

Finance and Technology under Negotiated Equity Constraints: An Evolutionary Game of Differentiated Climate Cooperation

Enying Zhang

Harbin University of Commerce

Luanyu Tang

tangluanyub2026@es.hrbcu.edu.cn

Harbin University of Commerce

Jiawei Zhao

Harbin University of Commerce

Research Article

Keywords: international environmental agreements, climate finance, technology cooperation, common but differentiated responsibilities, evolutionary game, climate clubs

Posted Date: October 6th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11058495/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Finance and Technology under Negotiated Equity Constraints:

An Evolutionary Game of Differentiated Climate Cooperation

Abstract: Broad agreement on the need for climate action coexists with persistent disagreement over burden sharing, finance, and technology support. This article develops a two-population evolutionary game of active and weak cooperation by two representative strategic country groups. The model combines a finance-equivalent negotiated distributive benchmark with recipient and provider participation constraints, while distinguishing the recipient effectiveness of technology support from its provider cost and its recognition under the negotiated support rule. Mutual high cooperation can be locally stable yet coexist with low cooperation, producing path dependence. The admissible finance interval depends on the lower constraint that binds. When recipient adequacy binds, technology widens the interval if recipient effectiveness exceeds provider net cost, $\eta > \kappa$. When the negotiated technology-recognition constraint binds, the condition becomes $\lambda\eta > \kappa$, where λ is the share of effective technology support recognized toward the distributive benchmark. This constraint switch shows that the cooperation value of technology depends on both physical effectiveness and institutional accounting. Pioneer coalitions can also affect cooperation by raising initial participation or cooperative synergies. The model maps these mechanisms cautiously to the Paris Agreement, the new collective quantified goal on climate finance, the enhanced transparency framework, and the Belém Technology Implementation Programme. It identifies when a negotiated distributive requirement and two-sided participation incentives can be jointly feasible and dynamically persistent.

Keywords: international environmental agreements; climate finance; technology cooperation; common but differentiated responsibilities; evolutionary game; climate clubs

1 Introduction

The Paris Agreement has near-universal participation and a dense architecture of nationally determined contributions, finance negotiations, transparency rules, and technology mechanisms (United Nations, 2015). Yet aggregate ambition and implementation remain insufficient, while burden sharing and support remain contested. The central institutional problem is therefore not an absence of agreement that climate action is necessary. It is how a negotiated distributive requirement can coexist with national participation incentives and become dynamically persistent.

The economics of international environmental agreements (IEAs) has long emphasized the divergence between global and national incentives. Because mitigation creates transboundary benefits, unilateral action is underprovided and stable coalitions may be substantially smaller than the socially efficient coalition (Barrett, 1994; Carraro & Siniscalco, 1993). Subsequent work has examined asymmetric countries, transfers, issue linkage, repeated interaction, domestic political constraints, technology, and endogenous cooperation intensity. A review of two decades of economic research in this journal concludes that future work should integrate

institutions, distribution, and social–ecological relations more directly into IEA analysis (Pouw et al., 2022).

Three developments make such integration particularly timely. First, distributive principles are embedded in the Paris architecture. Article 2.2 explicitly refers to equity and common but differentiated responsibilities and respective capabilities (CBDR-RC), while states continue to invoke historical responsibility, capability, vulnerability, and development needs in debates over ambition and support (Herrera et al., 2025). Second, finance and technology are distinct institutional pillars rather than a single generic transfer mechanism. Decision 1/CMA.6 (UNFCCC, 2024) established the new collective quantified goal on climate finance, while Decision 18/CMA.7 (UNFCCC, 2026) adopted the Belém Technology Implementation Programme. Third, transparency is operational through Article 13 but remains facilitative and non-punitive. Models that collapse finance, technology, monitoring, and sanction into a single enforcement parameter therefore obscure important institutional distinctions.

This article develops an institutionally grounded model of differentiated climate cooperation between two representative strategic country groups: a provider-type group, denoted D , and a recipient-type group, denoted S . These are analytical types rather than legal Annex categories or claims of within-group homogeneity. The model identifies how finance, technology, transparency, domestic green benefits, and international synergies affect the relative payoff to active cooperation. It separates provider domestic green benefits from international market synergies; treats technology support as an effective recipient benefit and a provider net cost; restricts finance to cooperation-linked mitigation and transition support; and represents CBDR-RC through a negotiated distributive-support benchmark rather than a universal monetary measure of justice.

The paper's main contribution is to show that the cooperation value of technology changes with the lower constraint that binds. This result follows from placing a negotiated distributive-support benchmark inside a two-sided participation framework and separating recipient effectiveness η , provider net cost κ , and the recognized share λ . Technology widens the admissible finance interval under $\eta > \kappa$ when recipient adequacy binds, but under $\lambda\eta > \kappa$ when the negotiated recognition constraint binds. The model also distinguishes two channels through which pioneer coalitions can matter: moving the system state across a separatrix and changing local participation-growth thresholds. The theoretical contribution therefore lies in the binding-constraint switch and its institutional interpretation, not in a new form of replicator dynamics.

