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Xueling Wang
Qingdao University
Qingjin Wang
icherlynw@icloud.com

Qingdao University
Tian Lan
Qingdao University

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Cooperation stability and bistability in green innovation consortia

Xueling Wang[1], Qingjin Wang[1]*, Tian Lan[1]

[1] School of Business, Qingdao University, Qingdao 266071, China

*Corresponding author: Qingjin Wang, Email: icherlynw@icloud.com

Abstract

Sustained cooperation in green innovation consortia depends on the incentives of governments, leading enterprises and knowledge-contributing members. This study develops a tripartite evolutionary game of institutional optimization, resource integration and deep participation. The payoff matrix yields three actor-specific cost ceilings for local stability of full cooperation. Under an illustrative baseline with uniformly positive enterprise and member margins, an analytical argument establishes convergence from every strictly interior initial state. Numerical integration of 125 initial states per scenario reproduces full cooperation and three stable partial-cooperation configurations under separate cost increases. Local stability does not, however, guarantee attraction from arbitrary initial states: with other baseline parameters fixed, full cooperation and enterprise-only active integration coexist for member participation costs between 60 and 160. At a cost of 150, different initial shares approach different corners. Parameter sweeps further distinguish changes in adjustment trajectories from changes in stability and attraction; both cost and return parameters can affect cooperative configurations. These theoretical findings support diagnosis of actor-specific payoff margins and initial cooperation conditions, while leaving empirical calibration, environmental outcomes and optimal policy allocation for future research.

Keywords: green innovation consortia; evolutionary game; cooperation stability; bistability; institutional optimization; resource integration

1 Introduction

Green innovation requires firms to combine technological capabilities with institutional support and knowledge located outside organizational boundaries. Eco-innovation research identifies environmental externalities and the interaction of regulatory, technological and market drivers as reasons why such projects differ from conventional innovation [1,2]. Evidence from Spanish manufacturing firms also associates environmental innovation with greater use of external R&D cooperation, including cooperation with suppliers and universities [3]. These findings motivate attention to the organization of collaborative effort alongside the development of individual technologies.

Innovation consortia provide a setting in which a leading enterprise coordinates complementary contributions from participating firms, universities and research institutes, with government involvement in the institutional environment [4,5,6]. Their organizational rationale is consistent with research on R&D partnerships and innovation networks: relevant knowledge and resources are distributed across organizations, while a coordinating actor can facilitate their combination [7,8]. In this paper, a green innovation consortium means an organized collaboration pursuing environmentally oriented innovation; the government, leading enterprise and member units represent institutional, coordination and knowledge-contribution roles.

The existence of complementary resources does not ensure sustained commitment. Governments must weigh institutional optimization against its administrative costs; leading enterprises must decide whether to integrate resources; and members must decide whether to contribute deeply. Alliance research distinguishes the difficulty of aligning tasks from concerns about capturing collaborative returns [9,10]. The relational view explains how complementary resources, knowledge-sharing routines and governance can generate joint benefits [11], but realizing these benefits requires continuing contributions from the participating actors. An organization may therefore favor greater cooperation when its partners are already active while limiting its own effort when their commitment is low.

Adner's structural approach to ecosystems similarly emphasizes interdependence across organizations and activities [12]. This interdependence creates the central puzzle: a fully cooperative configuration may be locally stable without being reached from the consortium's current state. Network governance research emphasizes that effective arrangements depend on the characteristics of the network [13,14]. Evolutionary game theory provides a way to examine how actor incentives change as the strategy shares of other actors change [15,16]. Together, these perspectives motivate distinguishing the incentives that sustain cooperation once established from the adjustment conditions that allow it to emerge.

Existing consortium models already examine low-carbon agricultural innovation [4], major engineering technology innovation [5], strategic, organizational and knowledge synergy [17], and technology spillovers and subsidies [18]. The present paper builds on this modeling tradition and asks a more specific question within its payoff structure: when do favorable local full-cooperation conditions imply attraction from interior states, and when can full and partial cooperation coexist? The distinction matters for governance because an intervention that makes the cooperative corner viable may still leave the current state in the attraction basin of another configuration.

The study makes three connected contributions. First, it links full-cooperation stability to actor-specific payoff margins and expresses the conditions as three cost ceilings. Second, it proves convergence from every strictly interior initial state under an illustrative baseline and establishes a member-cost interval in which full and partial cooperation are simultaneously stable. Third, it combines these analytical results with initial-state experiments and parameter sweeps to distinguish changes in adjustment paths from changes in stability and attraction. The contribution is a model-specific explanation of cooperation viability and reachability, rather than a claim that thresholds or bistability are new to evolutionary game theory.

The green innovation context motivates the actor roles and the need for coordinated commitment. Environmental performance, patent quality and technological success are not outcomes of the present equations, and the numerical parameters are not empirically calibrated. Section 2 develops the theoretical framing and research question. Sections 3 and 4 present the payoff structure and stability analysis. Section 5 reports numerical experiments, Section 6 relates the findings to consortium governance, and Section 7 concludes.

2 Literature review

2.1 Green innovation and the need for external cooperation

Sustainability-oriented innovation involves changes in products, processes and organizational practices [19]. Rennings explains why eco-innovation involves externalities associated with both innovation and environmental improvement, creating a rationale for attention to incentive design [1]. Horbach's panel analysis examines environmental innovation through regulatory, technological and market determinants [2]. Policy-mix research further argues that individual instruments need to be understood in relation to broader policy strategies and processes [20]. These studies motivate institutional involvement, but they do not imply that a single subsidy or regulation is sufficient to sustain cooperation among all consortium actors.

The empirical cooperation literature connects this institutional context to firms' use of external knowledge. De Marchi finds that environmental innovators cooperate more extensively with external partners than other innovators in the studied Spanish manufacturing sample, with differences across partner types [3]. Sánchez-Sellero and Bataineh examine green innovation in relation to R&D cooperation, expenditure, intensity and public funding [21]. These studies concern observed innovation activities and outcomes; the present paper addresses the narrower question of whether the organizational contributions underlying collaboration can be sustained under interdependent incentives.

R&D partnership research documents collaboration as an organizational arrangement between arm's-length transactions and organizational integration [7]. Such arrangements offer access to complementary expertise while leaving participants with distinct objectives and decision rights. This makes the consortium an appropriate setting

for studying conditional commitment: the value of institutional support, enterprise integration and member participation can depend on the other roles being performed. The model does not estimate environmental externalities; their role here is to explain why the collaboration problem is relevant to green innovation.

2.2 Consortium governance and enterprise orchestration

The Triple Helix perspective identifies interactions among government, industry and knowledge-producing organizations [6]. Collaborative governance research examines the institutional arrangements and interactions supporting collective action [22,23]. Provan and Kenis distinguish shared participant governance, lead organization governance and a separate network administrative organization, with different conditions for effectiveness [13]. The later review by van den Oord et al. synthesizes governance modes, contingency factors and network tensions, emphasizing the need to explain how authority and collaboration coordinate joint action [14]. Kim, Bae and Yang also examine government roles in consortium evaluation and arrangement [24]. A leading enterprise is therefore a substantive organizational assumption, not a universal feature of every innovation network.

Orchestration research clarifies what this leading role can involve. Dhanaraj and Parkhe connect hub-firm orchestration to knowledge mobility, innovation appropriability and network stability [8]. Reypens, Lievens and Blazevic identify connecting, facilitating and governing practices in a longitudinal multi-stakeholder innovation network and describe switching between dominating and consensus-based modes [25]. Ritala, De Kort and Gailly examine how brokering in a knowledge network supports relationships and benefits for its members [26]. These studies motivate distinguishing enterprise coordination from member contribution while showing that coordination involves more than the existence of a formal agreement.

