-till cultivation and straw return [19], while Qiu et al. (2021) document how mechanization services allow smallholders to overcome the scale barrier by substituting service scale for land scale [20].

This bridging role has a direct policy counterpart in China's increasing reliance on result-oriented subsidy-after-service arrangements, under which public support for service providers is disbursed only after the services demonstrably reach farmers. The performance-contingent logic of these arrangements is the real-world template for the agribusiness subsidy instrument introduced in Section 3, and it accords with the finding that hybrid incentives, combining upfront and performance-based components, outperform single-instrument designs [9].

Recent complex-systems research also motivates this extension beyond convergence-only evolutionary games. Xue et al. (2024) [21] integrate evolutionary game theory and system dynamics to analyze multi-player regulation, while Zhang et al. (2024) [22] develop a two-layer network evolutionary-game model for complex systems. In parallel, bibliometric and behavioral studies of artificial intelligence (AI) in management and technology adoption, such as Tatarczak (2024) [23] and Cheng et al. (2026) [24], show that digital tools and generative AI are becoming relevant boundary conditions for technology-diffusion games. These studies broaden the comparison set beyond agricultural adoption and highlight why this paper emphasizes non-convergent dynamics, threshold effects, and state-dependent policy instruments.

2.5. Research Gaps

Taken together, the four strands leave four gaps that this study addresses, and the contributions previewed in Section 1 map onto them directly. The first gap concerns non-convergent dynamics. Existing tripartite agricultural games predominantly analyze convergence to evolutionarily stable strategies and do not characterize what happens when convergence fails, whereas this study shows that under low initial willingness the system enters a conservative oscillation, the policy-reversal trap, and provides its analytical characterization through a first integral, situating it within the theory of conservative evolutionary dynamics studied by Hofbauer (1996) [12]. The second gap concerns the role of initial conditions. The literature largely treats policy effectiveness as state-independent, whereas this study demonstrates a sharp initial-willingness threshold that partitions the state space into distinct basins, an instance of the multiple-equilibria logic of adoption traps analyzed by Carter and Barrett (2006) [11]. Because the policy implications of multiple-equilibria configurations differ qualitatively from those of single-equilibrium settings, they justify decisive one-off intervention rather than indefinite low-level support, a point developed by Barrett and Carter (2013) [13]. The third gap concerns the comparison of instruments, whose relative effectiveness as a function of the system's regime is seldom isolated, and which this study addresses by showing that within the modeled trap penalties and capacity-building can engineer escape while untargeted farmer subsidies are less effective and may even deepen the oscillation. The fourth gap concerns context, since quantitative tripartite analyses tailored to the black-soil setting, incorporating its specific institutional instruments and a free-riding-proof performance subsidy, remain scarce.

3. Model Construction

3.1. Problem Description

Promoting green agricultural technologies, most notably conservation tillage practices such as the “Lishu Model” of no-till straw-mulching, is central to arresting the degradation of Northeast China’s black soil, whose organic matter has declined by 50 to 60 percent and whose topsoil has thinned from 50 to 60 cm to roughly 30 cm over less than a century of cultivation [2]. Yet the diffusion of such technologies is impeded by a structural coordination problem, in which the three principal actors involved each weigh private costs against private benefits and none can unilaterally guarantee a socially desirable outcome. The structure of these interactions, with the four channels linking the three populations, is summarized in Figure 1.

Tripartite Evolutionary Game: Green Technology Adoption in the Black Soil Region

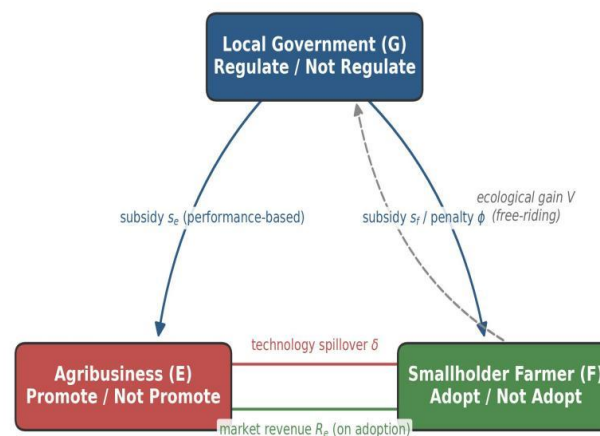


Figure 1. Structure of the tripartite evolutionary game.

We consider three boundedly rational populations of agents whose strategic interactions govern the diffusion process:

- Local governments (G), which decide whether to actively regulate, by monitoring implementation, disbursing subsidies, and penalizing non-adoption, or to remain passive. Active regulation is costly but advances food-security and ecological mandates under the Black Soil Protection Law (effective 1 August 2022) [2].
- Agribusinesses (E), a stylized representation of agricultural socialized-service organizations, cooperatives, and machinery-service firms, which decide whether to develop and promote the green technology package, supplying no-till seeders, straw-mulching services, and technical guidance, or to abstain. Because conservation tillage is scale-sensitive and equipment-intensive, smallholders typically cannot adopt it efficiently without such intermediaries, as Qiu et al. (2021) document [20].
- Smallholder farmers (F), who decide whether to adopt green technology or to continue conventional tillage.

The three populations are linked by four economically grounded channels that the model is designed to capture. First, the government–farmer channel operates through adoption subsidies and penalties for non-adoption. Second, the government–agribusiness channel operates through a performance-based subsidy paid only when promotion translates into actual adoption. Third, the agribusiness–farmer channel is bidirectional, since agribusiness promotion lowers the effective cost and raises the effective return of adoption for farmers through a technology-spillover effect, while farmer adoption in turn generates the service revenue that makes promotion profitable, an interdependence documented by Qing et al. (2023) [19]. Fourth, a free-riding channel arises because the ecological and

food-security gains from farmer adoption accrue to the government regardless of whether it incurs regulatory costs, a tension also present in other tripartite environmental games.

3.2. Basic Assumptions

Following the standard framework of evolutionary game theory under bounded rationality synthesized by Hofbauer and Sigmund (2003) [6], in which agents do not optimize globally but adjust their strategies over time by imitating relatively successful behaviors, the model adopts the following assumptions.

Assumption 1 (Players and strategies). *The three populations are local governments, agribusinesses, and smallholder farmers. Each has two pure strategies. The government chooses Regulate (active regulation with subsidy and penalty) or Not Regulate; the agribusiness chooses Promote (develop and extend the green technology) or Not Promote; the farmer chooses Adopt (the green technology) or Not Adopt. Let $x \in [0, 1]$ denote the proportion of governments that Regulate, $y \in [0, 1]$ the proportion of agribusinesses that Promote, and $z \in [0, 1]$ the proportion of farmers that Adopt. The complementary proportions are $1 - x$, $1 - y$, and $1 - z$, respectively.*

Assumption 2 (Government costs, benefits, and instruments). *Active regulation incurs a supervision cost C_g , covering monitoring, area verification, and quality inspection, which are responsibilities explicitly assigned to municipal and county governments in China's black-soil conservation-tillage implementation schemes [4]. When farmers adopt the green technology, the government obtains an ecological and food-security benefit V , which encompasses improved soil quality, grain-production capacity, and political performance, consistent with the strategic framing of black soil as "the giant panda of cultivated land" [2]. If the government does not regulate and farmers do not adopt, it bears an accountability loss θ reflecting top-down assessment pressure. When regulating, the government grants an adoption subsidy s_f to adopting farmers, financed under the cultivated-land fertility-protection transfers that cover some 220 million farming households [3] and imposes a penalty ϕ on non-adopting farmers, for example the forfeiture of subsidy eligibility. The instruments are modeled this way because monitoring, transfers, and penalties are precisely the levers the implementation schemes place in local-government hands.*

Assumption 3 (Performance-based agribusiness subsidy). *When regulating, the government grants the agribusiness a subsidy s_e , but only when promotion results in actual farmer adoption. This performance-contingent design follows the "subsidy-after-service" principle that has governed Chinese support for agricultural socialized services since 2013 [3] and mirrors the result-oriented "soil-fertility index insurance" piloted in Lishu County, under which incentive payments are released only after measured improvements in soil fertility [3]. This design forestalls a moral-hazard problem familiar in incentive design, whereby weak, non-contingent subsidies invite passive participation or outright free-riding by subsidized firms. By tying s_e to adoption, an agribusiness that promotes but fails to induce adoption (combination 2 below) receives no subsidy and bears its promotion cost C_e in full.*

Assumption 4 (Agribusiness costs and returns). *Promotion incurs a development-and-extension cost C_e (machinery, technical training, service provision). When farmers adopt, the agribusiness earns market revenue R_e (service fees and equipment sales). The model assumes $R_e > C_e$, so that promotion is profitable once adoption is achieved, which reflects the financial viability that sustains socialized-service provision [20].*

Assumption 5 (Farmer costs, returns, and spillover). *Adoption incurs a cost C_f , comprising machinery investment, learning costs, and the risk of short-term yield reduction during the transition. Adoption yields an incremental return R_f from yield gains (conservation tillage raises maize yields by roughly 8–10%) and input savings (CNY 1000–2920 per hectare in net cost reduction in Lishu demonstration fields) [3], together with avoidance of a long-run land-degradation loss L .*

incurred under continued conventional tillage [2]. When the agribusiness promotes, an adopting farmer obtains an additional benefit δ reflecting technology spillover, namely, access to machinery, mulching services, and technical knowledge that smallholders cannot efficiently obtain alone, an effect Qing et al. (2023) document empirically [19]. For the black-soil region in particular, Guo et al. (2022) confirm that knowledge of government subsidies and access to socialized technical services are decisive determinants of conservation-tillage adoption [18].

Assumption 6 (Sign conditions characterizing the adoption dilemma). To represent the empirically observed adoption difficulty, the model assumes $R_f - C_f + L < 0$, so that in the absence of agribusiness support and government intervention farmers have no autonomous incentive to adopt, because the short-run cost exceeds the immediate net return. However, $R_f - C_f + L + \delta > 0$, so that with agribusiness technology spillover adoption becomes individually rational. This pair of conditions formalizes the central role of agricultural socialized-service organizations, since they convert an otherwise unviable practice into a viable one, consistent with the scale barrier argument of Qiu et al. (2021) [20]. Economically, the inequalities say that the private adoption decision hinges entirely on whether the spillover δ is present, which is why the agribusiness population cannot be omitted from the model. We further assume $\theta > C_g$, so that accountability pressure exceeds the direct cost of supervision, giving the government a genuine regulatory motive.

A simple numerical illustration clarifies the economic meaning of these inequalities. Under the baseline calibration used in Section 5, $R_f = 2.5$, $C_f = 5$, $L = 2$, and $\delta = 3$. Hence $R_f - C_f + L = -0.5 < 0$, meaning that without agribusiness support the private return from adoption plus avoided degradation loss is still insufficient to offset adoption costs. Once agribusiness promotion supplies machinery services, technical guidance, and knowledge spillover, $R_f - C_f + L + \delta = 2.5 > 0$, so adoption becomes individually rational. The two inequalities therefore encode the core dilemma of conservation tillage: high short-term private costs prevent autonomous uptake, but long-term returns become positive when service organizations activate the technology-spillover channel.

All payoffs are defined as increments relative to a normalized baseline (conventional farming income for farmers, normal operating profit for agribusinesses) set to zero. Because the baseline appears in every strategy combination, it cancels out in the replicator dynamics and does not affect the evolutionary trajectories; this normalization is a standard modeling convention. Parameters are therefore dimensionless relative magnitudes: their absolute values are immaterial, and only their relative ordering governs the system's behavior. The robustness of our conclusions to this normalization is verified through sensitivity analysis and a $\pm 10\%$ parameter-perturbation test in Section 5. The notation is summarized in Table 1.

Table 1. Model parameters and their definitions.