The analysis has three layers. Negotiation specifies a distributive support requirement. Participation constraints determine whether both strategic groups prefer mutual high cooperation. Replicator dynamics then distinguish static feasibility from the prevalence and persistence of cooperative strategies under payoff-monotonic learning. This evolutionary step

complements rather than replaces conventional coalition-stability analysis: it shows when an institutionally feasible cooperative configuration becomes self-reinforcing once cooperation is sufficiently prevalent.

2 International environmental cooperation, differentiated responsibility, and evolutionary learning

2.1 Self-enforcing environmental agreements and institutional depth

The canonical IEA literature treats international environmental cooperation as a self-enforcement problem in the absence of supranational coercion. Barrett (1994) and Carraro and Siniscalco (1993) established that individually rational participation can generate coalitions well below the globally efficient size. Later work developed transfers, bargaining, uncertainty, political pressure groups, repeated interaction, and heterogeneous benefits and costs. Hagen et al. (2021), for example, show that domestic political pressure can alter both national abatement and agreement stability. Distefano and D'Alessandro (2021) connect international bargaining to evolutionary dynamics among domestic firms and consumers, demonstrating that international targets can fail when domestic behavioral conditions are unfavorable.

Recent theoretical research has shifted attention from binary membership to the depth and timing of cooperation. Eichner and Schopf (2025) endogenize cooperation intensity and show that appropriate depth can enlarge stable coalitions. Dynamic participation models show that future payoffs, re-entry, and state-contingent transfers can support broader cooperation than static coalition models (Okada, 2023). Kerr et al. (2025) further show that green investment and transfer timing interact. These developments imply that the central question is no longer simply who joins, but how support, investment, and cooperative benefits are structured.

2.2 Equity and differentiated responsibility

Efficiency and coalition stability have received more formal treatment than equity, even though equity is central to climate negotiations. Formal IEA research has begun to close this gap. Donnini and Sacco (2024) impose envy-freeness on coalition decisions, and Aprea et al. (2026) examine per-capita and average envy-free rules and their implications for stable coalitions. These studies endogenize equity properties of emissions or production allocations. In the Paris context, however, equity claims also span distributive, procedural, recognitional, and intergenerational dimensions (Barkai & Winkler, 2025), while states invoke responsibility, capability, vulnerability, and development needs in bargaining over ambition and support (Herrera et al., 2025). The present model isolates one narrower object: a negotiated distributive-support requirement.

The model neither measures legitimacy nor derives a comprehensive theory of climate justice. It introduces a finance-equivalent negotiated distributive-support benchmark, denoted FJ. In reduced form, $FJ = \Phi(RD, KD, NS)$, where RD summarizes responsibility considerations, KD

provider capability, and NS recipient development and transition needs. The mapping is left to negotiation because its content is politically contested. The analytical question is whether the resulting benchmark, once specified, can be satisfied together with recipient and provider participation constraints.

2.3 Finance, technology, transparency, and climate clubs

Climate finance is more complex than a generic side payment. The Paris regime combines provision and mobilization commitments with continuing disagreement over adequacy, concessionality, predictability, accounting, and burden sharing. Bergsvik et al. (2024) show that greater transparency in climate-finance reporting does not automatically eliminate ambiguity because categories and accounting practices remain contested. This motivates treating finance as a distinct institutional channel with a lower adequacy constraint and an upper provider-participation constraint.

Technology cooperation is also strategic. Green technologies can lower future mitigation costs and create commercial opportunities, but their diffusion depends on intellectual property, absorptive capacity, infrastructure, project risk, and provider incentives. Urpelainen (2013) shows that strategic technology development can improve cooperation when frontrunners invest and other countries are willing and able to adopt. Technology collaboration can also be coalition-based and sequential, making pioneer groups relevant to wider cooperation.

Climate clubs provide a related mechanism. Nordhaus (2015) emphasized club benefits and penalties as responses to free riding, while later work has stressed co-benefits, sectoral partnerships, standards, and open forms of multilateral cooperation. Hannam et al. (2017) show that partially excludable co-benefits can create a nucleus for deeper cooperation. Recent work in this journal likewise cautions against reducing climate clubs to carbon prices and border measures alone; sectoral alliances, common metrics, technology, and development partnerships may be equally important (von Luepke et al., 2024).

2.4 Evolutionary dynamics as a model of policy learning

Evolutionary game theory is used as a model of payoff-monotonic policy learning, not as a biological analogy among sovereign states. In large-population models, strategies with higher relative payoffs become more prevalent through experimentation, imitation, institutional learning, and diffusion (Weibull, 1995; Hofbauer & Sigmund, 1998; Sandholm, 2010). Here x and y represent strategy prevalence across heterogeneous states and repeated policy-learning episodes. McGinty (2010) applies this logic to IEAs and shows that evolutionary stability can differ from one-shot equilibrium concepts. The framework is therefore used to distinguish an institutionally feasible cooperative package from the conditions under which cooperative strategies become prevalent and self-reinforcing; it does not replace coalition or repeated-game approaches.

2.5 Analytical gap and literature positioning

A narrower gap remains at the intersection of formal equity, international support, and dynamic strategy prevalence. Formal equity models impose allocation or coalition-level fairness requirements but do not examine how finance and technology recognition jointly alter two-sided participation margins. Transfer and technology models analyze incentives without a negotiated distributive support constraint. Evolutionary IEA models explain strategy diffusion but generally do not identify how a change in the binding support constraint alters the value of technology cooperation.