The present model translates these roles into binary commitments: government institutional optimization, enterprise resource integration and member deep participation. Government support can enhance returns to integration and participation, while enterprise and member activity affect the government's incentive to optimize institutions. This representation captures conditional payoff links rather than the full practices identified in orchestration research. It does not compare alternative governance forms, model a changing network structure or equate an optimized institution with a universally superior governance arrangement.

2.3 Knowledge contribution and the costs of collaboration

Knowledge-based research explains both the attraction and the difficulty of collaborative innovation. Powell, Koput and Smith-Doerr study networks of learning in biotechnology, where innovation draws on knowledge distributed across organizations [27]. Phelps, Heidl and Wadhwa review how relationships and networks influence knowledge creation, diffusion, absorption and use [28]. Cohen and Levinthal emphasize the organizational capacity to recognize, assimilate and apply external knowledge [29]. These perspectives motivate the knowledge-contribution role of members, but active membership alone does not ensure successful learning or innovation.

The relational view links interorganizational benefits to relationship-specific assets, knowledge-sharing routines, complementary capabilities and governance [11]. At the same time, Gulati and Singh distinguish coordination costs from appropriation concerns in alliance organization [9]. The distinction between cooperation and coordination developed by Gulati, Wohlgezogen and Zhelyazkov also cautions against equating willingness to contribute with the ability to align activities effectively [10]. For the present analysis, these arguments motivate separate costs and conditional returns for enterprise integration and member participation; they do not identify the numerical coefficients in the payoff matrix.

Trust, contracts and relationship development can help organize collaboration [30], while contributors and free-riders can have different motivations and consequences [31]. The placement of losses nevertheless requires explicit modeling assumptions. In the retained matrix, K is borne under limited participation, and D_M is avoided by an active member in the fully supportive encounter. Neither term is an endogenous trust stock or a directly measured

knowledge-leakage cost. Keeping these meanings explicit prevents policy interpretations from reversing the actual incentive effects of the equations.

2.4 Evolutionary games and the emergence of cooperation

Evolutionary game theory represents adjustment through the relative payoffs of alternative strategies [15,32,33]. Hofbauer and Sigmund review the relationship between dynamic adjustment and equilibrium concepts and explain why a static equilibrium perspective cannot always characterize long-run behavior [16]. In a multi-population replicator system, one actor's payoff margin depends on the shares of other actor classes. This allows a cooperative strategy to become more or less attractive as the surrounding commitment changes, without assuming that all participants jointly optimize the consortium's performance.

Luo et al. apply a tripartite evolutionary game to low-carbon agricultural innovation consortia [4]. Qian et al. study stability in major engineering technology innovation consortia [5]. Tu and Chen analyze strategic, organizational and knowledge synergy [17], while Yang et al. examine spillovers and subsidies [18]. These papers provide directly relevant precedent for actor differentiation and incentive-based consortium models. The present study uses that tradition to examine its own payoff matrix through local stability conditions, an analytical baseline attraction result and an explicit region of coexistence.

Local stability, attraction and transient adjustment answer different questions. Negative corner eigenvalues establish recovery from sufficiently small feasible perturbations; they do not establish convergence from every interior initial state. An attracting configuration can coexist with another stable configuration, in which case initial shares help determine the outcome. A parameter can also change the speed or shape of adjustment without changing the limiting corner in a particular experiment. These distinctions require analysis of the coupled system [15,16]; a few trajectories cannot by themselves prove a global basin or a universal ranking of policy effects.

2.5 Research question and analytical scope

The literature provides the components of the present research question. Green innovation studies motivate external cooperation and institutional support; governance and orchestration studies explain the distinct roles needed to organize collaboration; and knowledge and alliance research explain why complementary benefits coexist with participation and coordination costs. Evolutionary dynamics then make these costs and returns conditional on the commitments of other actors. The resulting question is not simply whether cooperation has benefits, but whether the incentive structure sustains cooperation and allows it to emerge from the current distribution of commitments.

The paper therefore asks three related questions: what actor-specific conditions stabilize full cooperation; when do those conditions extend to attraction from interior states; and how do initial shares and parameter changes affect the limiting configuration and adjustment path? The first is addressed through corner eigenvalues, the second through a baseline convergence argument and a coexistence interval, and the third through controlled numerical experiments. Complex adaptive systems provide a broad perspective on interdependence and adaptation [34], but the implemented mechanism is payoff-based strategy adjustment. No historical-memory state, endogenous trust accumulation or predetermined developmental sequence is introduced.

3 Model assumptions and payoff structure

3.1 Actor classes and strategies

We consider three representative actor classes in a green innovation consortium: government (G), leading enterprise (E), and member units (M). Members comprise collaborating enterprises, universities, research institutes, and other knowledge-contributing organizations [6,23,35]. Each actor class has two strategies, summarized below.

Assumption 1 (Bounded rationality and adaptive adjustment). All three actors are boundedly rational. They do not solve the full game forward; instead, they adjust their strategy share in proportion to the payoff difference

between the active and the limited strategy, according to replicator dynamics. No mutation, explicit memory kernel, or introduction of absent strategies is assumed. The population interpretation concerns repeated or comparable consortium settings; it does not require a single government to be a biological population [15].

Assumption 2 (Binary strategies and strategy shares). Each actor class chooses between an active and a limited strategy. Government chooses between institutional optimization (share x) and maintaining the status quo (share 1−x). The leading enterprise chooses between resource integration (share y) and limited integration (share 1−y). Member units choose between deep participation (share z) and limited participation (share 1−z). All shares lie in [0,1]. Mean-field mixing makes joint encounter probabilities products of the shares.

Assumption 3 (Coupled payoffs and interdependent adaptation). Payoffs are coupled across actor classes. Government optimization multiplies enterprise integration returns; enterprise and member activity feeds back into the government's optimization margin; joint optimization and integration multiply member participation returns. These couplings capture the interdependent nature of consortium cooperation and motivate a coupled three-dimensional replicator system rather than independent cost–benefit decisions.

Assumption 4 (Payoff components and units). Baseline benefits are received under both strategies. Active strategies generate additional returns and incur additional costs; limited strategies may carry disorder or participation-related losses. Parameters are nonnegative, and θ, φ, γ and η are dimensionless. Payoffs are interpreted in a common normalized index so that enterprise and member return terms can enter the government payoff consistently. The normalized values are illustrative, not monetary estimates. Adjustment-rate coefficients are set to one for all three actor classes; changing relative actor rates may alter transient paths and attraction basins even when corner stability signs remain unchanged.

3.2 Parameters

Table 1 reports the parameter meanings and baseline values. Parameter interpretations follow the positions of the terms in the payoff matrix. In particular, θ weights the government return associated with enterprise and member activity; φ multiplies enterprise returns under institutional optimization; γ modifies member returns under joint optimization and integration; and η provides an additional member return whenever institutions are optimized.