Symbol	Definition	Real-World Anchor
x	Proportion of governments that Regulate	—
y	Proportion of agribusinesses that Promote	—
z	Proportion of farmers that Adopt	—
C_g	Government supervision cost	Monitoring, area/quality verification (national/Liaoning schemes) [4]
V	Government ecological & food-security benefit from adoption	National black-soil protection objectives [3]
θ	Government accountability loss (no regulation, no adoption)	Top-down assessment pressure
s_f	Adoption subsidy to farmers (when regulating)	Cultivated-land fertility-protection subsidy [3]

Table 1. Cont.

Symbol	Definition	Real-World Anchor
ϕ	Penalty on non-adopting farmers (when regulating)	Forfeiture of subsidy eligibility
s_e	Performance-based subsidy to agribusiness (regulating AND adoption)	“Subsidy-after-service”; soil-fertility index insurance [3]
C_e	Agribusiness promotion cost	Machinery, training, service provision
R_e	Agribusiness market revenue (when adoption occurs)	Service fees, equipment sales
C_f	Farmer adoption cost	Machinery, learning, transitional yield risk
R_f	Farmer incremental return from adoption	Yield gain 8–10%; input saving CNY 1000–2920/ha [3]
δ	Technology-spillover benefit (when promoted)	Access to machinery/services/knowledge [19]
L	Long-run land-degradation loss (non-adoption)	Soil organic-matter and topsoil decline [2]

3.3. Payoff Matrix

Based on Assumptions 1–6, the payoffs of the three agents under each of the eight strategy combinations are presented in Table 2, with entries ordered as (piG, piE, piF).

Table 2. Tripartite payoff matrix.

Government	Agribusiness	Farmer	Probability	π_G	π_E	π_F
Regulate	Promote	Adopt	xyz	$-C_g + V - s_f - s_e$	$-C_e + R_e + s_e$	$R_f - C_f + \delta + s_f$
Regulate	Promote	Not Adopt	$xy(1 - z)$	$-C_g + \phi$	$-C_e$	$-L - \phi$
Regulate	Not Promote	Adopt	$x(1 - y)z$	$-C_g + V - s_f$	0	$R_f - C_f + s_f$
Regulate	Not Promote	Not Adopt	$x(1 - y)(1 - z)$	$-C_g + \phi$	0	$-L - \phi$
Not Regulate	Promote	Adopt	$(1 - x)yz$	V	$-C_e + R_e$	$R_f - C_f + \delta$
Not Regulate	Promote	Not Adopt	$(1 - x)y(1 - z)$	$-\theta$	$-C_e$	$-L$
Not Regulate	Not Promote	Adopt	$(1 - x)(1 - y)z$	V	0	$R_f - C_f$
Not Regulate	Not Promote	Not Adopt	$(1 - x)(1 - y)(1 - z)$	$-\theta$	0	$-L$

Several structural features of Table 2 warrant emphasis, as they encode the four channels described in Section 3.1. The spillover benefit δ and the agribusiness revenue R_e appear only in combinations where promotion and adoption coincide (rows 1 and 5), capturing the bidirectional agribusiness–farmer linkage: neither party realizes these gains without the other. The performance-based subsidy s_e appears only when the government regulates and adoption occurs (row 1); when promotion fails to induce adoption (row 2), the agribusiness receives $-C_e$ alone, closing the subsidy-fraud channel. The government benefit V appears in every combination featuring farmer adoption (rows 1, 3, 5, 7), irrespective of regulation, formalizing the free-riding tension: the government reaps the social returns of adoption whether or not it pays to regulate. Finally, the degradation loss L appears in every non-adoption combination, and the accountability loss θ arises specifically when the government abstains from regulation while farmers fail to adopt.

4. Stability Analysis

4.1. Replicator Dynamics

Under bounded rationality, each population revises its strategy over time according to the replicator dynamic of Taylor and Jonker (1978) [15], in which the growth rate of a strategy’s frequency is proportional to the difference between its expected payoff and the

population average. Let $U_G^{(R)}$ and $U_G^{(NR)}$ denote the expected payoffs of a regulating and a non-regulating government, respectively, with analogous notation for the agribusiness ($U_E^{(P)}$, $U_E^{(NP)}$) and the farmer ($U_F^{(A)}$, $U_F^{(NA)}$). From the payoff matrix (Table 2), the expected payoffs are obtained by averaging each agent's payoffs over the mixed strategies of the other two populations.

For the government, regulating and not regulating yield

$$U_G^{(R)} = -C_g + \varphi + Vz - \varphi z - s_e yz - s_f z, \quad U_G^{(NR)} = Vz + \theta z - \theta.$$

For the agribusiness, promoting and not promoting yield

$$U_E^{(P)} = -C_e + R_e z + s_e xz, \quad U_E^{(NP)} = 0.$$

For the farmer, adopting and not adopting yield

$$U_F^{(A)} = -C_f + R_f + \delta y + s_f x, \quad U_F^{(NA)} = -L - \varphi x.$$

The evolutionary pressure acting on each population is its fitness difference, defined as the gap between the expected payoffs of its two strategies. For the government, agribusiness, and farmer these differences are, respectively,

$$\Delta U_G = U_G^{(R)} - U_G^{(NR)} = (\varphi + \theta)(1 - z) - C_g - s_f z - s_e yz \quad (1)$$

$$\Delta U_E = U_E^{(P)} - U_E^{(NP)} = z(R_e + s_e x) - C_e \quad (2)$$

$$\Delta U_F = U_F^{(A)} - U_F^{(NA)} = (R_f - C_f + L) + \delta y + (s_f + \varphi)x \quad (3)$$

Each fitness difference depends only on the strategy frequencies of the other two populations, never on the deciding population's own frequency; this property drives the replicator dynamics and recurs throughout the stability analysis, since the bracketed term of each replicator Equations (7)–(9) below is exactly the corresponding fitness difference. Averaging each population's two strategy payoffs by the relevant strategy frequency gives the mean payoffs

$$\bar{U}_G = xU_G^{(R)} + (1 - x)U_G^{(NR)} \quad (4)$$

$$\bar{U}_E = yU_E^{(P)} + (1 - y)U_E^{(NP)} \quad (5)$$

$$\bar{U}_F = zU_F^{(A)} + (1 - z)U_F^{(NA)} \quad (6)$$

Writing this compactly as $\bar{U}_i = p_i U_i^+ + (1 - p_i) U_i^-$, the replicator equation $\dot{p}_i = p_i(U_i^+ - \bar{U}_i) = p_i(1 - p_i)(U_i^+ - U_i^-)$ gives the following three-dimensional system:

$$\dot{x} = x(1 - x)[(\varphi + \theta)(1 - z) - C_g - s_f z - s_e yz] \quad (7)$$

$$\dot{y} = y(1 - y)[z(R_e + s_e x) - C_e] \quad (8)$$

$$\dot{z} = z(1 - z)[(R_f - C_f + L) + \delta y + (s_f + \varphi)x] \quad (9)$$

All algebraic derivations and the stability results below were independently verified using symbolic computation (SymPy). All symbolic calculations, ordinary differential equation numerical integration, trajectory visualization and parameter sensitivity analysis in this paper are fully implemented based on Python 3.8, with SymPy for symbolic algebra, SciPy for ODE solving, and Matplotlib for drawing phase portraits and evolutionary trajectory graphs.

Equations (7)–(9) already reveal three structural properties of the system.

First, the ecological benefit V does not appear in the government Equation (7). Although V enters both $U_G^{(R)}$ and $U_G^{(NR)}$, it does so identically (as Vz) and therefore cancels out in the payoff difference. Economically, because the social returns of farmer adoption accrue to the government whether or not it regulates, V provides no marginal incentive to regulate. The government's regulatory decision is governed entirely by the relative magnitudes of its supervision cost C_g , its policy instruments s_f and s_e , and the penalty/accountability terms ϕ and θ . This is a direct formal expression of the free-riding channel.

Second, the farmer's autonomous adoption incentive is captured by the state-independent term $(R_f - C_f + L)$ in Equation (9). Under Assumption 6, this term is negative, so in the absence of agribusiness promotion ($y = 0$) and government regulation ($x = 0$) the farmer's fitness difference is negative and adoption decays. Adoption is driven up only by the promotion-dependent term δy and the regulation-dependent term $(s_f + \phi)x$.

Third, the agribusiness is a pure responder: Equation (8) contains no state-independent incentive term. Promotion is profitable only insofar as $z(R_e + s_e x)$ exceeds C_e ; if farmers do not adopt ($z \rightarrow 0$), promotion is necessarily abandoned. The farmer population thus acts as the system's prime mover, with the agribusiness following.

4.2. Equilibrium Points and Local Stability

Setting $\dot{x} = \dot{y} = \dot{z} = 0$ yields, besides possible interior solutions, the eight pure-strategy equilibria located at the vertices of the unit cube, $E_k = (x^*, y^*, z^*) \in \{0, 1\}^3$. Following the standard method established by Friedman (1991) [16], local stability is assessed via the Jacobian matrix

$$J = \begin{pmatrix} \frac{\partial \dot{x}}{\partial x} & \frac{\partial \dot{x}}{\partial y} & \frac{\partial \dot{x}}{\partial z} \\ \frac{\partial \dot{y}}{\partial x} & \frac{\partial \dot{y}}{\partial y} & \frac{\partial \dot{y}}{\partial z} \\ \frac{\partial \dot{z}}{\partial x} & \frac{\partial \dot{z}}{\partial y} & \frac{\partial \dot{z}}{\partial z} \end{pmatrix}.$$

Differentiating the right-hand sides of (7)–(9) and using the fitness differences (1)–(3), the three diagonal entries of the Jacobian are

$$\frac{\partial \dot{x}}{\partial x} = (1 - 2x)\Delta U_G \quad (10)$$

$$\frac{\partial \dot{y}}{\partial y} = (1 - 2y)\Delta U_E \quad (11)$$

$$\frac{\partial \dot{z}}{\partial z} = (1 - 2z)\Delta U_F \quad (12)$$

Each off-diagonal entry retains a factor of $x(1 - x)$, $y(1 - y)$, or $z(1 - z)$ and therefore vanishes at every vertex of the unit cube, where each coordinate is 0 or 1 (verified symbolically), so the Jacobian is diagonal there and its three eigenvalues coincide with the diagonal entries. Because the prefactors $(1 - 2x)$, $(1 - 2y)$, and $(1 - 2z)$ each equal +1 when the corresponding coordinate is 0 and −1 when it is 1, every eigenvalue reduces to plus or minus the corresponding fitness difference evaluated at that vertex, which is exactly how the entries of Table 3 are generated. A vertex is an evolutionarily stable strategy, that is, an asymptotically stable equilibrium, if and only if all three eigenvalues are negative [16]. The eigenvalues at each vertex are listed in Table 3.

Table 3. Eigenvalues and stability conditions of the eight equilibria.

Equilibrium (x, y, z)	λ_x	λ_y	λ_z	Stability Condition
$E_1(0, 0, 0)$	$\phi + \theta - C_g$	$-C_e$	$R_f - C_f + L$	$C_g > \phi + \theta$ $R_f - C_f + L < 0$
$E_2(0, 0, 1)$	$-C_g - s_f$	$R_e - C_e$	$-(R_f - C_f + L)$	$R_e < C_e$ $R_f - C_f + L > 0$
$E_3(0, 1, 0)$	$\phi + \theta - C_g$	C_e	$R_f - C_f + L + \delta$	never ($\lambda_y = C_e > 0$)
$E_4(0, 1, 1)$	$-C_g - s_e - s_f$	$C_e - R_e$	$-(R_f - C_f + L + \delta)$	$R_e > C_e$ $R_f - C_f + L + \delta > 0$
$E_5(1, 0, 0)$	$C_g - \phi - \theta$	$-C_e$	$R_f - C_f + L + \phi + s_f$	$C_g < \phi + \theta$ $R_f - C_f + L + \phi + s_f < 0$
$E_6(1, 0, 1)$	$C_g + s_f$	$R_e + s_e - C_e$	$-(R_f - C_f + L + \phi + s_f)$	never ($\lambda_x = C_g + s_f > 0$)
$E_7(1, 1, 0)$	$C_g - \phi - \theta$	C_e	$R_f - C_f + L + \delta$ $+ \phi + s_f$	never ($\lambda_y = C_e > 0$)
$E_8(1, 1, 1)$	$C_g + s_e + s_f$	$C_e - R_e - s_e$	$-(R_f - C_f + L + \delta$ $+ \phi + s_f)$	never ($\lambda_x = C_g + s_e + s_f > 0$)

Three results of direct policy relevance follow.