The contribution is therefore not the use of replicator dynamics, country asymmetry, transfers, or technology cooperation in isolation. McGinty (2010) established an evolutionary IEA approach; Biancardi and Villani (2015) and Villani and Biancardi (2019) combine asymmetric cooperation with green R&D; Li and Fujita (2021) analyze transfers under heterogeneity; Luqman et al. (2022) study rewards and penalties; Urpelainen (2013) formalizes strategic technology development; and Kerr et al. (2025) connect transfers to green investment. Donnini and Sacco (2024) and Aprea et al. (2026) provide the closest formal equity comparators. This paper connects these strands through a two-sided participation interval, a negotiated distributive benchmark, and a technology-recognition rule that changes the relevant comparative-static condition when the binding lower constraint switches.

Table 1. Positioning relative to selected literature

Study	Core contribution	What remains outside that analysis	Relevance here
McGinty (2010)	Evolutionary framework for IEAs	No negotiated equity floor or binding-constraint switch	Evolutionary IEA benchmark
Biancardi & Villani (2015)	Dynamic IEA stability with developed/developing asymmetry and green R&D	No negotiated distributive benchmark or finance-credit interaction	Closest asymmetric technology comparator
Villani & Biancardi (2019)	Replicator dynamics with R&D investment in IEAs	No two-sided finance interval or negotiated technology-recognition rule	Closest evolutionary technology comparator
Li & Fujita (2021)	Transfers in IEAs with developed/developing heterogeneity	No evolutionary learning or technology-credit rule	Closest transfer comparator
Luqman et al. (2022)	Rewards and penalties in an evolutionary IEA model	No integrated finance–technology–equity mechanism	Evolutionary reward/penalty comparator
Urpelainen (2013)	Strategic clean-technology development	No finance-equity participation set	Motivates technology channel
Kerr et al. (2025)	Dynamic transfers with green investment	No evolutionary threshold or negotiated equity floor	Motivates transfer–investment interaction
Donnini & Sacco (2024); Aprea et al. (2026)	Formal equity constraints in IEA coalition formation	No finance–technology recognition rule or evolutionary strategy prevalence	Formal equity comparators
This paper	Two-sided participation interval with finance, technology, a negotiated distributive benchmark, and a technology-recognition rule	Reduced-form two-population setting	Constraint-dependent finance–technology effects within an evolutionary framework

Table 1 locates the paper relative to these strands. The replicator system is standard. The theoretical content comes from the interaction of three institutionally distinct margins—recipient effectiveness, provider cost, and negotiated recognition—and from the switch

between recipient adequacy and the negotiated distributive requirement as the active lower constraint.

3 Model

3.1 Actors, strategies, and scope

Consider two large populations representing provider-type countries (D) and recipient-type countries (S), labeled developed and developing for continuity with the differentiated-cooperation literature. Each country repeatedly chooses between active cooperation (C) and weak cooperation (N). Let $x \in [0,1]$ denote the share of D using C and $y \in [0,1]$ the corresponding share of S. D and S are representative strategic types, not legal Annex categories. The population formulation permits heterogeneous strategy adoption while using representative reduced-form payoff parameters within each group.

A cooperating country generates a transboundary climate benefit. Let b_D and b_S denote the climate benefits generated by one population's active cooperation and accruing to the developed and developing populations, respectively. These terms exclude actor-specific domestic industrial or transition co-benefits; the model abstracts from a separate developing-country co-benefit parameter, while provider-side domestic green benefits are represented separately by m_D because they are central to the provider participation margin. Active cooperation costs are c_D and c_S . Developed-country cooperation additionally yields a domestic green benefit m_D from energy security, technological learning, health co-benefits, and domestic green-industry development. This term is kept separate because the analysis distinguishes autonomous provider-side industrial incentives from h_D , an additional international market and standardization benefit available only when both populations cooperate.

An analogous recipient-side domestic co-benefit would shift the recipient payoff intercept and finance threshold without changing the qualitative structure of the propositions, so the baseline omits it. The baseline also assumes source-symmetric transboundary climate benefits: the benefit accruing to a population from one unit of active cooperation does not depend on which population generates it. Source-specific terms would enlarge the parameter set without altering the participation-constraint logic.

Let s_D and s_S denote other mutual-cooperation synergies. Cooperation-linked mitigation and transition finance $F \geq 0$ is transferred from D to S when mutual cooperation is institutionalized. It does not represent all climate finance: unconditional adaptation support and loss-and-damage finance lie outside the model. Technology cooperation has intensity $T \geq 0$. S obtains an effective technology benefit ηT , where η summarizes adoption and absorptive capacity; D bears a net technology cost κT , already net of licensing revenue, scale economies, and strategic commercial gains. Positive institutional rewards r_D and r_S capture non-financial reputational and procedural benefits of participation. To avoid double counting, market and

standardization gains are assigned to h_D , coordination complementarities to s_D and s_S , and financial transfers exclusively to F .