Table 1 Parameter definitions and illustrative baseline values

Symbol	Definition	Baseline
B_G	Government baseline benefit	50
R_G	Additional institutional optimization benefit	10
C_O	Institutional optimization cost	100
C_N	Status quo management cost	15
D_G	Institutional disorder loss	20
θ	Weight on enterprise and member activity in government optimization returns	1.5
B_E	Enterprise baseline benefit	60
R_E	Enterprise integration benefit	30
C_I	Enterprise integration cost	20

Symbol	Definition	Baseline
D_E	Enterprise loss outside joint government optimization and member participation	25
φ	Multiplier of enterprise integration returns under institutional optimization	1.2
γ	Multiplier of member returns under joint optimization and enterprise integration	1.3
B_M	Member baseline benefit	40
R_M	Member participation benefit	50
C_C	Member participation cost	35
D_M	Member disorder loss avoided under joint optimization and integration	30
η	Additional member-return coefficient under institutional optimization	1.1
K	Additional loss under limited member participation	10
x, y, z	Active-strategy shares of government, enterprise and members	Initial grid 0.1–0.9
t	Dimensionless model time	0–5

Note. Baseline benefits B_G, B_E, B_M cancel from strategy payoff differences and do not affect the replicator dynamics. Numerical values are illustrative scenario settings rather than empirical estimates; Section 5 reports sensitivity to key parameters.

The values are selected to illustrate analytically distinct configurations. No fsQCA observations, interviews or longitudinal consortium data are used to estimate them. Institutional transparency, coordination quality and relational arrangements motivate the mechanisms, but are not independently measured or estimated explanatory variables in this game.

3.3 Payoff matrix

The tripartite payoff matrix is constructed in Table 2. A state (g,e,m) records the pure strategy of each actor class, with 1 denoting the active strategy and 0 its alternative.

Table 2 Tripartite game payoff matrix

State	Government payoff	Enterprise payoff	Member payoff
(1,1,1)	$B_G + R_G - C_O$ $+\theta(R_E + R_M)$	$B_E + \varphi R_E - C_I$	$B_M + \gamma R_M + \eta R_M$ $-C_C$
(1,1,0)	$B_G + R_G - C_O + \theta R_E$	$B_E + \varphi R_E - C_I$ $-D_E$	$B_M - D_M - K$
(1,0,1)	$B_G + R_G - C_O + \theta R_M$	$B_E - D_E$	$B_M + R_M + \eta R_M$ $-C_C - D_M$
(1,0,0)	$B_G + R_G - C_O - D_G$	$B_E - D_E$	$B_M - D_M - K$

State	Government payoff	Enterprise payoff	Member payoff
(0,1,1)	$B_G - C_N$	$B_E + R_E - C_I - D_E$	$B_M + R_M - C_C - D_M$
(0,1,0)	$B_G - C_N - D_G$	$B_E + R_E - C_I - D_E$	$B_M - D_M - K$
(0,0,1)	$B_G - C_N - D_G$	$B_E - D_E$	$B_M + R_M - C_C - D_M$
(0,0,0)	$B_G - C_N - D_G$	$B_E - D_E$	$B_M - D_M - K$

Two restrictions determine the member mechanism. A deeply participating member receives ηR_M under institutional optimization even when enterprise integration is limited. A limited-participation member receives $B_M - D_M - K$ in every encounter. The common D_M loss cancels from the participation margin outside joint government optimization and enterprise integration; the active member avoids that loss in the fully supportive encounter. Consequently, D_M is a loss-avoidance differential in this specification, not a separate participation-side leakage cost. K is an additional limited-participation loss, not an active trust-construction cost.

The specification is deliberately parsimonious. It aggregates knowledge contribution into one binary strategy and captures institutional and organizational effects through payoff terms. It does not specify how collaboration changes patent quality, breakthrough probability, or carbon emissions; cooperative states are therefore interpreted as strategic configurations rather than technological outcomes.

4 Model solution

4.1 Expected payoffs and replicator dynamics

For actor class $i \in \{G,E,M\}$, let U_{i1} and U_{i0} be the expected payoffs of its active and limited strategies, conditional on the other actors' shares. Define $\Delta_i = U_{i1} - U_{i0}$. Weighting Table 2 by the other two shares gives the following six expected payoffs:

$$U_{G1} = B_G + R_G - C_O + \theta(R_E\, y + R_M\, z) - D_G(1-y)(1-z)$$

$$U_{G0} = B_G - C_N - D_G(1-yz)$$

$$U_{E1} = B_E + R_E[1 + (\varphi - 1)x] - C_I - D_E(1-xz)$$

$$U_{E0} = B_E - D_E$$

$$U_{M1} = B_M + R_M - C_C - D_M + \eta R_M\, x + xy[D_M + (\gamma - 1)R_M]$$

$$U_{M0} = B_M - D_M - K$$

For example, the government's optimization-side disorder loss is weighted by $(1-y)(1-z)$, while the status quo loss is weighted by $1-yz$. Their difference is $D_G(y+z-2yz)$. Subtracting the limited-strategy payoff from the active-strategy payoff gives:

$$\Delta_G(y,z) = C_N - C_O + R_G + D_G(y + z - 2yz) + \theta(R_E\, y + R_M\, z) \quad (1)$$

$$\Delta_E(x,z) = R_E - C_I + x[(\varphi - 1)R_E + D_E\, z] \quad (2)$$

$$\Delta_M(x,y) = K - C_C + R_M + \eta R_M\, x + xy[D_M + (\gamma - 1)R_M] \quad (3)$$

In particular, $U_{M0}=B_M-D_M-\mathrm{K}$ is constant across encounters. Consequently, K enters Δ_M positively because it is borne under limited participation, whereas C_C enters negatively because it is borne under deep participation. The term $\eta R_M x$ is present whenever institutions are optimized, including when enterprise integration is limited. Both placements follow the specified matrix; interpreting K as a participation-side trust-building cost would change the model.

Payoff-based adjustment gives the three coupled replicator equations:

$$\frac{dx}{dt} = x(1-x)\Delta_G \quad (4)$$

$$\frac{dy}{dt} = y(1-y)\Delta_E \quad (5)$$

$$\frac{dz}{dt} = z(1-z)\Delta_M \quad (6)$$

The cube $[0,1]^3$ is invariant because every coordinate derivative is zero on its corresponding boundary. Exact absence of a strategy is therefore absorbing in that coordinate. Interior initial states remain interior at finite model time in the exact continuous system. Model time is dimensionless; no correspondence to calendar time is claimed.

A positive payoff difference increases the associated active share and a negative difference decreases it. These are conditional adjustment directions. They do not by themselves establish local stability of the coupled three-dimensional system. Likewise, a zero conditional payoff difference implies indifference with other shares fixed, not strict asymptotic stability or an evolutionarily stable strategy in the classical symmetric-game sense [33].

4.2 Conditional thresholds and comparative statics

The sign of each payoff difference provides the most general conditional decision rule. Threshold expressions are useful only after accounting for the sign and possible zero value of their denominators.

For government optimization, define the intercept $a_G(z)$ and slope $b_G(z)$ below. Then $\Delta_G=a_G+b_G y$. If $b_G>0$, optimization is favored when $y>y^*$; if $b_G<0$, the inequality reverses. At $b_G=0$, only a_G determines the direction. A threshold outside [0,1] describes one direction throughout the feasible interval rather than an interior dividing surface.

$$a_G(z) = C_N - C_O + R_G + (D_G + \theta R_M)z$$

$$b_G(z) = D_G(1-2z) + \theta R_E, \quad y^* = -\frac{a_G(z)}{b_G(z)}$$

For enterprise integration, define $b_E(z)$ as below. When $b_E>0$, integration is favored for $x>x_E{}^*$; when $b_E<0$, the inequality reverses. At $b_E=0$, the sign of R_E-C_I determines adjustment. The restriction $\varphi\geq 1$ ensures $b_E\geq 0$, although equality can occur.

$$b_E(z) = (\varphi-1)R_E + D_E\, z, \quad x_E{}^* = \frac{C_I - R_E}{b_E(z)}$$

For member participation, define $b_M(y)$ as below. When $b_M>0$, participation is favored for $x>x_M{}^*$; when $b_M<0$, the inequality reverses. At $b_M=0$, the sign of $\mathrm{K}-C_C+R_M$ determines adjustment. The restriction $\gamma\geq 1$ ensures $b_M\geq 0$, although equality remains possible.

$$b_M(y) = \eta R_M + y[D_M + (\gamma-1)R_M], \quad x_M{}^* = \frac{C_C - K - R_M}{b_M(y)}$$

These derivatives describe local payoff incentives, not automatically monotone effects on every trajectory or its convergence time. No strategy-selection probability is inferred from threshold-surface volumes. Such a probability would require a specified distribution of initial states and classification of joint-system outcomes; a static payoff-favorable region is generally not a dynamic attraction basin.