Result 1 (The full-coordination state is never stable). At $E_8(1, 1, 1)$, the intuitively ideal state in which the government regulates, the agribusiness promotes, and farmers adopt, the eigenvalue $\lambda_x = C_g + s_e + s_f > 0$ unconditionally. Once promotion and adoption are established ($y = z = 1$), the penalty and accountability terms vanish (they are multiplied by $1 - z = 0$), the benefit V has already canceled, and regulation entails only the cost C_g plus the subsidies $s_e + s_f$. The government therefore strictly prefers to withdraw. Persistent government regulation coexisting with universal adoption is thus dynamically unsustainable, a finding that contrasts with the common presumption that the government-monitored full-cooperation state is the policy goal.

Result 2 (The ideal ESS is government withdrawal). The interior-relevant ESS is $E_4(0, 1, 1)$: the government withdraws, while the agribusiness promotes and farmers adopt, sustained by the market alone. This vertex is an ESS when $R_e > C_e$, so that promotion is profitable by Assumption 4, and when $R_f - C_f + L + \delta > 0$, so that adoption is individually rational given spillover by Assumption 6, both of which are guaranteed by the assumptions. The socially desirable outcome is therefore self-sustaining without continued public expenditure, a pattern consistent with the notion that subsidized green practices can persist after subsidy withdrawal once the market has stabilized.

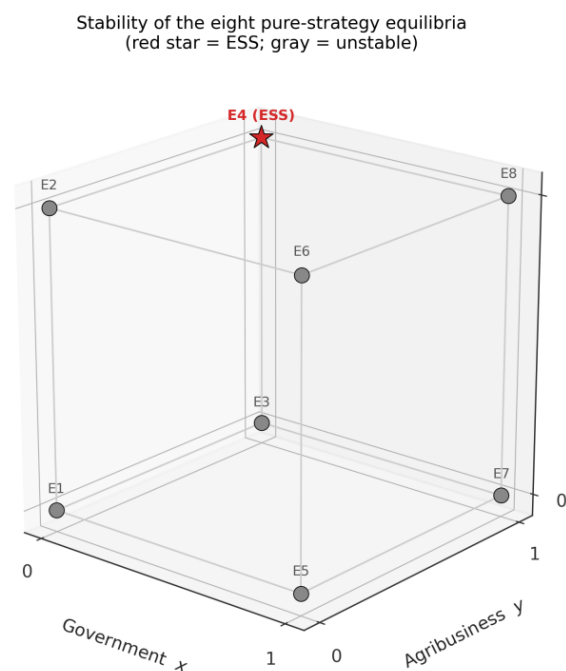
Result 3 (Regulation is transitional, not terminal). Every equilibrium with $x^* = 1$ requires farmer non-adoption to be stable (only E_5 can satisfy this, and only when adoption remains unattractive even under regulation). Sustained government regulation is thus stable only while farmers remain unwilling to adopt. The government's role is to push λ_z positive through the term $(s_f + \phi)x$, thereby driving farmers across the adoption threshold, after which it should exit. Public intervention is properly understood as a transitional instrument for building autonomous adoption capacity, by raising R_f , lowering C_f , and enlarging δ , rather than as a permanent fixture.

As Table 4 shows, this classification clarifies the scope of Result 2. E_2 cannot be simultaneously stable with E_4 because E_2 requires $R_e < C_e$ whereas E_4 requires $R_e > C_e$. E_5 , by contrast, can coexist with E_4 if $\phi + \theta > C_g$, $R_f - C_f + L + \phi + s_f < 0$, and $R_f - C_f + L + \delta > 0$ hold at the same time; equivalently, adoption without spillover and regulation remains unattractive even under the penalty/subsidy package, while adoption with agribusiness spillover is viable. This double-stability case is excluded by the baseline calibration, for which $R_f - C_f + L = -0.5$ and $R_f - C_f + L + \phi + s_f = 4.5 > 0$, so E_5 is unstable. Thus, E_4 is the unique stable pure-strategy vertex under the baseline, but it is not globally attractive because low-initial-willingness trajectories can enter the boundary oscillatory regime.

Table 4. Parameter-interval classification of vertex stability, where $A = R_f - C_f + L$.

Equilibrium	Point	Stability Condition	Implication
E1	(0, 0, 0)	$\phi + \theta < C_g$ and $R_f - C_f + L < 0$	Low-adoption ESS if regulation incentive is weak.
E2	(0, 0, 1)	$R_e < C_e$ and $R_f - C_f + L > 0$	Cannot coexist with E_4 under Assumption 4.
E3	(0, 1, 0)	Never	$\lambda_y = C_e > 0$.
E4	(0, 1, 1)	$R_e > C_e$ and $R_f - C_f + L + \delta > 0$	Ideal ESS under baseline and maintained assumptions.
E5	(1, 0, 0)	$\phi + \theta > C_g$ and $R_f - C_f + L + \phi + s_f < 0$	Can coexist with E_4 in broader parameter intervals.
E6	(1, 0, 1)	Never	$\lambda_x = C_g + s_f > 0$.
E7	(1, 1, 0)	Never	$\lambda_y = C_e > 0$.
E8	(1, 1, 1)	Never	$\lambda_x = C_g + s_f + s_e > 0$.

The stability classification of all eight vertices is visualized in Figure 2, in which only E_4 emerges as an evolutionarily stable strategy.

**Figure 2.** Stability of the eight pure-strategy equilibria (red star: the ESS E_4 ; gray: unstable).

4.3. Conservative Dynamics and Sustained Oscillation

Results 1–3 describe the system's behavior when it converges. However, the conditions of Assumption 6 ($R_f - C_f + L < 0$) imply that farmers possess no autonomous adoption incentive, raising the possibility that, for sufficiently low initial willingness, the system fails to converge to any ESS. We now show that this is indeed the case, and that the resulting dynamics are conservative.

Consider the boundary face $y = 0$ (agribusiness absent), to which trajectories starting from low initial willingness are attracted (Section 5). On this face, the system reduces to the planar system.

The following first-integral result is therefore a boundary-regime result, not a claim that the full three-dimensional system is globally conservative. The analysis applies after low-initial-willingness trajectories have approached the agribusiness-absent face $y = 0$;

the full system can still exhibit transient three-dimensional motion before this reduction becomes accurate.

$$\dot{x} = x(1-x)[(\varphi + \theta)(1-z) - C_g - s_f z] \quad (13)$$

$$\dot{z} = z(1-z)[(R_f - C_f + L) + (s_f + \varphi)x] \quad (14)$$

Writing $A(z)$ and $B(x)$, the orbit equation is separable. Integrating,

$$A(z) = (\varphi + \theta)(1-z) - C_g - s_f z, \quad B(x) = (R_f - C_f + L) + (s_f + \varphi)x.$$

$$\frac{dz}{dx} = \frac{z(1-z)B(x)}{x(1-x)A(z)}.$$

$$H(x, z) = \int \frac{B(x)}{x(1-x)} dx - \int \frac{A(z)}{z(1-z)} dz = \text{const} \quad (15)$$

so $H(x, z)$ is a first integral (conserved quantity) of the planar system. Because $\frac{1}{u(1-u)} = \frac{1}{u} + \frac{1}{1-u}$, each integral evaluates to a combination of logarithmic and linear terms, giving H the same logarithm-plus-linear structure as the classical conserved quantity of the Lotka–Volterra predator–prey system. Numerically, H is conserved along trajectories to machine precision (relative variation below 10^{-11} over $t \in [0, 300]$ for all tested initial conditions), confirming the analytical construction.

The system (13) and (14) therefore possesses a unique interior fixed point that is a neutral center: trajectories form a family of nested closed orbits, each lying on a level set $H = \text{const}$, and the system circulates indefinitely without converging. These conserved-quantity diagnostics are displayed in Figures 3–5: the bold yellow curves highlight several representative orbits selected for illustration; background color and thin contour lines show the full level-set structure of $H(x, z)$, as indicated by the color bar, the nested closed orbits coincide with the level sets of the first integral H (Figure 3), which together form a three-dimensional landscape over the (x, z) face (Figure 4), and the planar phase portrait shows the vector field circulating around the neutral center without inward or outward drift (Figure 5). This places the model within the class of conservative, Hamiltonian-like evolutionary dynamics analyzed by Hofbauer (1996) [12] and by Akin and Losert (1984) [25] for asymmetric and zero-sum conflicts, in which interior equilibria of the replicator dynamics have eigenvalues with zero real part and are only neutrally stable rather than asymptotically stable, as discussed by Hofbauer and Sigmund (1998) [26]. It is worth emphasizing that the oscillation is neutrally stable and center-type, not an asymptotically stable limit cycle. The orbits are non-isolated, and as Section 5 confirms numerically, a perturbed trajectory does not return to its original orbit but settles onto a neighboring one. Establishing whether higher-order or structural modifications could convert this center into an isolated limit cycle would require a normal-form, or Lyapunov-coefficient, analysis in the sense of Hofbauer (1996) [12], and lies beyond the scope of this study.

The conservative nature of the oscillation carries a distinctive policy implication, as developed in Section 6: because the dynamics preserve H , a one-off policy shock does not dissipate but permanently relocates the system to a different orbit. Escaping the oscillatory regime altogether therefore requires not a transient impulse but a structural change in parameters sufficient to move the system into the basin of attraction of E_4 .

The government's incentive to regulate depends on the system's position in state space. The sign of its fitness difference, ΔU_G , is governed by the critical surface $\Delta U_G = 0$, which partitions the cube into two regions, as shown in Figure 6. Above this surface, where farmer adoption is already high, the regulatory fitness difference turns negative and the government tends to withdraw; below it, the government tends to regulate. Figure 6a. locates this surface inside the strategy cube, and Figure 6b plots the sign of ΔU_G in the

representative slice $x = 0.5$, with the boundary $\Delta U_G = 0$ separating the regulate region from the withdraw region. This state-dependent sign structure is the mechanism underlying the government's eventual exit, and it motivates the convergence and trap behavior.

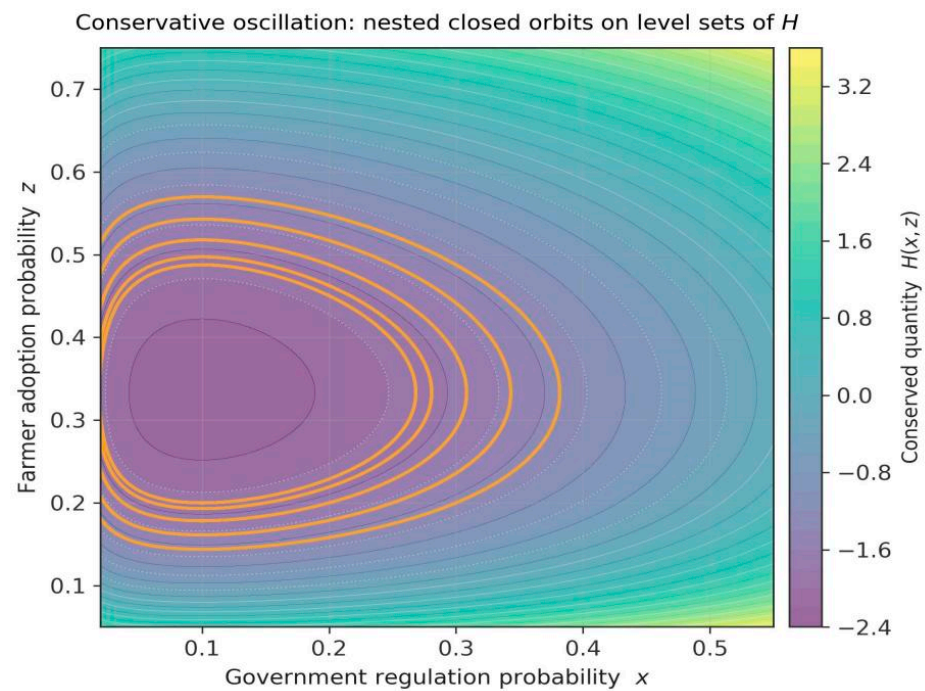


Figure 3. Nested closed orbits on the $y = 0$ face, coinciding with the level sets of the first integral $H(x, z)$.