Finally, $q \in [0,1]$ measures how reliably weak cooperation is observed and translated into institutional feedback, while group-specific opportunity-cost coefficients determine the consequences that follow. Their interaction can capture reputational, financing, investor, market, or club-related losses; it is not a fine imposed by the Paris Agreement. The model also includes a non-negative finance-equivalent negotiated distributive-support benchmark representing the minimum support required under the rule selected by the parties. The associated eligibility and accounting rule determines which forms of support are recognized toward that benchmark.

The model separates three objects. The term ηT is the recipient's effective benefit from technology cooperation, $\lambda \eta T$ is the amount recognized toward the negotiated distributive benchmark, and κT is the provider's net cost. Thus η describes physical and absorptive effectiveness, λ describes institutional eligibility and valuation, and κ describes the provider participation burden. The recognition parameter can reflect negotiated rules on additionality, verification, usability, and the treatment of non-cash support. Because these objects need not coincide, the same technology transfer can have the same physical effect and provider cost but a different contribution to the negotiated requirement under a different recognition rule.

All payoff components use common normalized monetary-equivalent units. The coefficient on F is normalized to one on both sides of the transfer, so η and κ are comparable within the model. This normalization supports the theoretical comparison; it is not an estimated welfare weighting scheme.

Table 2. Model parameters

Parameter	Interpretation
x, y	Shares of provider-/recipient-type countries choosing active cooperation
b_D, b_S	Climate benefits accruing to D and S from one population's active cooperation; exclude actor-specific domestic industrial/transition co-benefits
c_D, c_S	Costs of active cooperation
m_D	Developed-country domestic green benefit available under unilateral cooperation
h_D	International market/standardization benefit requiring mutual cooperation
s_D, s_S	Additional mutual-cooperation synergies
F	Cooperation-linked mitigation and transition finance from D to S
T	Technology-cooperation intensity
η, κ	Recipient effectiveness and provider net unit cost of technology cooperation
r_D, r_S	Non-financial reputational/procedural rewards from cooperation
q	Reliability of observation and institutional feedback
p_D, p_S	Opportunity costs triggered by observed weak cooperation
F^J	Finance-equivalent negotiated distributive-support benchmark under the chosen equity rule
λ	Share of effective technology support credited toward the negotiated benchmark

Table 2 summarizes the parameters. The model covers a cooperation-linked mitigation and transition package. It does not represent the full architecture of climate finance or a comprehensive account of climate justice.

Unless otherwise stated, the payoff-benefit, cost, synergy, reward, and opportunity-loss parameters are non-negative. The technology-comparative-static results maintain $\eta > 0$ and $\kappa > 0$; F , T , and $F^{\wedge}J$ are non-negative, while q and λ lie in $[0,1]$. These sign restrictions define the maintained parameter domain for the propositions below.

3.2 Payoff matrix

Table 3. Payoffs in the two-population game

D \ S	C	N
C	D: $2b_D + s_D + m_D + h_D - c_D - F - \kappa T + r_D$ S: $2b_S + s_S - c_S + F + \eta T + r_S$	D: $b_D + m_D - c_D + r_D$ S: $b_S - qp_S$
N	D: $b_D - qp_D$ S: $b_S - c_S + r_S$	D: $-qp_D$ S: $-qp_S$

As Table 3 shows, m_D is available whenever D cooperates, whereas h_D requires mutual cooperation. F raises S payoff but lowers D payoff. T likewise raises S payoff through ηT and lowers D payoff through κT . This separation keeps the two-strategy game simple while allowing finance, technology, and green industrial incentives to operate through distinct margins.

3.3 Replicator dynamics

Let U_D^C and U_D^N denote expected payoffs to active and weak cooperation in D. Their difference is:

$$\begin{aligned}\Delta_D &= U_D^C - U_D^N = \alpha_D + \beta_D y \\ \alpha_D &= b_D + m_D - c_D + r_D + qp_D \\ \beta_D &= s_D + h_D - F - \kappa T\end{aligned}$$

For S:

$$\begin{aligned}\Delta_S &= U_S^C - U_S^N = \alpha_S + \beta_S x \\ \alpha_S &= b_S - c_S + r_S + qp_S \\ \beta_S &= s_S + F + \eta T\end{aligned}$$

Payoff-monotonic policy learning is represented by the standard replicator system:

$$\begin{aligned}\dot{x} &= x(1-x)(\alpha_D + \beta_D y) \\ \dot{y} &= y(1-y)(\alpha_S + \beta_S x)\end{aligned}$$

The system has four corner equilibria $E1=(0,0)$, $E2=(1,0)$, $E3=(0,1)$, and $E4=(1,1)$. If β_D and β_S are non-zero, an interior equilibrium $E5=(-\alpha_S/\beta_S, -\alpha_D/\beta_D)$ exists when both coordinates lie in $(0,1)$.