Differentiation of the payoff differences yields conditional incentive effects. Increasing C_O, C_I or C_C reduces its own actor margin with derivative −1. For government, the derivatives with respect to R_G and C_N equal one, and the derivative with respect to D_G is y+z−2yz, which is nonnegative on the cube. For enterprise, the derivatives with respect to φ and D_E are xR_E and xz. For members, the derivatives with respect to K, η, γ and D_M are one, xR_M, xyR_M and xy. These nonnegative derivatives can equal zero at some states and do not establish strictly positive changes in a global selection probability.

Increasing D_E or D_M can favor the active strategy here because of the losses assigned to the alternative strategy and the loss exemption under supportive encounters. This comparative static does not imply that governments should deliberately increase risk or harm. Knowledge-leakage protection, if modeled as a reduction in a distinct participation-side risk, would require a separate payoff term and a new stability analysis. Similarly, a threshold surface or its geometric volume describes a conditional payoff region, not the basin of attraction of the coupled system.

4.3 Corner equilibria and local stability

Let F=(F_G,F_E,F_M) be the right-hand sides of equations (4)–(6), and let J be its Jacobian with respect to (x,y,z). Its diagonal and off-diagonal entries are:

$$J_{GG} = (1-2x)\Delta_G, \quad J_{EE} = (1-2y)\Delta_E, \quad J_{MM} = (1-2z)\Delta_M$$

$$J_{GE} = x(1-x)[D_G(1-2z) + \theta R_E]$$

$$J_{GM} = x(1-x)[D_G(1-2y) + \theta R_M]$$

$$J_{EG} = y(1-y)[(\varphi - 1)R_E + D_E\, z]$$

$$J_{EM} = y(1-y)D_E\, x$$

$$J_{MG} = z(1-z)[\eta R_M + yH], \quad J_{ME} = z(1-z)xH$$

$$H = D_M + (\gamma - 1)R_M$$

All eight corners are equilibrium points. At a corner (g,e,m), off-diagonal Jacobian entries vanish because they contain the factor $q_i(1-q_i)$. The three eigenvalues are therefore:

$$\lambda_G = (1-2g)\Delta_G(e,m)$$

$$\lambda_E = (1-2e)\Delta_E(g,m)$$

$$\lambda_M = (1-2m)\Delta_M(g,e) \quad (7)$$

A corner is locally asymptotically stable if all three eigenvalues are strictly negative. A positive eigenvalue makes it unstable. A zero eigenvalue makes the equilibrium nonhyperbolic, so linearization alone is inconclusive [36]. Table 3 orders the eigenvalues for all eight corners.

Its abbreviations are A=$C_N - C_O + R_G$, L=K−C_C+R_M and H=D_M+(γ−1)R_M; these are payoff combinations rather than new independent parameters.

Corner configurations are alternative equilibria, not necessarily successive development stages. Under fixed parameters, a system exactly at a corner remains there. Claims of transitions between corners require changing parameters, perturbations or mechanisms that introduce absent strategies.

Table 3 Corner eigenvalues with actor directions identified

Corner	Eigenvalues in government, enterprise and member directions

Corner	Eigenvalues in government, enterprise and member directions
$E_1(0,0,0)$	$\lambda_G = C_N - C_O + R_G$ $\lambda_E = R_E - C_I$ $\lambda_M = K - C_C + R_M$
$E_2(1,0,0)$	$\lambda_G = C_O - C_N - R_G$ $\lambda_E = R_E\phi - C_I$ $\lambda_M = K - C_C + R_M + R_M\eta$
$E_3(0,1,0)$	$\lambda_G = C_N - C_O + D_G + R_G + \theta R_E$ $\lambda_E = C_I - R_E$ $\lambda_M = K - C_C + R_M$
$E_4(0,0,1)$	$\lambda_G = C_N - C_O + D_G + R_G + \theta R_M$ $\lambda_E = R_E - C_I$ $\lambda_M = C_C - K - R_M$
$E_5(1,1,0)$	$\lambda_G = C_O - C_N - D_G - R_G - R_E\theta$ $\lambda_E = C_I - R_E\phi$ $\lambda_M = D_M - C_C + K + R_M\eta + R_M\gamma$
$E_6(0,1,1)$	$\lambda_G = C_N - C_O + R_G + R_E\theta + R_M\theta$ $\lambda_E = C_I - R_E$ $\lambda_M = C_C - K - R_M$
$E_7(1,0,1)$	$\lambda_G = C_O - C_N - D_G - R_G - R_M\theta$ $\lambda_E = D_E - C_I + R_E\phi$ $\lambda_M = C_C - K - R_M - R_M\eta$
$E_8(1,1,1)$	$\lambda_G = C_O - C_N - R_G - R_E\theta - R_M\theta$ $\lambda_E = C_I - D_E - R_E\phi$ $\lambda_M = C_C - D_M - K - R_M\eta - R_M\gamma$

Table 3 retains the payoff expressions and labels the associated actor direction explicitly. Its corner classification does not imply that there are exactly eight equilibria. Boundary mixed equilibria and interior equilibria may arise for other parameter combinations; their existence, feasibility and stability must be checked from the coupled equations rather than assumed from a fixed count.

4.4 Full cooperation cost ceilings

At (1,1,1), Eq. (7) yields three strict inequalities:

$$C_O < C_O^* = C_N + R_G + \theta(R_E + R_M)$$

$$C_I < C_I^* = \varphi R_E + D_E$$

$$C_C < C_C^* = K + D_M + (\eta + \gamma)R_M \quad (8)$$

These inequalities are necessary and sufficient for strictly negative corner eigenvalues at full cooperation. The starred quantities are cost ceilings, not optimal cost choices. At equality at least one eigenvalue is zero. The conditions characterize local stability and do not establish global attraction from arbitrary initial states.

At a cost ceiling, the corresponding payoff difference is zero when the other two shares equal one. Because each payoff difference is independent of its own actor share, that boundary edge then consists of equilibria. Thus the full-cooperation corner is not an isolated asymptotically attracting point at equality. This does not determine the behavior of all nearby interior trajectories, which can still depend on the other margins.

4.5 Attraction from interior states under the baseline

The illustrative baseline provides a stronger result than corner stability alone. Substituting Table 1 into Eqs. (1)–(3) gives:

$$\Delta_G = -75 + 20(y + z - 2yz) + 45y + 75z$$

$$\Delta_E = 10 + 6x + 25xz$$

$$\Delta_M = 25 + 55x + 45xy \quad (9)$$

For every feasible state, $\Delta_E \geq 10$ and $\Delta_M \geq 25$. Therefore, for an interior initial state, $d[\log(y/(1-y))]/dt \geq 10$ and $d[\log(z/(1-z))]/dt \geq 25$. Both y and z converge to one. As this occurs, Δ_G converges to 45. By continuity, Δ_G is eventually bounded below by a positive constant, so an initially interior x also converges to one. Hence all strictly interior baseline initial states converge to (1,1,1), although x may first decline.