Conserved-quantity landscape (orbits ride constant- H level sets)

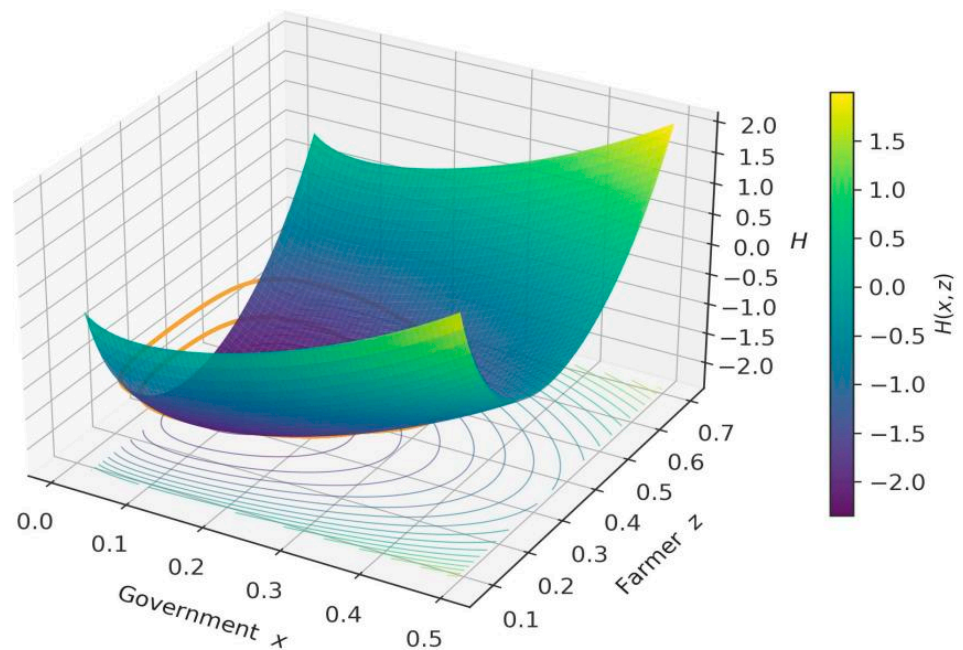


Figure 4. Three-dimensional landscape of the conserved quantity $H(x, z)$.

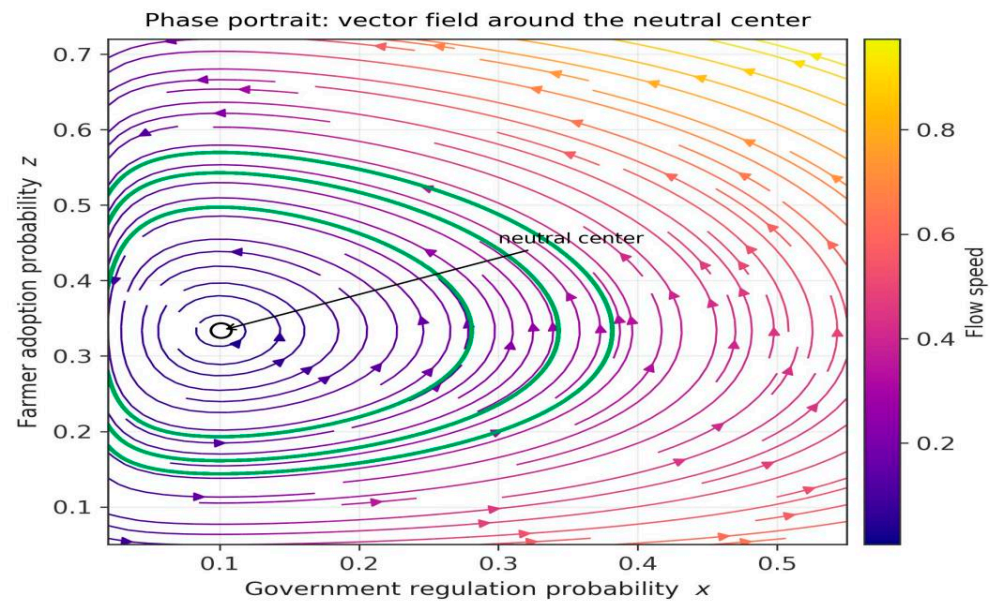


Figure 5. Phase portrait of the planar (x,z) subsystem around the neutral center.

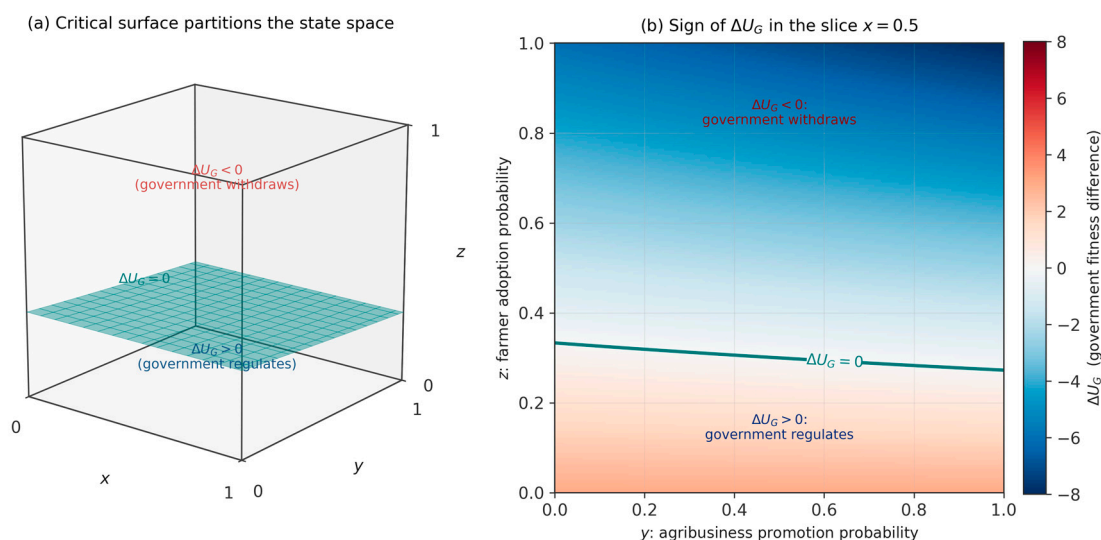


Figure 6. Partition of the state space by the critical surface $\Delta U_G = 0$.

5. Numerical Simulation

This section reports numerical simulations that visualize the evolutionary trajectories, validate the analytical results of Section 4, and explore the comparative effectiveness of the policy instruments. All ordinary differential equations are integrated with adaptive high-order solvers, using an explicit Runge–Kutta method for the trajectory portraits and the implicit Radau method, with relative tolerance 10^{-9} , for the high-precision conservation and long-horizon tests. The analytical derivations are cross-checked with symbolic computation.

5.1. Parameter Setting

Consistent with the parameter-calibration approach set out in Section 3.2, we assign dimensionless relative values anchored to the real-world magnitudes summarized in Table 1. The baseline configuration is reported in Table 5. The values satisfy all sign conditions of Assumption 6. The combination $R_f - C_f + L$ equals -0.5 and is therefore negative, so farmers lack an autonomous adoption incentive, which reflects the documented

difficulty of conservation-tillage uptake. At the same time, $R_f - C_f + L + \delta$ equals 2.5 and is positive, so adoption becomes individually rational under agribusiness spillover, and $R_e - C_e$ equals 2 and is positive, so promotion is profitable once adoption occurs. The accountability term satisfies $\theta - C_g = 1 > 0$.

Table 5. Baseline parameter values.

Parameter	C_g	C_e	C_f	R_e	R_f	V	θ	ϕ	s_e	s_f	δ	L
Value	3	4	5	6	2.5	5	4	2	2	3	3	2

As established in Section 3, the absolute values are immaterial and only the relative ordering governs the dynamics. The robustness of all qualitative findings to the specific values chosen is examined in Sections 5.5 and 5.6 through one- and two-dimensional parameter sweeps, and is confirmed by the ± 10 percent random perturbation test reported at the end of Section 5.5.

The calibration should therefore be read as mechanism-oriented rather than as an empirical point estimate. Each value is chosen to satisfy the sign ordering implied by the institutional evidence: the farmer's autonomous incentive is negative, agribusiness promotion is profitable only with adoption, the spillover term makes adoption viable, and accountability pressure gives the government a motive to regulate. The sensitivity and threshold analyses below test whether the qualitative results survive when these relative magnitudes change.

5.2. Baseline Evolution and Path Dependence

We first integrate the full system (7)–(9) from a range of interior initial states. Figure 7 presents the evolutionary trajectories of the three populations under six representative initial conditions, revealing two qualitatively distinct long-run outcomes: most trajectories converge rapidly, whereas those starting from low initial willingness fail to settle and instead oscillate persistently.

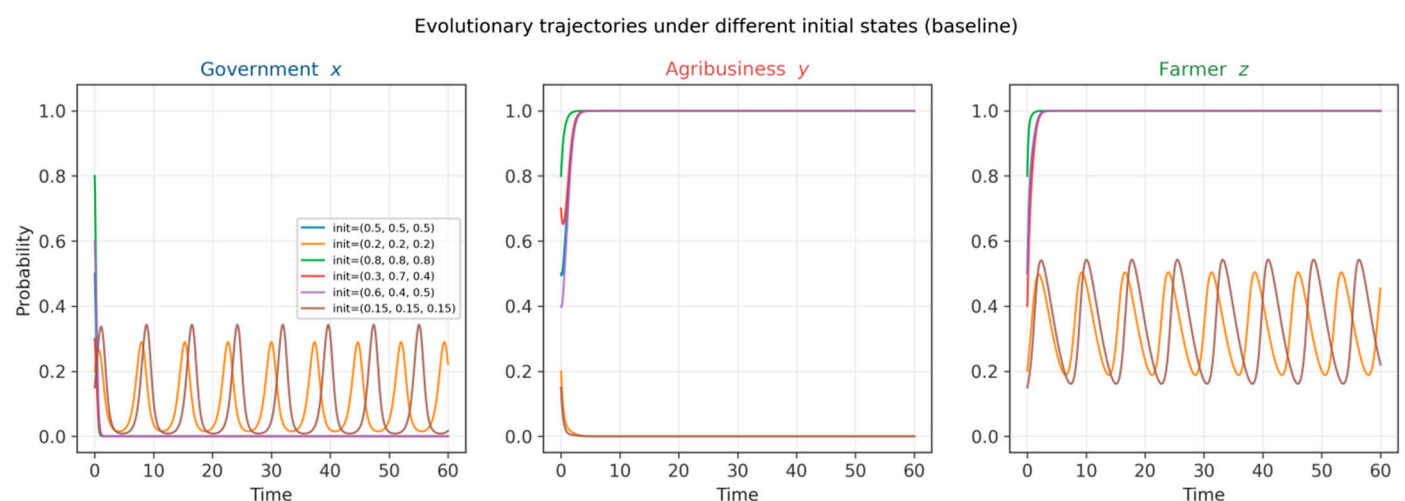


Figure 7. Evolutionary trajectories of the three populations under six representative initial conditions.