4 Local stability and path dependence

4.1 Corner equilibria

The Jacobian is:

$$J = \begin{bmatrix} (1-2x)(\alpha_D + \beta_D y) & \beta_D x(1-x) \\ \beta_S y(1-y) & (1-2y)(\alpha_S + \beta_S x) \end{bmatrix}$$

Table 4. Local stability of corner equilibria

Equilibrium	Local stability condition	Interpretation
$E_1 = (0,0)$	$\alpha_D < 0$ and $\alpha_S < 0$	Low cooperation is locally stable
$E_2 = (1,0)$	$\alpha_D > 0$ and $\alpha_S + \beta_S < 0$	Only D cooperation is stable
$E_3 = (0,1)$	$\alpha_D + \beta_D < 0$ and $\alpha_S > 0$	Only S cooperation is stable
$E_4 = (1,1)$	$\alpha_D + \beta_D > 0$ and $\alpha_S + \beta_S > 0$	Mutual high cooperation is locally stable

Table 4 yields Lemma 1: mutual high cooperation is locally asymptotically stable if and only if both participation margins are positive, $\alpha_D + \beta_D > 0$ and $\alpha_S + \beta_S > 0$. This establishes the two-sided participation requirement used below.

4.2 Interior saddle point and path dependence

The coordination case of greatest substantive interest occurs when unilateral active cooperation is unattractive ($\alpha_D < 0$ and $\alpha_S < 0$) but mutual cooperation is attractive ($\alpha_D + \beta_D > 0$ and $\alpha_S + \beta_S > 0$), with $\beta_D > 0$ and $\beta_S > 0$. Then E_1 and E_4 are locally stable and the interior equilibrium is:

$$x^* = -\frac{\alpha_S}{\beta_S} = \frac{c_S - b_S - r_S - qp_S}{s_S + F + \eta T}$$

$$y^* = -\frac{\alpha_D}{\beta_D} = \frac{c_D - b_D - m_D - r_D - qp_D}{s_D + h_D - F - \kappa T}$$

At E_5 the Jacobian has zero diagonal terms and:

$$\det(J_{E_5}) = -\beta_D \beta_S x^* (1 - x^*) y^* (1 - y^*) < 0$$

Hence E_5 is a saddle point. Its stable manifold is the separatrix between the basins of attraction of low and high cooperation. When both populations are above their nullcline thresholds, cooperation grows in both groups; when both are below, both decline. Mixed cases depend on the position relative to the separatrix rather than on a rectangular threshold rule.

Proposition 1. Under $\alpha_D < 0$, $\alpha_S < 0$, $\alpha_D + \beta_D > 0$, and $\alpha_S + \beta_S > 0$, the system is bistable. The interior equilibrium is a saddle point, and interventions can alter long-run cooperation either by moving the state across the separatrix or by changing the parameters that determine the separatrix.

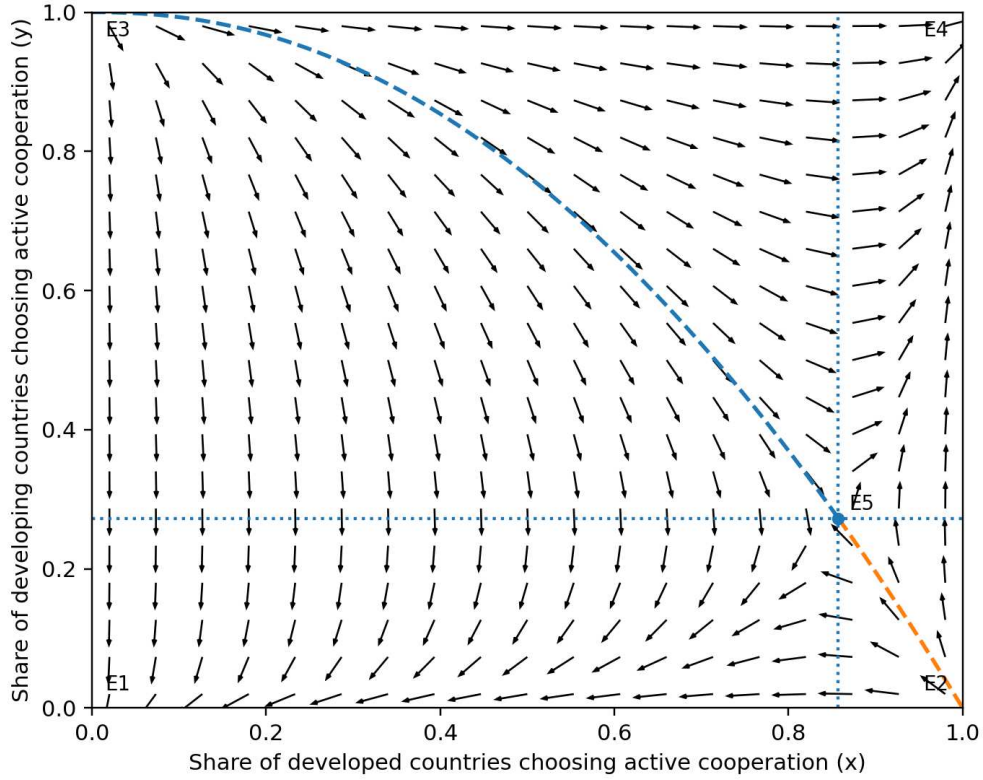


Fig. 1 Phase portrait under the common baseline with $\alpha_D = -0.30$, $\beta_D = 1.10$, $\alpha_S = -1.80$, and $\beta_S = 2.10$. The dotted vertical and horizontal lines are the nullclines $x = x^*$ and $y = y^*$; the curved dashed line is the stable manifold (separatrix) through E5. Values are normalized and illustrative, not empirical estimates

Figure 1 illustrates the resulting coordination problem: the same institutional environment can sustain either low or high cooperation depending on initial conditions and threshold-shifting interventions.