This result follows from the chosen payoff margins. It is not evidence of a universal endogenous tendency toward cooperation across innovation consortia. It does not apply to every boundary initial condition because the replicator system has no mutation mechanism. For example, x(0)=0 implies x(t)=0 for all model time.

4.6 Bistability under member cost variation

Hold all parameters at their baseline values except C_C. At full cooperation, the eigenvalues in the government, enterprise and member directions are −45, −41 and $C_C - 160$. At (0,1,0), they are −10, −10 and $60 - C_C$. Therefore both corners are locally asymptotically stable for:

$$60 < C_C < 160 \quad (10)$$

This interval demonstrates that the local full-cooperation ceiling is not a universal tipping point for initial-state outcomes. For example, at C_C=150, full cooperation and (0,1,0) are simultaneously stable. Initial shares determine which basin is entered. This is a property of the retained payoff matrix, not an empirical estimate of a real consortium threshold.

The invariant face y=1 also contains a mixed equilibrium in this interval. On that face, the government and member payoff differences reduce to −10+55z and $60 - C_C$+100x. Setting both to zero gives:

$$(x, y, z) = ((C_C - 60)/100, 1, 2/11) \quad (11)$$

The x–z linearization at this mixed equilibrium has zero diagonal entries and positive off-diagonal entries. Its two eigenvalues therefore have opposite signs; the enterprise direction is negative because its margin is positive. The equilibrium is a saddle. It provides a boundary organizing feature of the bistable dynamics, while the full three-dimensional separating surface is not derived here. The numerical basin cross-section in Section 5 is an illustration, not an analytical characterization of that surface.

5 Numerical simulation

5.1 Integration and verification

Simulations used Python with NumPy 2.3.5, SciPy 1.17.0 [37] and Matplotlib 3.10.8. The solve_ivp implementation of DOP853 [38] used relative tolerance 10^{-9}, absolute tolerance 10^{-11} and maximum step 0.01 over

dimensionless model time [0,5]. Trajectories were sampled every 0.001 time units. The basin cross-section used [0,20] and maximum step 0.02. Model time is not calibrated to calendar time.

Integration used logit coordinates $s_i=\log(q_i/(1-q_i))$, for which $ds_i/dt=\Delta_i$ and $q_i=1/(1+\exp(-s_i))$. All initial shares were strictly interior. This transformation keeps the internal state finite without clipping a small strategy share to an absorbing boundary. Reported distances to a corner were evaluated from the logit state using a stable sigmoid expression, so proximity to one was not recorded as an exact zero merely because a floating-point share rounded to one.

For each of the four cost scenarios, initial shares were selected independently from {0.1,0.3,0.5,0.7,0.9}, producing 125 combinations and 500 integrations in total. An endpoint was classified as close to its specified corner if the maximum coordinate distance at t=5 was below 10^{-6}. These structured grid counts describe numerical experiments, not probabilities of real consortium outcomes.

Payoff differences computed directly from Table 2 were compared with Eqs. (1)–(3) at 1,000 random states and parameter vectors using seed 20261009. The maximum absolute discrepancy was 2.27e-13. Representative trajectories starting at (0.5,0.5,0.5) were rerun with relative tolerance 10^{-11}, absolute tolerance 10^{-13} and maximum step 0.005. The largest trajectory discrepancy across the four scenarios was 6.09e-11. These checks establish implementation consistency for the experiments, not empirical validity of the payoffs.

For adjustment comparisons, $T_{0.01}$ is the first sampled time after which the maximum coordinate distance from the reported attracting corner remains at most 0.01 through the end of the integration. It is a finite-horizon operational measure. Table 4 reports its median and maximum across each initial-state grid, without equating these model-time values to months or years.

5.2 Baseline trajectories

The baseline ceilings are C_O^*=145, C_I^*=61 and C_C^*=160. Enterprise and member margins are positive throughout the state space, while the government margin can initially be negative. Figure 1 shows equal initial shares of 0.1, 0.5 and 0.9. Enterprise integration and member participation increase monotonically. A low government share can initially decline and subsequently recover when the other actors become sufficiently active. The convergence claim follows from Section 4.5, not from these three plotted starts alone.

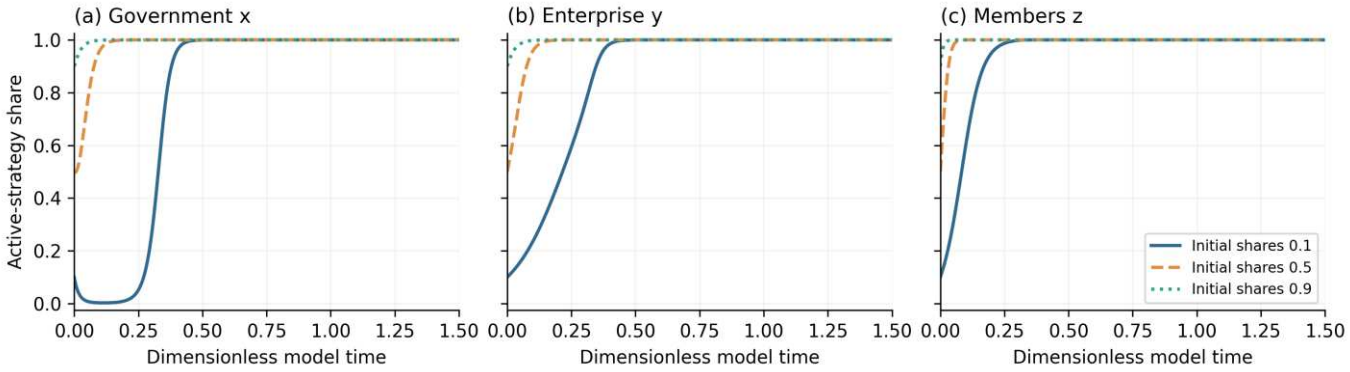


Figure 1 Baseline trajectories. Panels (a), (b) and (c) show government optimization x, enterprise integration y and member deep participation z. Each curve starts with all three shares equal to 0.1, 0.5 or 0.9. All parameters are fixed at Table 1 values. The displayed window is [0,1.5]; integration continues to t=5.

5.3 Cost perturbations and partial cooperation

Changing one baseline cost at a time gives three partial-cooperation examples. At C_O=160, trajectories approach (0,1,1), with corner eigenvalues (−15,−10,−25) in government, enterprise and member order. At C_I=70, they approach (1,0,1), with eigenvalues (−20,−9,−80). At C_C=170, they approach (0,1,0), with eigenvalues

(−10,−10,−110). All 125 grid starts in each scenario satisfy the endpoint criterion. These observations are supported by corner stability, but the grid does not prove that no other attraction structures exist outside the sampled starts.

The zero coordinates represent the alternative strategies specified in Section 3, not necessarily organizational exit. Thus (0,1,1) indicates status quo institutions with active enterprise integration and deep member participation; (1,0,1) indicates institutional optimization with limited enterprise integration; and (0,1,0) indicates active enterprise integration with status quo institutions and limited member participation. Figure 2 displays one representative trajectory per scenario.