When the initial willingness of the three populations is sufficiently high, all trajectories converge to the ideal ESS $E_4(0, 1, 1)$: the government withdraws while the agribusiness promotes and farmers adopt, exactly as predicted by Result 2. The three populations reach this state rapidly and remain there (Figure 8).

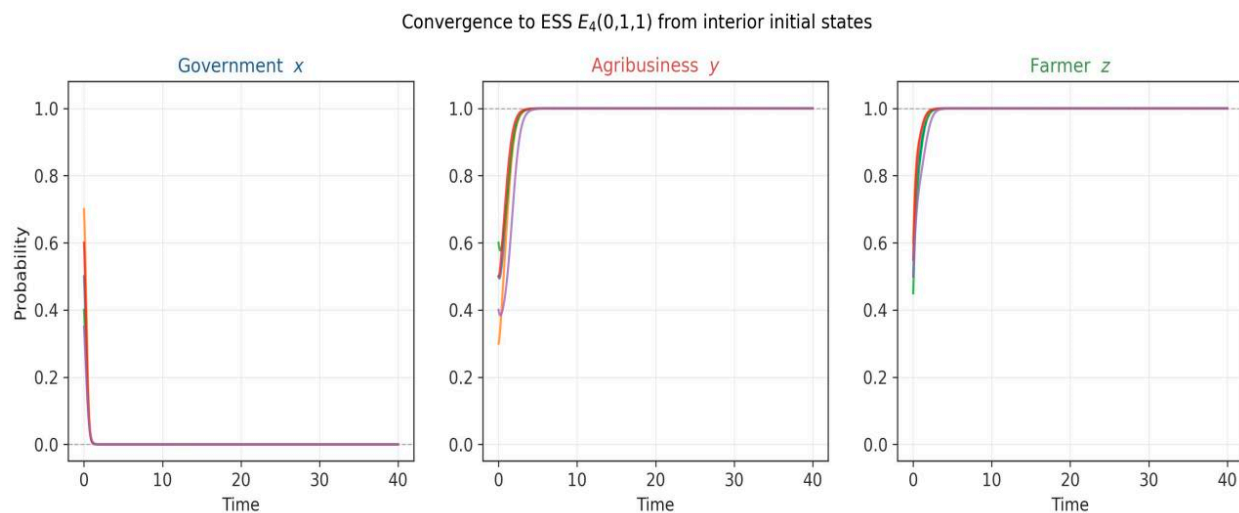


Figure 8. Convergence to the ideal ESS $E_4(0, 1, 1)$ from several high-willingness initial states. Colors distinguish the six representative initial conditions, consistent with Figure 7.

However, the outcome is not globally determined: it depends on the initial state. Integrating from 100 random initial points reveals two distinct fates (Figure 9). The majority of the trajectories (87 of 100 under the baseline) converge to E_4 , but a substantial minority (13 of 100), all originating from low initial willingness, are drawn instead toward the boundary face $y = 0$, where they enter a persistent oscillation rather than settling at any vertex. Systematic scanning of symmetric initial points (p, p, p) locates the dividing line sharply: under the baseline calibration, trajectories with $p \gtrsim 0.33$ converge to E_4 , whereas those with $p \lesssim 0.33$ become trapped in oscillation. This critical threshold value, which is specific to the chosen parameters and is intended as a qualitative illustration rather than an empirical estimate, is robust across asymmetric initial points as well, since only when all three populations begin with low willingness does the system fail to take off.

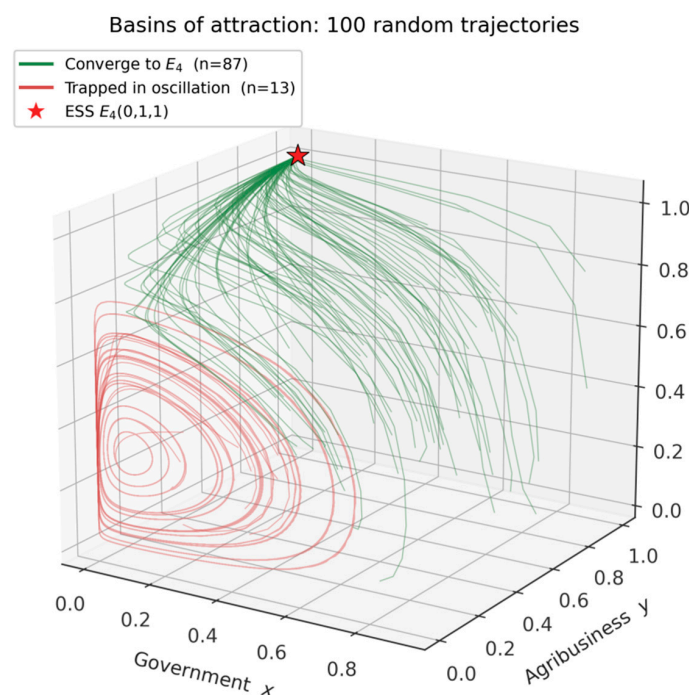


Figure 9. Basins of attraction of 100 random trajectories (green: converge to E_4 ; red: trapped in oscillation).

To visualize the strength of this attraction, Figure 10 overlays 150 trajectories launched from randomly chosen high-willingness initial states, together with six highlighted representative trajectories starting from the open circles. Although the initial conditions differ widely, every trajectory is drawn to the same vertex $E_4(0, 1, 1)$, forming a dense bundle that converges on the stable equilibrium. This confirms that, once initial willingness is sufficient, convergence to the market-sustained outcome is robust to the precise starting point.

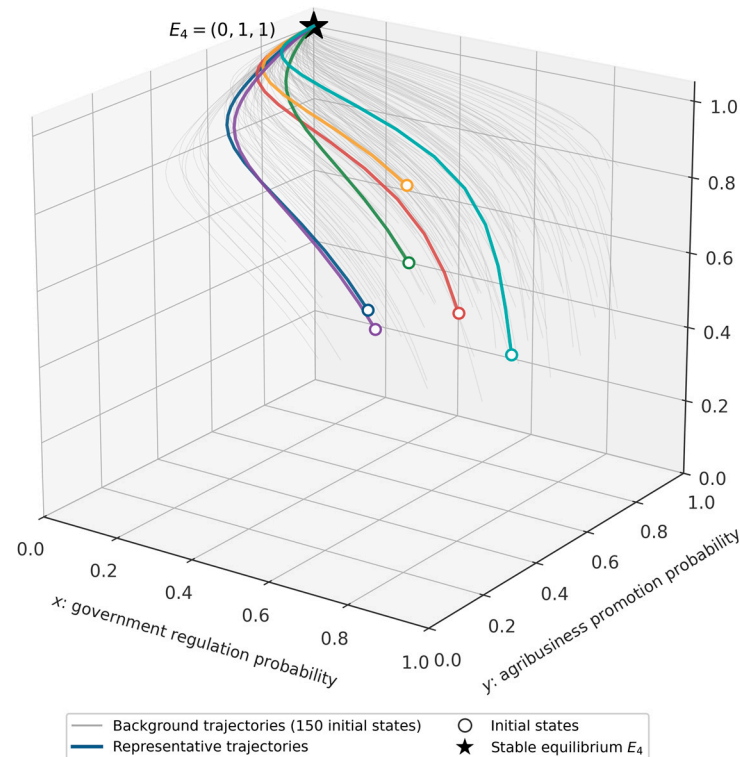


Figure 10. Convergence of 150 random trajectories to the ESS $E_4(0, 1, 1)$. Gray lines are the 150 background trajectories; the six colored trajectories correspond to the six representative initial conditions shown in Figure 8.

This path dependence is related to the multiple-equilibria logic discussed by Carter and Barrett (2006), but the analogy must be used carefully [11]. Poverty traps are typically characterized by a stable low-level equilibrium, whereas the trap identified here is a persistent, conservative fluctuation on the boundary subsystem. Its policy implication is therefore not that a one-off asset-like impulse is sufficient, but that temporary shocks merely move the system to a neighboring orbit unless structural parameters such as the penalty, service capacity, or effective adoption cost shift enough to place the trajectory inside the basin of E_4 .

5.3. The Policy-Reversal Trap

The oscillatory regime entered from low initial willingness merits closer examination, because, as established analytically in Section 4.3, it is conservative. Figure 11 shows the long-run behavior on the $y = 0$ face, where the government's regulation probability x and the farmers' adoption probability z oscillate persistently and in sustained fashion while the agribusiness remains absent at y close to zero. The oscillation neither grows nor decays, and high-precision integration confirms that its amplitude is constant to within machine precision across the intervals $t \in [50, 100]$, $[150, 200]$, and $[250, 300]$.

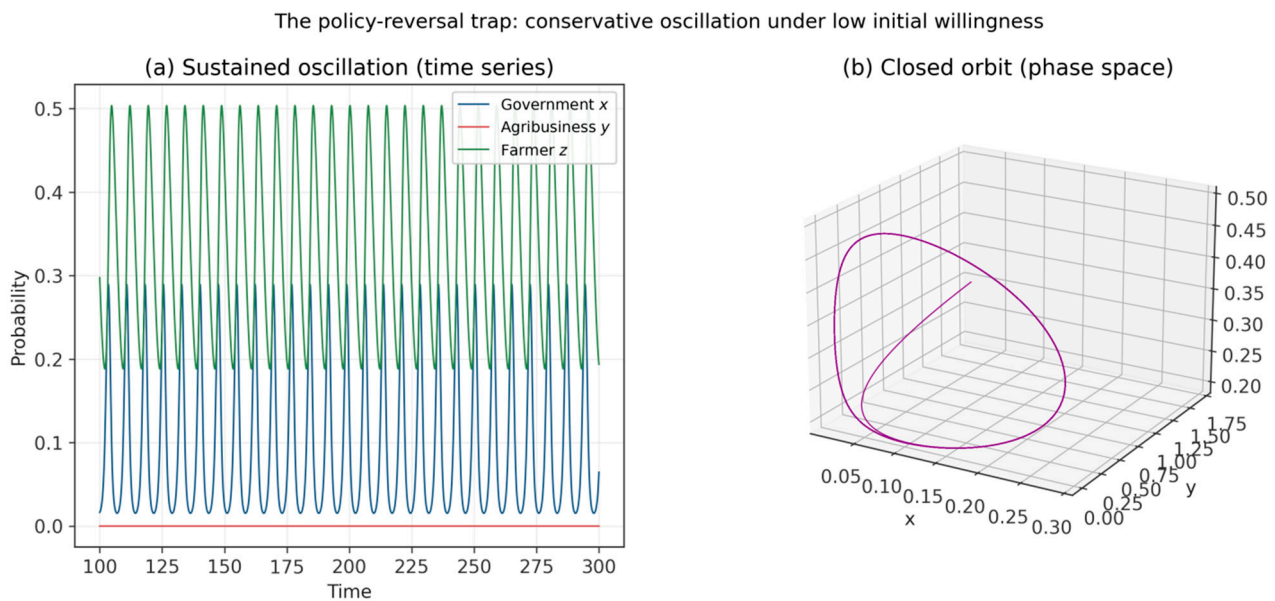


Figure 11. (a) Sustained oscillation of x and z with agribusiness absent ($y \approx 0$); (b) the corresponding closed orbit in phase space.

To validate the reduction to the $y = 0$ face, Figure 12 reports the speed at which low-initial-willingness trajectories lose agribusiness participation. Under the baseline calibration, $y(t)$ falls below 0.01 within 1.4 to 6.6 time units for q_0 in $[0.16, 0.32]$, with slower convergence as q_0 approaches the critical threshold. This confirms that the conservative oscillation analyzed in Section 4.3 is a boundary phenomenon reached after rapid attraction toward the agribusiness-absent face.