5 Negotiated distributive constraints and the finance–technology interaction

5.1 Two-sided climate-finance constraints

From $\alpha_D + \beta_D > 0$ and $\alpha_S + \beta_S > 0$, mutual high cooperation is locally asymptotically stable only if two finance inequalities hold. Recipient participation requires:

$$F > F_{\min} = c_S - b_S - s_S - r_S - qp_S - \eta T$$

Provider participation requires:

$$F < F_{\max} = b_D + m_D + s_D + h_D - c_D + r_D + qp_D - \kappa T$$

Thus finance relaxes the recipient-side participation constraint while tightening the provider-side participation margin. The incentive-compatible finance interval is defined by the two participation inequalities above together with the non-negativity requirement on finance; it is non-empty exactly when the provider-side ceiling lies above both the recipient-side lower bound and zero.

5.2 The negotiated distributive support benchmark

Incentive compatibility does not by itself satisfy a negotiated distributive requirement. Let $F^J = \Phi(R_D, K_D, N_S) \geq 0$ denote the finance-equivalent distributive-support benchmark specified by the equity rule negotiated by the parties, where R_D , K_D , and N_S summarize responsibility, capability, and recipient needs. The model does not specify Φ because equity operationalization remains politically contested. F^J is therefore a finance-equivalent negotiated benchmark criterion, not an objective or exhaustive measure of climate justice.

Under the benchmark cash-only rule, the negotiated-equity-constrained set is:

$$\mathcal{A}^J = \{F: F_{\min} < F < F_{\max}, F \geq F^J, F \geq 0\}$$

which is non-empty if and only if:

$$F_{\max} > \max\{F_{\min}, F^J, 0\}$$

Throughout the paper, “negotiated-equity-compatible” means only that this stated finance-equivalent distributive benchmark is satisfied. It does not imply procedural, recognitional, intergenerational, or comprehensive justice.

5.3 Technology effects under cash-only recognition

When the cash-only rule applies, the width of the admissible finance interval is:

$$W^J(T) = \max\{0, F_{\max}(T) - \max\{F^J, F_{\min}(T)\}\}$$

This definition sets the interval width to zero whenever the lower bound is not below the provider ceiling. Because the finance-equivalent benchmark is non-negative, zero cannot be the unique binding lower constraint under the cash-only rule; it coincides with the benchmark only when the benchmark equals zero. The within-regime comparative statics are therefore piecewise.

If the recipient-adequacy threshold is the active lower bound, $F_{\min} > \max\{0, F^J\}$, then:

$$\frac{\partial W^J}{\partial T} = \eta - \kappa$$

so technology widens the admissible finance interval if and only if $\eta > \kappa$.

If the negotiated distributive benchmark is the active lower constraint, $F^J > \max\{0, F_{\min}\}$, and F^J is fixed with respect to T , then:

$$\frac{\partial W^J}{\partial T} = -\kappa < 0$$

At the boundary where recipient adequacy and the negotiated benchmark coincide, the interval width is continuous but generally not differentiable. The kink marks a switch in the binding institutional constraint rather than a smooth marginal adjustment.

5.4 Technology recognition under a generalized support rule

The negative derivative under a binding cash-only benchmark follows from an institutional rule: technology support does not count toward the negotiated distributive requirement. To expose that rule rather than leave it implicit, consider a generalized recognition condition:

$$F + \lambda\eta T \geq F^J, \quad 0 \leq \lambda \leq 1$$

where λ is the share of effective technology support credited toward the negotiated distributive benchmark. The cash-only benchmark is the special case $\lambda = 0$; $\lambda = 1$ grants full finance-equivalent credit to the recipient's effective technology benefit.

Recognition does not turn technology assistance into cash or assume that the two instruments are perfect substitutes. It records only the fraction of effective technology support that the parties agree to count when assessing compliance with the negotiated distributive benchmark. Eligibility, additionality, verification, valuation, and recipient acceptance can therefore change λ without changing η or κ . The rule is an institutional design choice, while technology effectiveness and provider cost are properties of the underlying cooperation channel.

The admissible set becomes:

$$\mathcal{A}_\lambda^J = \{F: F_{\min} < F < F_{\max}, F \geq F^J - \lambda\eta T, F \geq 0\}$$

with width:

$$W_\lambda^J(T) = \max\{0, F_{\max}(T) - \max\{0, F_{\min}(T), F^J - \lambda\eta T\}\}$$

When the recipient-adequacy threshold is the active lower bound, the derivative remains $\eta - \kappa$. When the negotiated technology-recognition constraint is the active lower bound, however:

$$\frac{\partial W_\lambda^J}{\partial T} = \lambda\eta - \kappa$$

The result is institutional as well as technological. When the negotiated recognition constraint binds, the same physical technology support can expand or contract the admissible interval depending on whether the recognized recipient value, $\lambda\eta$, exceeds the provider net cost, κ .