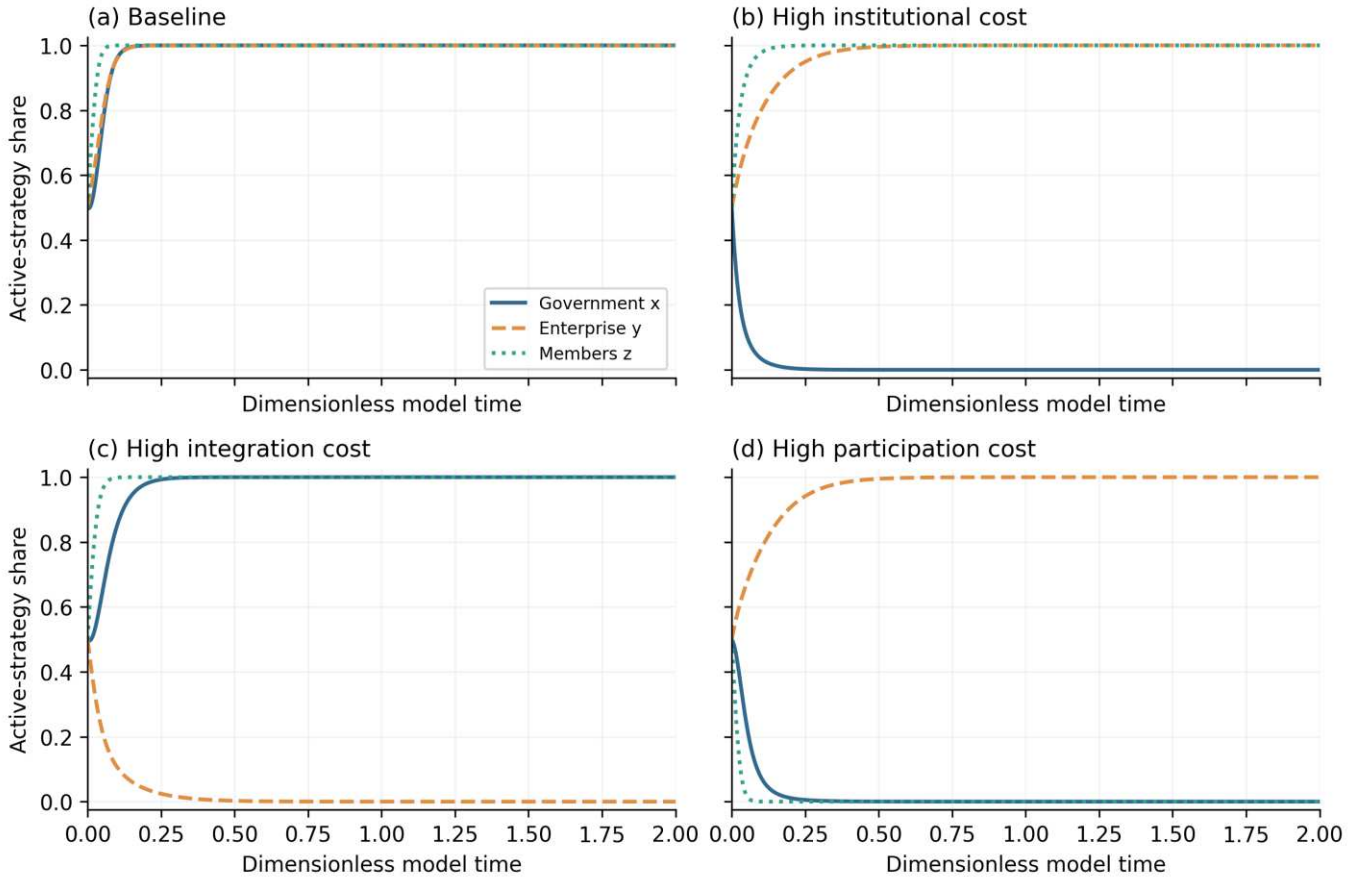


Figure 2 Full and partial cooperation under separate cost increases. Panels show (a) baseline, (b) C_O=160, (c) C_I=70 and (d) C_C=170. The three curves are x, y and z, identified by consistent colors and line styles. Initial shares are (0.5,0.5,0.5); all unvaried parameters follow Table 1. The plotted time window is [0,2].

Table 4 Scenario outcomes and adjustment times across the initial state grid

Scenario	Corner	Close / runs	Max distance at t=5	Median $T_{0.01}$	Max $T_{0.01}$
Baseline	(1,1,1)	125/125	2.00e-84	0.157	0.433
C_O=160	(0,1,1)	125/125	1.72e-21	0.419	0.679
C_I=70	(1,0,1)	125/125	2.32e-19	0.418	0.753
C_C=170	(0,1,0)	125/125	6.79e-17	0.519	1.737

Note. The grid is the Cartesian product of {0.1,0.3,0.5,0.7,0.9}. Distances are the maximum absolute coordinate differences from the listed corners, evaluated from logits. $T_{0.01}$ is defined in Section 5.1. Small numerical distances are not exact finite-time attainment of a corner.

5.4 Return parameters and transient adjustment

Figure 3 varies φ over {1,10,20} from (0.5,0.5,0.5). All displayed trajectories approach full cooperation. The larger multipliers strengthen the enterprise margin when x is positive and alter the coupled government and member trajectories. These wide values are stress-test settings rather than estimated institutional effects. The unchanged attracting corner in this sweep is conditional on the retained parameters and initial state.

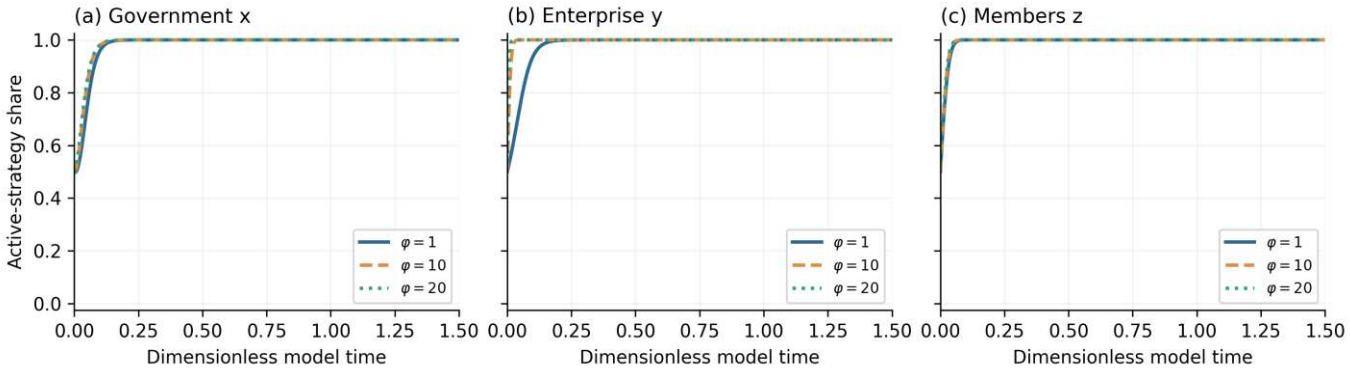


Figure 3 Sensitivity to the institutional multiplier φ. Panels (a), (b) and (c) show x, y and z for φ=1, 10 and 20. Initial shares are (0.5,0.5,0.5); other parameters retain Table 1 values. The baseline multiplier is 1.2, so the three curves are alternative stress-test settings. The plotted window is [0,1.5].

Figure 4 varies R_E over {10,30,50}. The representative trajectories again approach full cooperation, but their adjustment paths differ. At R_E=10 the enterprise margin is not uniformly positive: it equals −10+2x+25xz and can be negative at early states. Therefore the proof in Section 4.5 does not extend automatically to that sweep value. R_E directly enters both enterprise and government margins; member effects operate indirectly through the evolving x and y shares. Small changes in the plotted member trajectory should not be interpreted as absence of coupling.