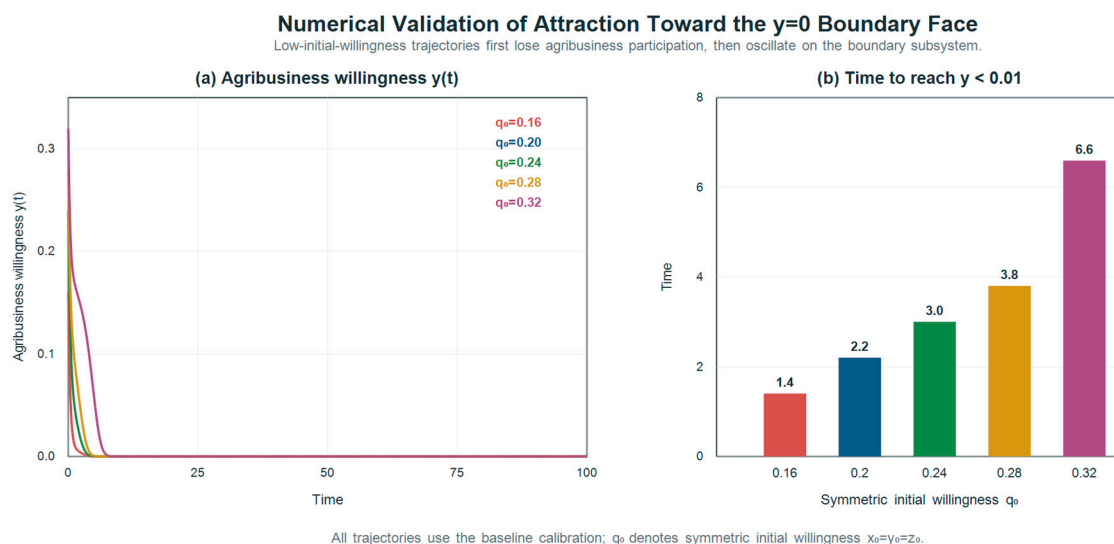


Figure 12. Numerical validation of attraction toward the $y = 0$ boundary face under low initial willingness.

We call this the policy-reversal trap, in which government regulation and farmer adoption rise and fall in a perpetual cycle without ever reaching the coordinated outcome. When farmers begin to abandon adoption, accountability pressure draws the government back toward regulation; the resulting subsidies and penalties revive adoption; but as adoption rises, regulation becomes costly and the government withdraws (Result 1), whereupon adoption again decays. The agribusiness, finding adoption too sporadic to be profitable,

stays out entirely, and the spillover channel δ that would render adoption self-sustaining is never engaged. Because the dynamics conserve the quantity H , as shown in Section 4.3, the system has no tendency to spiral inward toward coordination or outward toward collapse, and is instead locked onto a closed orbit.

The conserved-quantity structure underlying this trap was displayed in Figures 3–6: the actual orbits coincide precisely with the level sets of the analytically derived first integral $H(x, z)$, each orbit “rides” a contour of constant H in the three-dimensional landscape, and the vector field circulates around the neutral center without inward or outward drift.

5.4. The Roles of Agribusiness and Government

To isolate each actor’s contribution, we compare the full model against counterfactuals in which one actor is held inactive.

Agribusiness as the enabler of self-sustaining adoption: Figure 13 contrasts farmer adoption under the full model with a counterfactual in which the agribusiness is permanently absent ($y = 0$). With agribusiness promotion, adoption rises rapidly to unity; without it, adoption never stabilizes, instead oscillating persistently between roughly 0.1 and 0.7. The technology-spillover benefit δ is thus the decisive ingredient that converts farmer adoption from an unstable, policy-dependent fluctuation into a stable equilibrium, which is consistent with the finding of Qing et al. (2023) that access to socialized technical services is a primary determinant of conservation-tillage adoption [19].

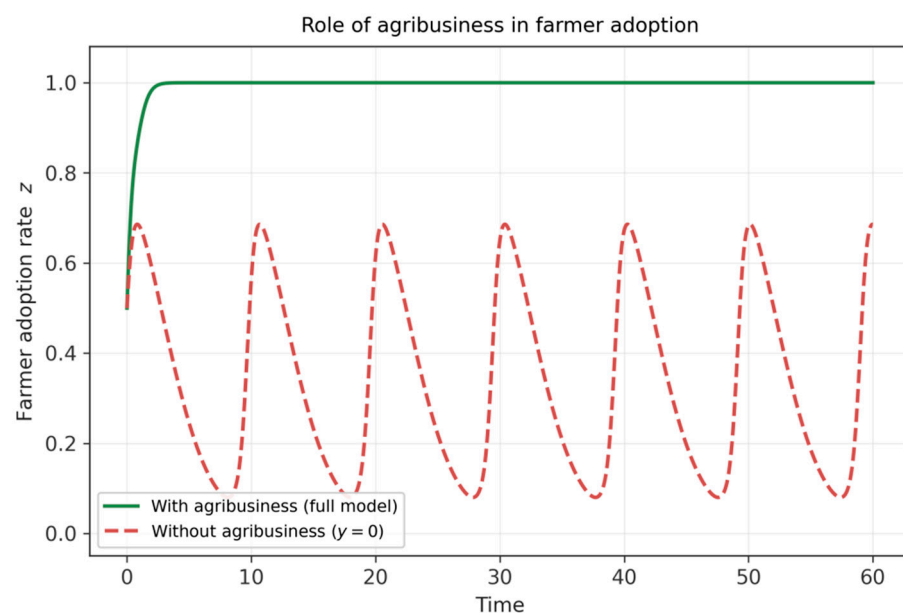


Figure 13. Farmer adoption with agribusiness promotion (solid) and without it (dashed, $y = 0$).

Government as catalyst, not permanent guarantor: Figure 14 examines whether the market can sustain adoption once the government has withdrawn ($x = 0$). The answer depends critically on the agribusiness’s initial activity. When agribusinesses start with sufficient promotion willingness ($y_0 \gtrsim 0.5$), the market self-organizes to full adoption with no government involvement; but when agribusiness willingness is too low ($y_0 = 0.2$), the market collapses to zero adoption. This sharpens Result 3. The government’s essential function is to activate the agribusiness–farmer linkage during the early phase, after which the market becomes self-sustaining and public intervention is dispensable. The government acts as a catalyst that lowers the activation barrier rather than as a permanent guarantor of the outcome, a coordination role that closely parallels the take-off intervention emphasized by Carter and Barrett (2006) in the poverty-trap literature [11].

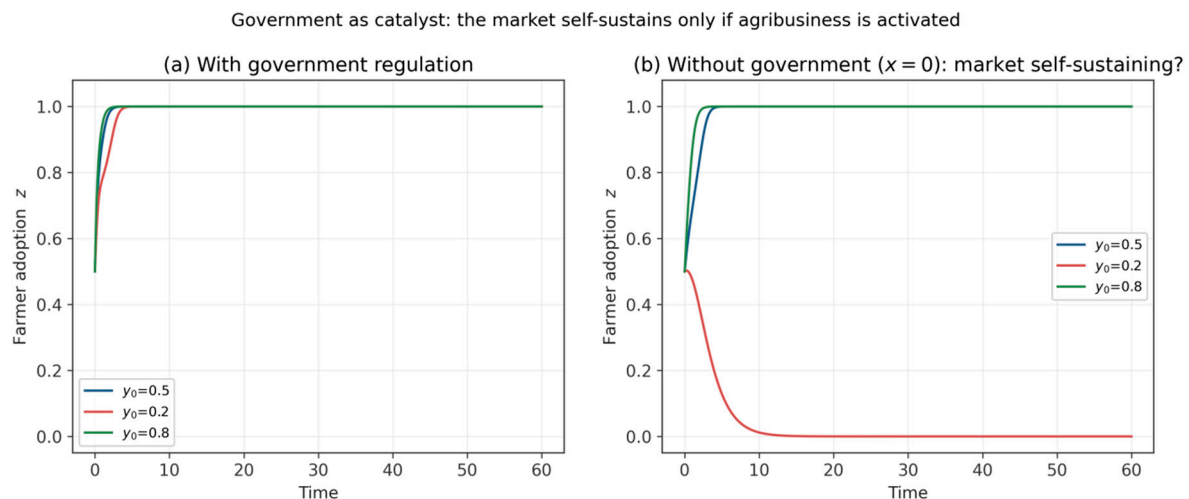


Figure 14. Farmer adoption (a) with government regulation and (b) without government ($x = 0$), for several agribusiness initial values y_0 .

5.5. Sensitivity Analysis and Policy Thresholds

We next vary each policy instrument while holding the others at baseline, measuring the long-run average adoption rate $\bar{z}$, defined as the time-average of z over the second half of a long simulation, which is well defined whether the system converges or oscillates. To probe robustness, each instrument is evaluated from both a high initial state well inside the basin of E_4 and a low initial state inside the oscillatory regime. The results, summarized in Figure 15, reveal a pronounced asymmetry between the price-type instrument, namely, the subsidies, and the coercive or capacity-building instruments, namely, the penalty and the spillover.

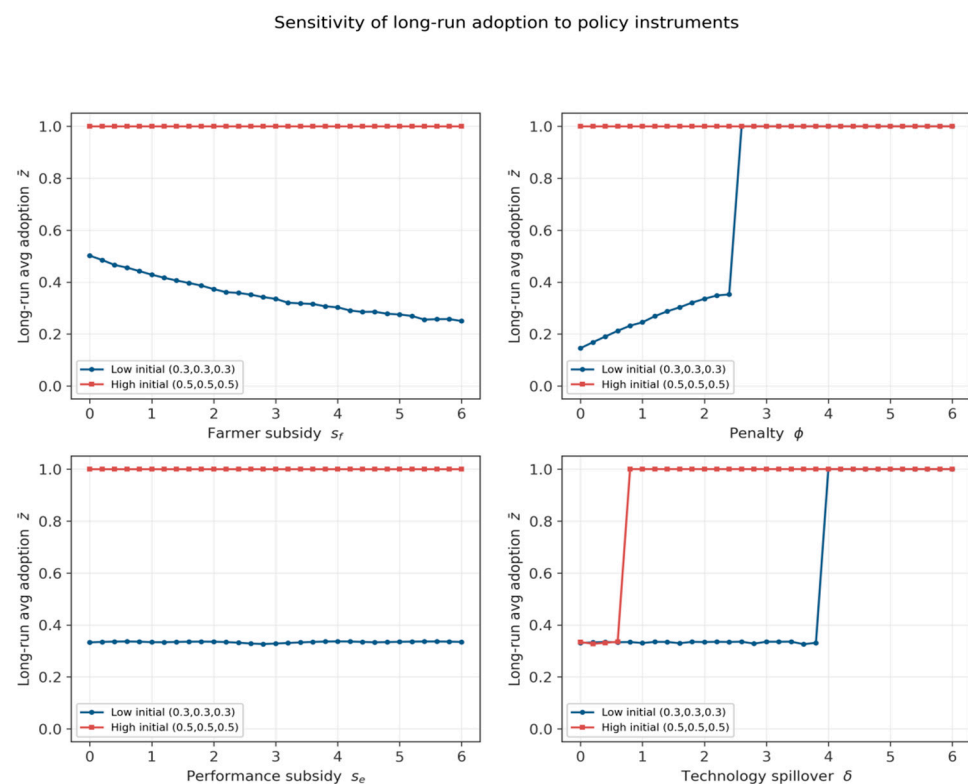


Figure 15. Sensitivity of long-run average adoption to the four instruments, from high and low initial states.

Penalty exhibits a sharp threshold. From a low initial state, average adoption rises only modestly as the penalty ϕ increases from zero, until, at a critical value, which falls between $\phi = 2.5$ and $\phi = 3.0$ under the baseline calibration and should be read as a model-specific illustration rather than a real-world policy level, it jumps discontinuously to full adoption, so that a sufficiently credible penalty lifts the system out of the oscillatory trap and into the basin of E_4 . The location of this threshold is itself state-dependent, being higher for lower initial willingness, which mirrors the moving Micawber threshold described by Carter and Barrett (2006) [11].