Proposition 2. Within a non-empty local high-cooperation regime, the effect of technology support on the negotiated-equity-constrained finance interval depends on the active lower constraint and the recognition parameter λ . If recipient adequacy is the active lower bound, technology increases the interval width if and only if $\eta > \kappa$. If the negotiated technology-recognition constraint is active, technology increases the interval width if and only if $\lambda\eta > \kappa$. Under cash-only recognition, $\lambda=0$, technology tightens the provider margin without relaxing the negotiated benchmark in that region.

Figure 2 illustrates the cash-only special case used as the baseline numerical benchmark; Subsection 6.3.4 compares it with alternative technology-recognition rules.

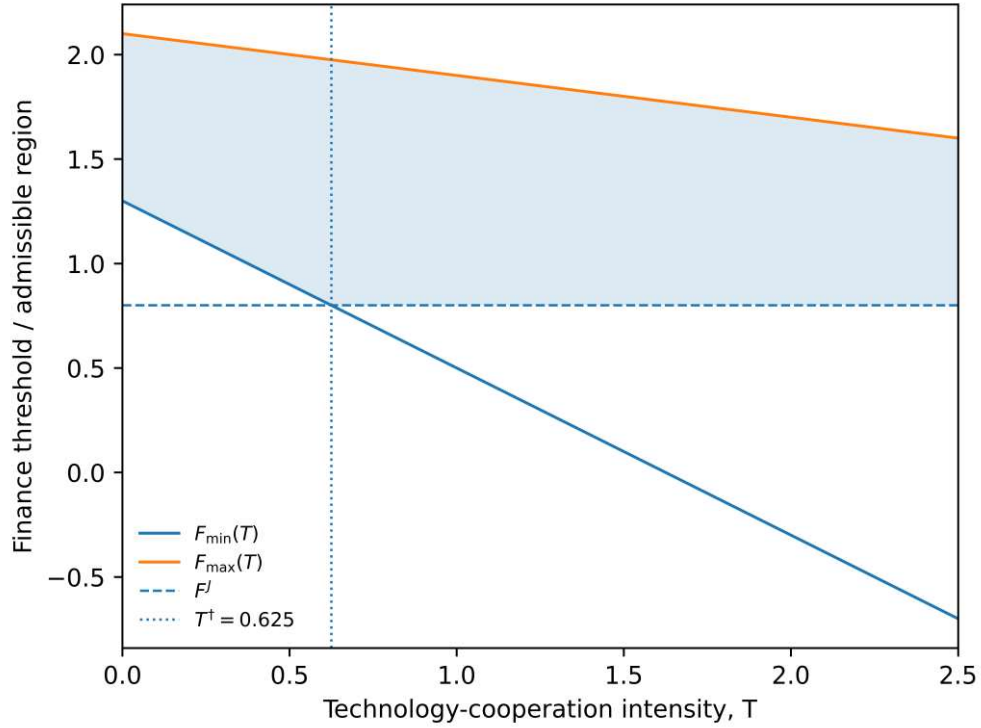


Fig. 2 Cash-only negotiated-equity-constrained finance region under the common baseline; the vertical line marks $T^\dagger=0.625$, with $\eta=0.80$, $\kappa=0.20$, $F^I=0.80$ and $T \in [0, 2.5]$

6 Additional institutional channels and numerical results

6.1 Transparency as credible observation

When $p_D, p_S > 0$, both participation margins increase with q . Transparency thus improves strategic feedback in the model. The interpretation must remain faithful to Article 13: q is not a punishment probability. It captures the reliability of emissions and support information, comparability, review credibility, and the ability of other institutions to condition reputation, investment, partnerships, or market benefits on observed behavior.

Under the cash-only benchmark, the effect on the negotiated-equity-compatible interval is also piecewise. When the recipient-adequacy threshold is the active lower bound, higher q relaxes both participation bounds and raises the interval width by the sum of the provider- and recipient-side conditional opportunity-loss coefficients. When the negotiated benchmark is the active lower constraint, higher q raises the provider ceiling and increases the interval width at a rate equal to the provider-side conditional opportunity-loss coefficient. This reinforces the institutional value of credible information without recasting the Paris transparency framework as coercive enforcement.

6.2 Open pioneer coalitions and local nullcline-threshold shifts

Climate clubs, sectoral alliances, and development partnerships can affect cooperation through two channels. A state-shift effect raises x or y directly by organizing an initial coalition. A structural nullcline-threshold effect changes the parameters determining x^* and y^* .