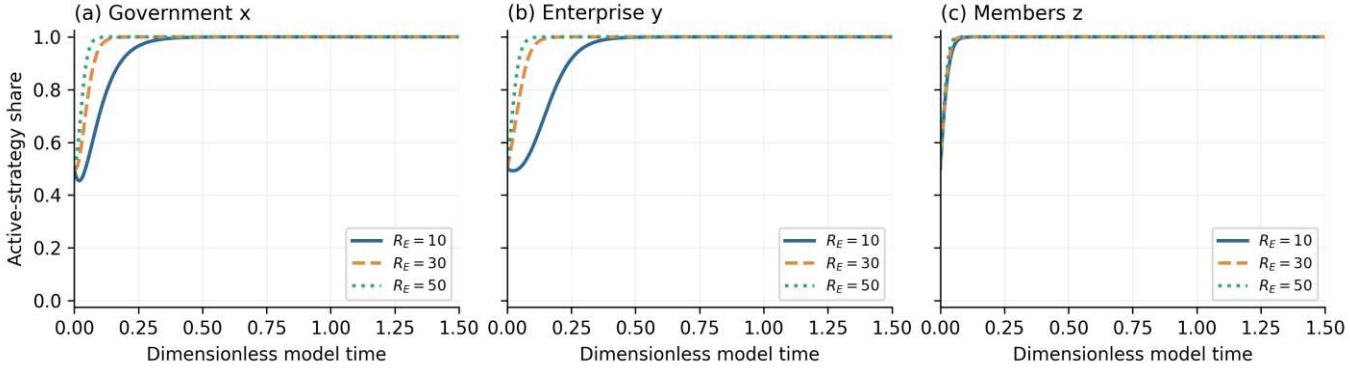


Figure 4 Sensitivity to enterprise integration return R_E. Panels (a), (b) and (c) show x, y and z for R_E=10, 30 and 50. Initial shares are (0.5,0.5,0.5), all other parameters follow Table 1, and the displayed time window is [0,1.5]. R_E=30 is the baseline.

Neither sweep supports a general separation of costs as configuration-changing parameters and returns as speed-only parameters. For example, at C_I=70 with R_E=30 and D_E=25, increasing φ above 1.5 restores a positive enterprise margin at full cooperation. Likewise, increasing θ raises $C_O{}^*$. Whether an intervention changes the attracting outcome depends on the complete parameter vector and initial condition, including possible bistability.

5.5 Local thresholds and coexistence

Figure 5 varies each cost around its full-cooperation ceiling. At the selected government and enterprise costs, below-threshold representative trajectories approach full cooperation and above-threshold trajectories approach the illustrated partial configurations. The member-cost panel behaves differently: at C_C=150, which is below the full-

cooperation ceiling of 160, the initial state (0.5,0.5,0.5) approaches (0,1,0). Thus the panel itself demonstrates why a local stability threshold cannot be interpreted as a universal initial-state tipping point.

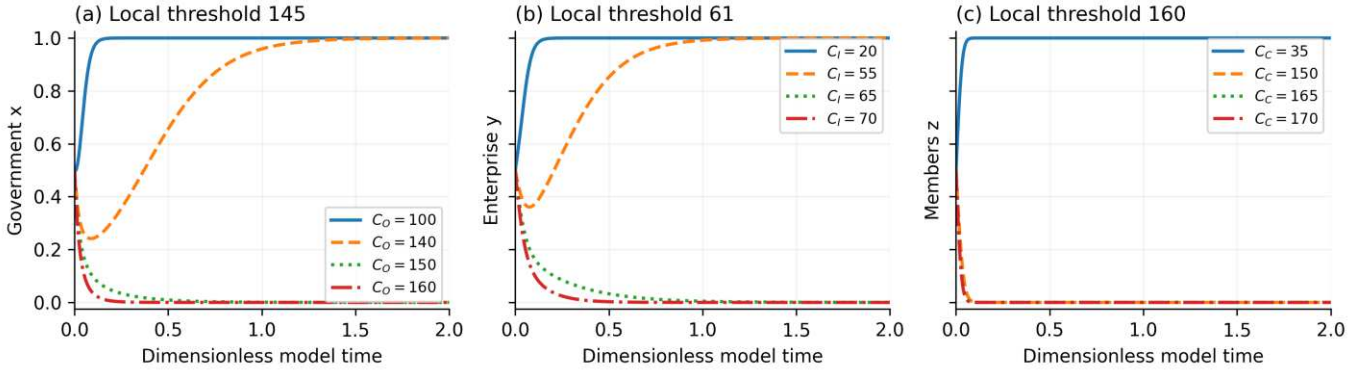


Figure 5 Cost sensitivity relative to local full-cooperation ceilings. Panels show the relevant actor share: (a) x for C_O=100, 140, 150 and 160; (b) y for C_I=20, 55, 65 and 70; (c) z for C_C=35, 150, 165 and 170. The local ceilings are 145, 61 and 160, respectively. Initial shares are (0.5,0.5,0.5), with other parameters at baseline. The C_C=150 trajectory approaches partial cooperation despite local stability of full cooperation.

Figure 6 examines C_C=150 within the analytically established bistable interval. Starting from (0.5,0.5,0.5) gives (0,1,0), whereas starting from (0.9,0.9,0.9) gives (1,1,1). A cross-section fixes y(0)=0.5 and varies x(0) and z(0) independently over 25 equally spaced values from 0.02 to 0.98. Classification at t=20 assigns 515 of the 625 starts to (0,1,0) and 110 to (1,1,1), with none unresolved under the 10^{-6} criterion. These are grid-specific counts, not estimates of basin volumes or real-world probabilities.

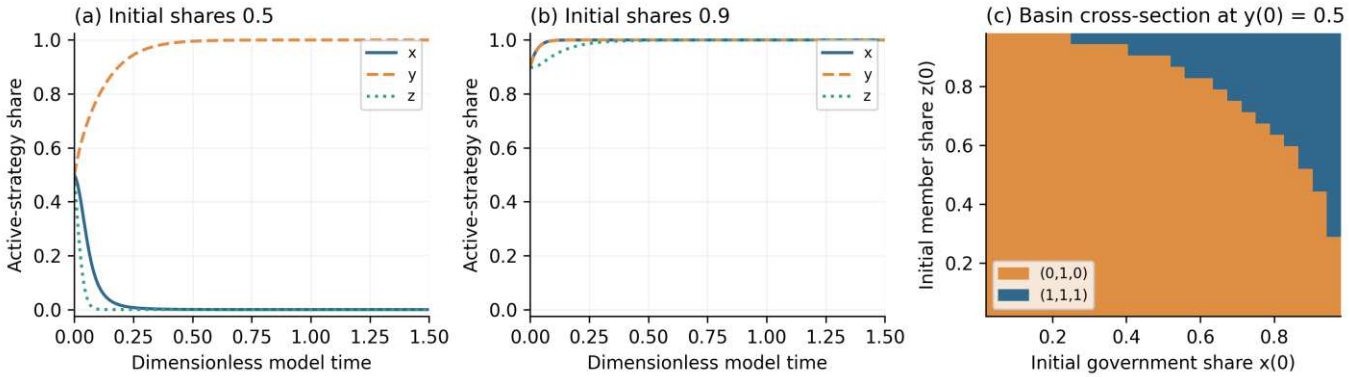


Figure 6 Initial-state dependence at C_C=150. Panels (a) and (b) show x, y and z from equal initial shares of 0.5 and 0.9. Panel (c) shows the numerical basin cross-section at y(0)=0.5, using a 25×25 grid for x(0),z(0)∈[0.02,0.98]. Orange denotes approach to (0,1,0) and blue to (1,1,1) at t=20. Other parameters are fixed at baseline. The finite grid illustrates coexistence; it does not derive the separating surface.