Within the trap, the farmer subsidy is the weakest instrument. Strikingly, within the model, increasing the farmer subsidy s_f from a low initial state does not raise long-run adoption but monotonically lowers it, from about 0.50 at $s_f = 0$ to about 0.25 at $s_f = 6$. The mechanism is transparent from Equation (7), in which s_f enters the government's fitness difference with a negative sign through the term $-s_f z$, so that a larger subsidy raises the cost of regulation and hastens the government's withdrawal. In the oscillatory regime, where the government's continued presence is precisely what intermittently revives adoption, premature withdrawal deepens the trap. This counterintuitive result holds only within the oscillatory regime and reflects the single channel through which subsidies act in the model, namely, the government's cost of regulation; it does not capture the demand-side or risk-reducing effects that farmer subsidies may exert in practice. Once the system is in the basin of E_4 , reached from high initial willingness, the subsidy level is irrelevant because adoption reaches unity regardless.

The mechanism follows directly from the replicator equations. In the government equation, s_f enters the regulatory fitness difference through the negative term $-s_f z$; once adoption becomes visible, a larger farmer subsidy increases the fiscal cost of regulation and accelerates government withdrawal. In the low-willingness regime, however, intermittent government presence is exactly what revives farmer adoption. The penalty ϕ works differently: it strengthens the regulatory payoff when non-adoption is prevalent and raises farmers' payoff from adopting relative to non-adopting, helping the system cross the basin boundary. This is why subsidies can be ineffective in the modeled trap while penalties remain capable of engineering escape.

Performance-based agribusiness subsidy is inert in the trap. The instrument s_e has almost no effect from a low initial state. Equation (8) shows why, since s_e acts only through the term $s_e x z$, which requires both government presence and farmer adoption to be non-negligible. In the trap, where the government has effectively withdrawn so that x approaches zero, the channel is switched off.

Technology spillover crosses a threshold. Increasing δ raises long-run adoption and, beyond a critical value, lifts even low-willingness systems to full adoption. This confirms the pivotal role of agribusiness capacity and echoes the finding of Qiu et al. (2021) on the importance of mechanized service provision in overcoming smallholder scale barriers [20].

To consolidate these threshold effects, Figure 16 plots, for each instrument, whether the low-willingness system ultimately escapes to E_4 as the instrument's intensity increases. Penalty ϕ and spillover δ each exhibit a clean escape threshold, located near $\phi \approx 2.5$ and $\delta \approx 4$ under the baseline calibration, these values being illustrative of the mechanism rather than calibrated policy targets, whereas neither the farmer subsidy s_f nor the performance subsidy s_e enables escape anywhere in the tested range. Monetary transfers alone therefore cannot release a trapped system, whereas credible penalties or enhanced agribusiness capacity can.

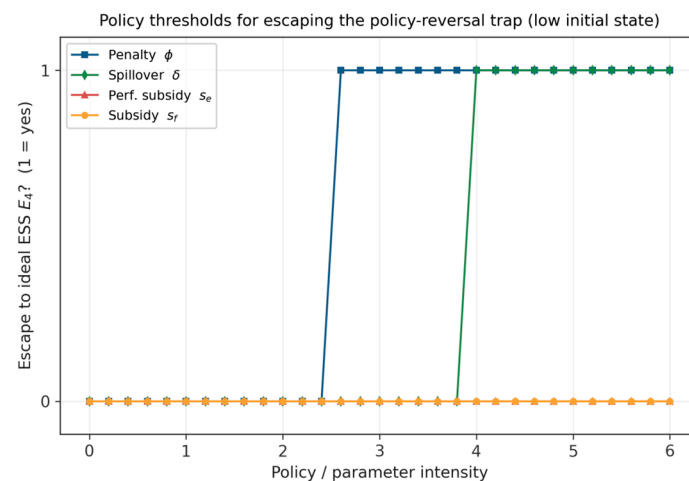


Figure 16. Escape from the policy-reversal trap versus instrument intensity, from a low initial state.

Figure 17 further examines whether the approximately 0.33 initial-willingness threshold is robust to key parameter changes. The threshold declines from about 0.373 to 0.050 as the penalty φ rises from 0.5 to 4.0, and from about 0.448 to 0.277 as the technology-spillover parameter δ rises from 1.0 to 5.0. By contrast, increasing the farmer subsidy s_f leaves the threshold almost unchanged around 0.326 once s_f exceeds 0.75, while higher supervision cost C_g raises the threshold. The threshold is therefore not a fixed empirical constant; it is a state-dependent boundary whose location is most responsive to credible enforcement, service-capacity spillover, and regulatory cost.

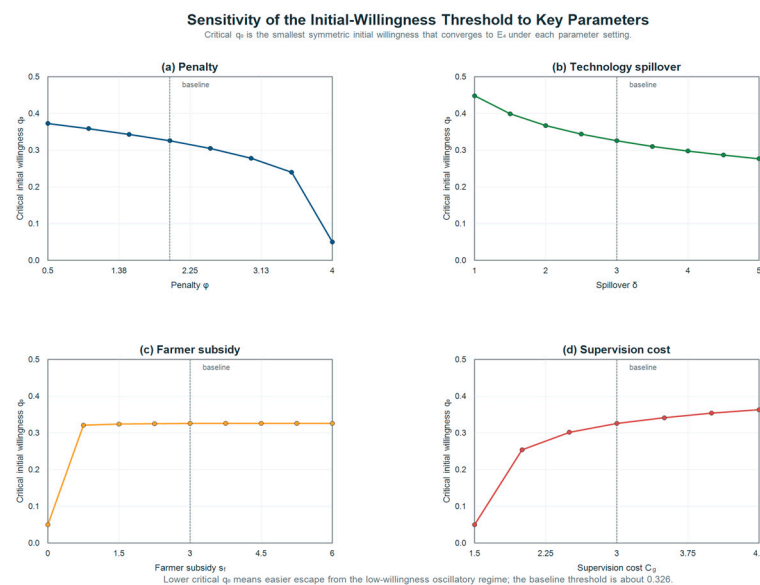


Figure 17. Response of the critical initial-willingness threshold to key parameters.

A ± 10 percent random perturbation of all baseline parameters, applied over 30 independent draws, leaves the stability of E_4 intact, since every perturbed configuration starting from a high initial state still converges to E_4 . The qualitative conclusions are therefore not artifacts of the specific baseline values. Figure 18 displays the time evolution of all thirty perturbed systems, every one of which converges to $E_4(0, 1, 1)$. Here x^* , y^* , z^* denote the final (steady-state) values reached by x , y , z , respectively, consistent with the equilibrium notation $E_4(0, 1, 1)$ used throughout.

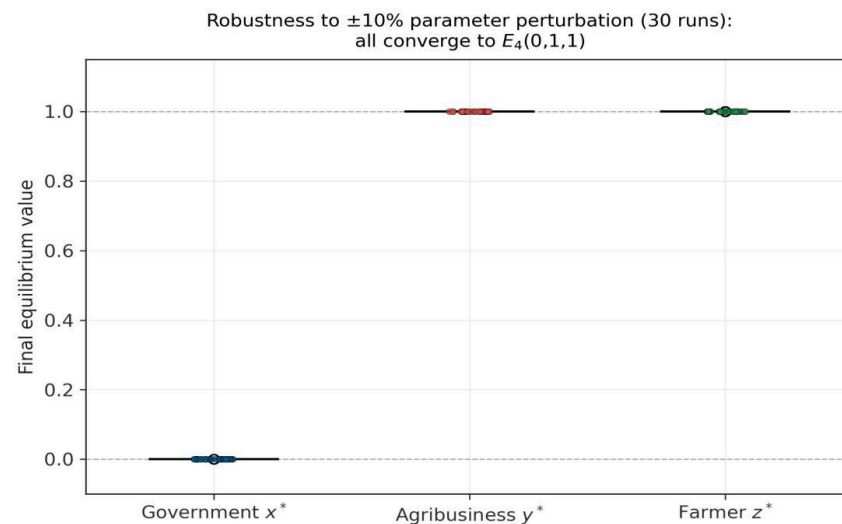


Figure 18. Robustness to $\pm 10\%$ parameter perturbation: time evolution of all 30 perturbed systems, every one of which converges to $E_4(0,1,1)$.

5.6. Policy-Mix Analysis: Subsidy Versus Penalty

Finally, we examine the joint and comparative effects of the two front-line farmer-facing instruments. Figure 19 presents the long-run average adoption as a surface over the penalty–subsidy plane (ϕ, s_f) from a low initial state. The surface is dominated by a steep cliff along the penalty axis, since adoption climbs from the low-adoption plateau to the full-adoption plateau as ϕ crosses its threshold, while movement along the subsidy axis produces no comparable ascent and, in the low-adoption region, even a slight descent. The geometry makes visually explicit that, for a system mired in the policy-reversal trap, penalty is the effective lever and subsidy is not.

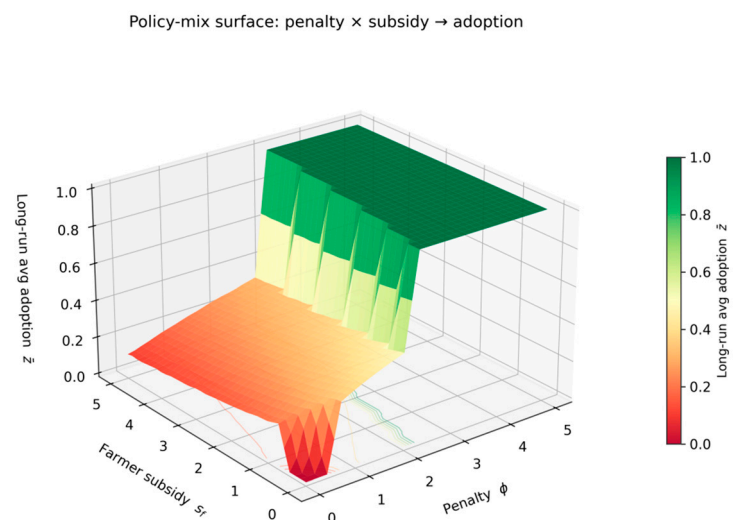


Figure 19. Long-run average adoption over the penalty–subsidy (ϕ, s_f) plane, from a low initial state.

Figure 20 makes the comparison directly, plotting $\bar{z}$ against intensity for the two instruments applied singly from a low initial state. The penalty curve stays flat and then jumps as it escapes the trap past its threshold, while the subsidy curve declines monotonically and thereby deepens the trap. The two curves cross well before the penalty threshold, after which their divergence is stark. This contrast is consistent with evolutionary-game evidence that farmers' sensitivity to penalties for non-compliance is at least as high as their

sensitivity to subsidies, so that insufficient punishment, rather than insufficient subsidy, can sustain passive behavior.

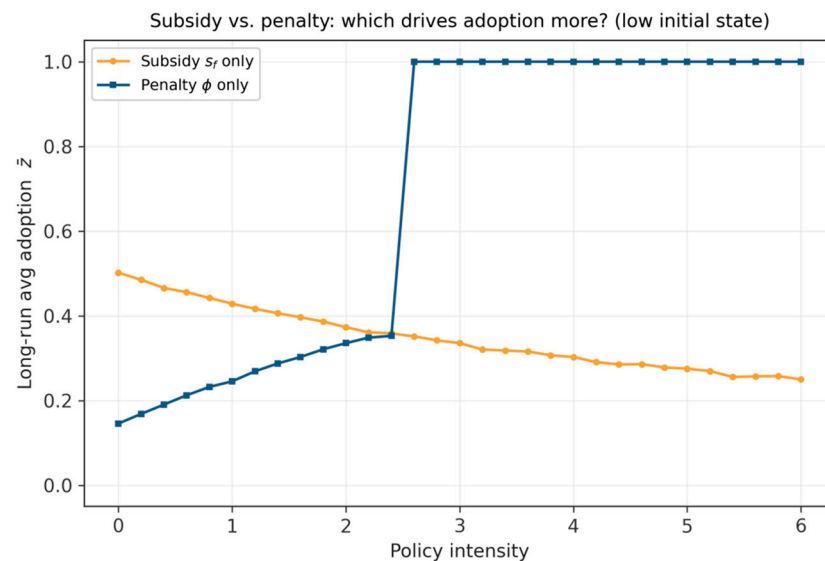


Figure 20. Long-run average adoption versus intensity for subsidy and penalty applied singly, from a low initial state.