6 Discussion and governance implications

6.1 Main findings

The first result is an actor-specific characterization of local full-cooperation stability. Each cost ceiling expresses one negative corner eigenvalue condition. These thresholds are conditional on the remaining parameters and are not optimal spending levels or empirically estimated policy limits.

The second result distinguishes attraction from local viability. The baseline has full interior attraction because enterprise and member margins remain uniformly positive and the government margin eventually becomes positive. Under member-cost variation, however, full cooperation and (0,1,0) coexist throughout $60<C_C<160$. A locally

stable full-cooperation configuration can therefore remain unreachable from some interior initial states under unchanged parameters.

The third result concerns the interpretation of parameter experiments. Selected return sweeps change transient paths without changing the displayed limiting configuration, whereas selected cost increases produce partial cooperation. Both return and cost parameters can nevertheless change corner stability, and either can influence coupled trajectories and basin membership. Parameter effects must be described by region and initial condition rather than assigned a universal cost-versus-benefit label.

6.2 Relationship to consortium research

The results connect consortium orchestration to the distinction between maintaining commitment and mobilizing it. Governance research emphasizes the fit between network arrangements and their context [13,14], and orchestration studies describe practices that connect participants and sustain their contributions [8,25]. The model adds a formal incentive interpretation: positive margins at full cooperation explain viability near that configuration, whereas competing attraction basins determine whether it emerges from a more distant starting state. Thus governance diagnosis needs information about current commitment as well as the payoffs expected under full cooperation.

At C_C=150, the same parameter vector sustains two locally stable configurations. Starting with equal shares of 0.5 approaches enterprise integration without institutional optimization or deep member participation, whereas equal shares of 0.9 approach full cooperation. This is an illustration of conditional incentives and self-reinforcing adjustment in the model. It does not imply that observed consortia are divided into these two groups or that the simulated grid counts estimate their prevalence. The relevant implication is that making full cooperation locally viable is a different task from moving a particular consortium into its attraction basin.

Knowledge and relational research also qualify the meaning of the cooperative corner. External collaboration can provide access to distributed knowledge [27,28], while its use depends on learning capabilities [29]. Coordinated commitment and successful task integration are distinct [10]. The model represents commitment to institutional optimization, enterprise integration and member participation, but contains no learning-output or environmental-performance equation. Consistent with consortium performance studies [35,39] and research on collaboration and breakthrough invention [40], full cooperation should be interpreted as an organizational condition rather than proof of superior technological success.

Compared with the directly related evolutionary-game studies of low-carbon and engineering innovation consortia [4,5], synergy [17] and subsidy–spillover interactions [18], the present contribution is the explicit connection between actor margins, a proved baseline attraction result and a bistability example. Its cost ceilings offer an interpretable expression of corner stability. Its coexistence interval shows why those ceilings should not be treated as universal tipping points. The model therefore provides a focused analytical complement to empirical work on R&D cooperation and green innovation [3,21], rather than replacing evidence on how actual projects perform.

The configurations are not mandatory developmental stages. With fixed parameters, an exact corner remains fixed because the replicator dynamics do not introduce an absent strategy. Nor does initial-state dependence imply that historical memory has been modeled: the dynamics depend on the current state. Movement from an absorbing corner requires a perturbation or an extension of the adjustment mechanism. These distinctions keep the interpretation consistent with the specified deterministic system [16].

6.3 Conditional governance implications

Consortium support should be assessed as a coordinated set of institutional and organizational arrangements, consistent with policy-mix research [20] and context-dependent network governance [13,14]. Diagnose actor margins together with initial cooperation conditions. A negative payoff difference identifies an immediate incentive constraint, but other actors' evolving shares can change it. In a bistable region, improving a local full-cooperation

margin may still leave the current state in the partial-cooperation basin. An intervention assessment should therefore examine both the modified payoffs and representative initial states rather than rely on a ceiling alone.

Match instruments to the modeled channel. Reducing administrative costs can be represented by a lower C_O; shared coordination infrastructure or simplified contracting by a lower C_I; and easier knowledge-sharing procedures by a lower C_C. Changes in enterprise returns under institutional optimization act through φ or R_E. Member institution-enabled returns act through ηR_M, and joint institutional–enterprise support acts through γ. Orchestration and brokering research provide organizational examples of such coordination and knowledge-mobilization activities [8,25,26]. These mappings are modeling interpretations that require empirical validation; they do not equate different policy instruments to interchangeable coefficients.

Interpret relational losses cautiously. K represents an additional consequence of limited participation. Predictable access to collaborative opportunities or relationship-specific benefits can motivate this term, but the model does not justify punitive exclusion as an optimal policy. Moreover, D_M increases the active-strategy margin under joint optimization and integration because the active member avoids a loss borne by the alternative. Lowering D_M cannot be presented as a participation-promoting IP-protection channel in the current specification. A distinct leakage-risk term would be needed to evaluate that mechanism.

Coordinate support across actors when interactions are important. The baseline government share can initially decline while enterprise and member shares rise. This shows that short-run movement is not always informative about the limiting configuration. It motivates examining coordinated or time-dependent support, but the present autonomous model does not compare intervention schedules or establish that enterprise–member support must always precede institutional reform.

Distinguish cooperation viability from policy efficiency. A return increase or cost reduction may shift stability, alter attraction or accelerate adjustment. The model has no public budget constraint, instrument cost schedule or welfare objective, so it cannot rank interventions by cost-effectiveness, prove diminishing policy returns or identify an optimal allocation. Such decisions require additional information beyond the signs of payoff margins.

6.4 Limitations

The principal limitation is that parameter values are illustrative and uncalibrated. The numerical thresholds and basin cross-section are theoretical examples, not observed magnitudes. Empirical research could estimate coordination costs and conditional returns using consortium cases, interviews or longitudinal records, and test whether the retained payoff restrictions are plausible.

The model aggregates heterogeneous participating firms, universities and institutes into one actor class. It assumes binary strategies, mean-field encounters and common adjustment-rate normalization. It omits network topology, explicit trust accumulation, historical memory, stochastic shocks and mutation. These extensions can change trajectories, attraction basins or feasible equilibria. The numerical grid covers selected scenarios and is not an exhaustive bifurcation analysis.

Finally, green innovation is the application context rather than an independently modeled environmental outcome. Carbon reduction, patent quality and technological breakthrough probabilities require separate measurement or payoff mechanisms. Concrete IP protection, tax relief, absorptive capacity and technical complexity are not estimated in the present system. Empirical studies of environmental innovation and external R&D cooperation offer starting points for measuring outcomes and partner contributions [2,3,21], while knowledge-network research motivates measuring capabilities and relations separately from membership [28,29]. Future work should distinguish empirically calibrated institutional effects from alternative theoretical payoff specifications.

7 Conclusion

A tripartite evolutionary game links government institutional optimization, enterprise resource integration and member deep participation through conditional payoff differences. The retained matrix yields three cost ceilings for local full-cooperation stability and a baseline in which every strictly interior initial state converges to full cooperation. Separate cost increases generate three locally stable partial-cooperation examples.

The decisive qualification is that local stability does not establish global reachability. With other baseline parameters fixed, full cooperation and (0,1,0) coexist for member costs between 60 and 160, and initial shares determine which outcome emerges. Governance diagnosis should therefore consider actor incentives, coupled adjustment and attraction conditions together. The model supplies theoretical benchmarks for further empirical calibration rather than verified environmental impacts or an optimal policy prescription.

Author contributions

Xueling Wang---- Conceptualization, Methodology, Writing – original draft; Qingjin Wang---Resources, Supervision; Tian Lan---Software, Formal analysis

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Data availability

The datasets used and analysed during the current study available from the corresponding author on reasonable request.

Competing interests

The author(s) declare no competing interests.

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