6. Discussion and Policy Implications

6.1. Theoretical Implications

Two findings of the analysis carry broader theoretical interest and distinguish this study from much of the tripartite-game literature.

The first is the state-dependence of policy effectiveness. Conventional comparative-statics reasoning, and most existing evolutionary-game studies, implicitly treat a policy instrument as having a stable directional effect, so that more subsidy always means more adoption. The results from this study overturn this presumption. Because the system possesses multiple basins of attraction separated by a critical initial-willingness threshold (Section 5.2), the very same instrument can act in opposite directions depending on the regime the system occupies. Open-ended subsidy commitments, by contrast, risk both fiscal waste and, within the trap, counterproductive effects. The policy-relevant object is therefore not the sign of a partial derivative but the geometry of the basins and the system's position within them. For the agricultural-diffusion setting, this formalizes the broader transitions-governance insight that instrument effectiveness is contingent on context and complementarity rather than fixed [27].

The second is the conservative character of the non-convergent regime. Where most agricultural-diffusion games either converge to an evolutionarily stable strategy or, at most, report numerical oscillation without further characterization, this study shows analytically that the low-willingness regime is governed by a first integral and is therefore conservative, taking the form of a neutrally stable center rather than an asymptotically stable limit cycle, as established in Section 4.3. This places agricultural technology diffusion within the class of Hamiltonian-like evolutionary dynamics that Hofbauer (1996) identified for asymmetric conflicts [12], and it carries a concrete consequence for policy. Because the dynamics preserve the conserved quantity H , a one-off policy shock does not dissipate but merely relocates the system to a neighboring orbit of equal energy. Transient interventions thus cannot extinguish the policy-reversal oscillation and only change its amplitude. Escaping the trap requires a structural change in parameters sufficient to move the system into the basin of the desirable equilibrium, rather than a temporary impulse. This conclusion is

sharper and more cautionary than the usual reading under which stronger intervention always works, and it follows directly from the conservative geometry.

6.2. Reconciliation with Existing Findings

Our results both corroborate and qualify several established conclusions. They corroborate the recurring finding that penalties are at least as important as subsidies in driving compliance, and that insufficient punishment sustains free-riding, because in this model the penalty and the capacity-building spillover are precisely the instruments capable of engineering escape from the trap, whereas subsidies are not. They also corroborate the observation that subsidized green practices can persist after subsidy withdrawal once the market stabilizes, which is exactly the content of the ideal equilibrium E_4 , in which the government has exited and the market sustains adoption unaided.

At the same time, our results qualify two common presumptions. First, the intuitively desirable full-coordination state, in which the government regulates while the agribusiness promotes and farmers adopt simultaneously, is shown to be dynamically unstable by Result 1, because once promotion and adoption are established, continued regulation is pure cost and the government rationally withdraws. Studies that designate the fully monitored cooperative state as the policy goal therefore mistake a transient configuration for a stable one. Second, the presumption that subsidies monotonically promote adoption holds only outside the trap, and within it the relationship reverses. Both qualifications stem from two features routinely omitted in two-party or convergence-only analyses, namely, the government's free-riding incentive and the system's multiple equilibria, which together underscore the value of a full three-population treatment that also accounts for non-convergence.

6.3. Policy Implications for the Black Soil Region

Four concrete implications follow for conservation-tillage promotion in Liaoning and the wider Northeast.

Treat public intervention as a transitional catalyst with a built-in exit: The stable desirable outcome is market-sustained adoption with the government withdrawn (Result 2), and permanent regulation is both unstable and unnecessary (Result 1). Policy should therefore be designed from the outset as a phased intervention whose purpose is to build autonomous adoption capacity, by raising farmers' net returns R_f , lowering adoption costs C_f , and enlarging agribusiness spillover δ , after which support tapers. This aligns with the phase-out logic increasingly adopted in environmental governance, under which structured, time-bound support cushions the transition while signaling a clear direction to the market and allowing supply chains to develop [28]. Open-ended subsidy commitments, by contrast, risk fiscal waste and, within the modeled trap, may prove self-defeating through their effect on the government's incentive to regulate.

This recommendation should not be interpreted as the disappearance of public responsibility. In real black-soil governance, government withdrawal means tapering extraordinary direct subsidies and intensive intervention after the agribusiness–farmer linkage becomes self-sustaining, while retaining baseline monitoring, data verification, legal enforcement, and the capacity to respond to shocks. Institutional changes, market imperfections, heterogeneous risk preferences, and extreme weather may all justify continued adaptive governance even when the model's market-sustained equilibrium has been reached.

Prioritize credible penalties and capacity-building over transfers when willingness is low: For regions or cohorts that begin from low adoption willingness, and therefore lie inside the modeled trap, the results indicate that untargeted farmer subsidies are unlikely to engineer escape on their own and may, through the regulatory-cost channel,

entrench the oscillation, whereas a credible penalty exceeding the model's threshold, or a sufficient enhancement of agribusiness service capacity, can. In practical terms, this favors strengthening the enforcement and verification of conservation-tillage requirements, which is the monitoring role assigned to municipal and county governments [4], and investing in the socialized-service ecosystem, over simply enlarging per-hectare cash transfers.

Sequence instruments to the system's state: Because effectiveness is state-dependent, a single uniform policy is suboptimal. Where willingness is already past the threshold, the market will carry adoption and the government can move quickly to taper support, whereas where it is below, intervention must first lift the system across the threshold before any tapering. Differentiated, regime-aware sequencing, rather than a uniform subsidy schedule, is the appropriate design, and is consistent with the emphasis on sequencing and complementarity in the transitions-governance literature [27].

Use performance-contingent support for service providers: The performance-based subsidy s_e , disbursed only upon realized adoption, both forecloses subsidy capture and ties public money to outcomes. The soil-fertility-index-insurance and subsidy-after-service models already piloted in the black-soil region [3] are concrete instruments of this kind and merit expansion, though this analysis adds the caveat that such support operates through the government's continued presence and is therefore most effective during the catalytic phase rather than after withdrawal.

6.4. Limitations and Future Research

Several limitations qualify these conclusions and point to future work. First, the parameters are dimensionless relative magnitudes calibrated to documented orders of magnitude rather than estimated from primary data. While sensitivity analysis and perturbation testing establish the robustness of the qualitative findings, dimensional calibration using farm-level survey or administrative data, following the field-based and expert-elicitation approaches employed elsewhere in the literature, would sharpen the quantitative thresholds and is a natural next step. Second, the analytical characterization of the conserved quantity is established on the agribusiness-absent boundary face $y = 0$, to which trapped trajectories are drawn, and a complete classification of the interior three-dimensional dynamics, including whether higher-order or structural perturbations could convert the center into an isolated limit cycle, would require the normal-form analysis noted by Hofbauer (1996) and lies beyond the scope of this study [12]. Third, the model abstracts from heterogeneity within each population, such as farm size, tenure security, and risk preference among farmers, and scale and capitalization among agribusinesses, each of which Guo et al. (2022) and related work identify as consequential [18]. Incorporating such heterogeneity, spatial interaction, or stochastic shocks would extend the analysis toward greater realism. Finally, the three-population framework could be enriched by explicitly modeling financial institutions or downstream grain buyers, both of which feature prominently in the upgraded Lishu Model production unit.

A further limitation is that the model treats information, learning, and technical-service capacity as fixed parameters. Future research could endogenize digital advisory systems and generative AI as mechanisms that alter farmers' perceived costs, agribusiness service capacity, and government monitoring efficiency. For example, generative AI may lower knowledge-search costs and improve personalized extension, but it may also create unequal access, misinformation risk, or overreliance on digital recommendations. Incorporating these channels would connect green agricultural technology diffusion with the emerging literature on generative-AI use intention [24] and digital transformation.

7. Conclusions

Arresting the degradation of Northeast China's black soil depends on the widespread adoption of conservation tillage, yet this adoption emerges from the strategic interaction of three boundedly rational actors, namely, local governments, agribusinesses, and small-holder farmers, none of whom can secure the desirable outcome alone. This paper has developed a tripartite evolutionary game of green agricultural technology adoption, calibrated to the black-soil setting and equipped with a free-riding-proof, performance-based subsidy. Deriving the replicator dynamics, analyzing the stability of all equilibria, constructing a first integral of the non-convergent regime, and conducting extensive numerical and sensitivity experiments, we reach four principal conclusions.

First, the intuitively ideal state of full coordination, in which the government regulates while the agribusiness promotes and farmers adopt simultaneously, is dynamically unstable. The stable desirable outcome is instead one in which the government withdraws while the market sustains adoption on its own. Government regulation is properly understood as a transitional catalyst rather than a permanent guarantor, since its role is to activate the agribusiness–farmer linkage and carry farmers across the adoption threshold, after which it should exit.

Second, when initial willingness is low the system does not converge to any evolutionarily stable strategy but enters a sustained, conservative oscillation, the policy-reversal trap, in which government regulation and farmer adoption rise and fall in perpetual cycle while agribusiness stays out. This regime is characterized analytically through a first integral that is conserved along trajectories to machine precision, which situates it within the class of Hamiltonian-like evolutionary dynamics. Because the dynamics are conservative, a transient policy impulse cannot extinguish the oscillation; only a structural change in parameters can.

Third, the system's fate is governed by a sharp critical threshold in initial willingness that partitions the state space into a basin converging to the market-sustained equilibrium and a basin trapped in oscillation. Policy effectiveness is consequently state-dependent, since the same instrument can act in opposite directions in the two regimes, so that the relevant policy object is the geometry of the basins and the system's position within them rather than the sign of a comparative-static effect.

Fourth, the instruments differ sharply in their power to release a trapped system. Credible penalties exceeding a state-dependent threshold, together with sufficient enhancement of agribusiness service capacity, can engineer escape, whereas untargeted farmer subsidies are markedly less effective and, within the modeled trap, may even deepen the oscillation, because larger subsidies hasten the government's costly withdrawal. The policy corollary is to treat intervention as a phased, regime-aware catalyst that prioritizes credible enforcement and capacity-building over open-ended transfers when willingness is low, sequences instruments to the system's state, and ties support for service providers to realized adoption.

These findings refine the common presumptions that the fully monitored cooperative state is the policy goal and that subsidies monotonically promote adoption, and they offer black-soil governance a concrete, dynamically grounded rationale for transitional, differentiated, and performance-contingent policy design. Future work may calibrate the model dimensionally with farm-level data, complete the classification of the interior three-dimensional dynamics, incorporate heterogeneity and stochastic shocks among the three populations, and extend the framework to include financial institutions and downstream buyers. More broadly, the conserved-quantity perspective introduced here, which links agricultural-diffusion dynamics to Hamiltonian evolutionary systems, may prove useful for understanding policy-reversal cycles in other domains of environmental governance.

Taken together, the analysis qualifies the word ‘trap’ in a precise dynamical sense. The low-willingness regime is not stagnation at a stable low-level equilibrium; it is persistent fluctuation sustained by a conserved quantity on the boundary face. Consequently, policy should focus on structural parameter changes that move the system across the basin boundary, while avoiding the overgeneralization that larger subsidies or immediate government withdrawal will always improve practical outcomes.

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Conflicts of Interest: The authors declare no conflict of interest.

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