Within the coordination regime $\alpha_S < 0$, $\beta_S > 0$, the recipient-side nullcline threshold is:

$$x^* = -\frac{\alpha_S}{\beta_S}$$

and:

$$\frac{\partial x^*}{\partial F} = \frac{\alpha_S}{\beta_S^2} < 0, \quad \frac{\partial x^*}{\partial T} = \frac{\eta \alpha_S}{\beta_S^2} < 0$$

Thus finance and technology support reduce the provider-type participation share required for cooperation to grow among recipient-type countries. But these same instruments tighten the provider side because $\beta_D = s_D + h_D - F - \kappa T$. Accordingly:

$$\frac{\partial y^*}{\partial F} = -\frac{\alpha_D}{\beta_D^2} > 0, \quad \frac{\partial y^*}{\partial T} = -\frac{\kappa \alpha_D}{\beta_D^2} > 0$$

when $\alpha_D < 0$ and $\beta_D > 0$. Finance and technology therefore lower the recipient-side nullcline threshold while raising the provider-side nullcline threshold, conditional on remaining inside the coordination regime. If F or T becomes large enough to make $\alpha_D + \beta_D \leq 0$, mutual high cooperation ceases to be locally stable.

By contrast, international green-market and standardization benefits improve the provider side:

$$\frac{\partial y^*}{\partial h_D} = \frac{\alpha_D}{\beta_D^2} < 0$$

with an analogous result for s_D .

Proposition 3. Within the bistable coordination regime, a pioneer coalition that raises initial participation or increases cooperative synergies can promote wider cooperation through a state-shift channel and a structural local-growth-threshold channel. A coalition that creates positive club synergies such as h_D can lower the provider-side nullcline threshold without imposing the same direct participation cost as additional finance, whereas finance and technology generate a two-sided trade-off: they lower the recipient-side nullcline threshold but raise the provider-side nullcline threshold.

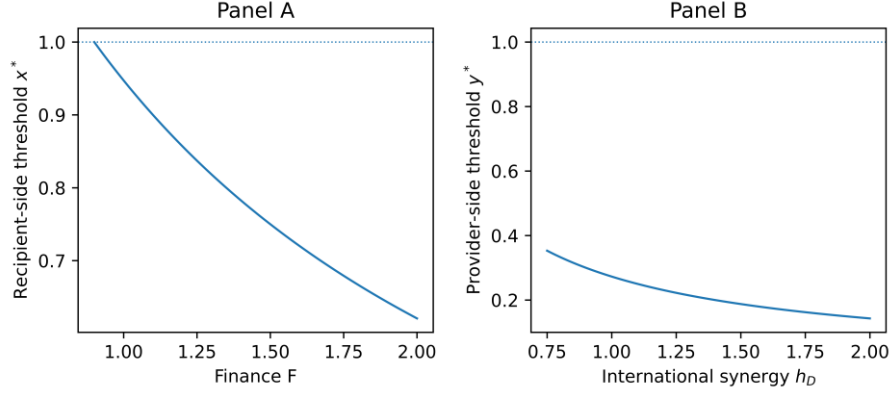


Fig. 3 Local nullcline-threshold comparative statics under the common baseline. Panel A shows x^* against F at $T = 0.50$; Panel B shows y^* against h_D at $F = 1.20$, $T = 0.50$. The panels use different horizontal variables and are not intended for unit-for-unit comparison. Boundary values are shown for illustration; the signed comparative statics apply strictly within the open bistable region

6.3 Numerical illustration and sensitivity checks

The analytical propositions do not depend on any specific numerical calibration. This section uses one common normalized baseline to verify internal consistency, illustrate the admissible sets, and show the active-lower-bound switch. The exercises are numerical illustrations, not estimates for particular countries.

6.3.1 Common baseline parameterization

All numerical figures use the following normalized baseline unless a caption states which parameter is varied. The reference finance level is 1.20 and the reference technology-cooperation intensity is 0.50 whenever finance or technology is not itself the variable on the horizontal axis.

Table 5. Common normalized baseline used in Figures 1–5

Parameter	Value	Parameter	Value
b_D	0.80	b_S	0.30
c_D	2.20	c_S	2.50
m_D	0.60	h_D	1.00
s_D	1.40	s_S	0.50
r_D	0.20	r_S	0.10
q	0.60	$p_D = p_S$	0.50
F^J	0.80	λ	0 unless varied
η	0.80	κ	0.20
F_0	1.20	T_0	0.50

At $T = 0$, the baseline gives $F_{\min} = 1.30$ and $F_{\max} = 2.10$, so the cash-only negotiated-equity-constrained set is non-empty. For the phase portrait, $F = 1.20$ and $T = 0.50$, yielding $\alpha_D = -0.30$, $\alpha_S = -1.80$, $\beta_D = 1.10$, and $\beta_S = 2.10$. Hence both low and high cooperation

are locally stable and the interior saddle lies inside the unit square. The baseline is therefore algebraically consistent with the analytical regime used in Figures 1–5.

6.3.2 Sensitivity to technology effectiveness and provider cost

Figure 4 varies (η, κ) while holding the remaining baseline parameters fixed. The three scenarios are $(0.80, 0.20)$, $(0.50, 0.50)$, and $(0.20, 0.60)$. Under the cash-only rule $\lambda = 0$, the slope is $\eta - \kappa$ while the recipient-adequacy threshold is the active lower bound and switches to $-\kappa$ once the negotiated distributive benchmark becomes the active lower constraint. This slope switch occurs only if the interval remains non-empty until the negotiated benchmark becomes binding. In the $(\eta, \kappa) = (0.20, 0.60)$ scenario, feasibility is lost before that constraint switch occurs, so the within-feasibility path contains no justice-benchmark slope regime.

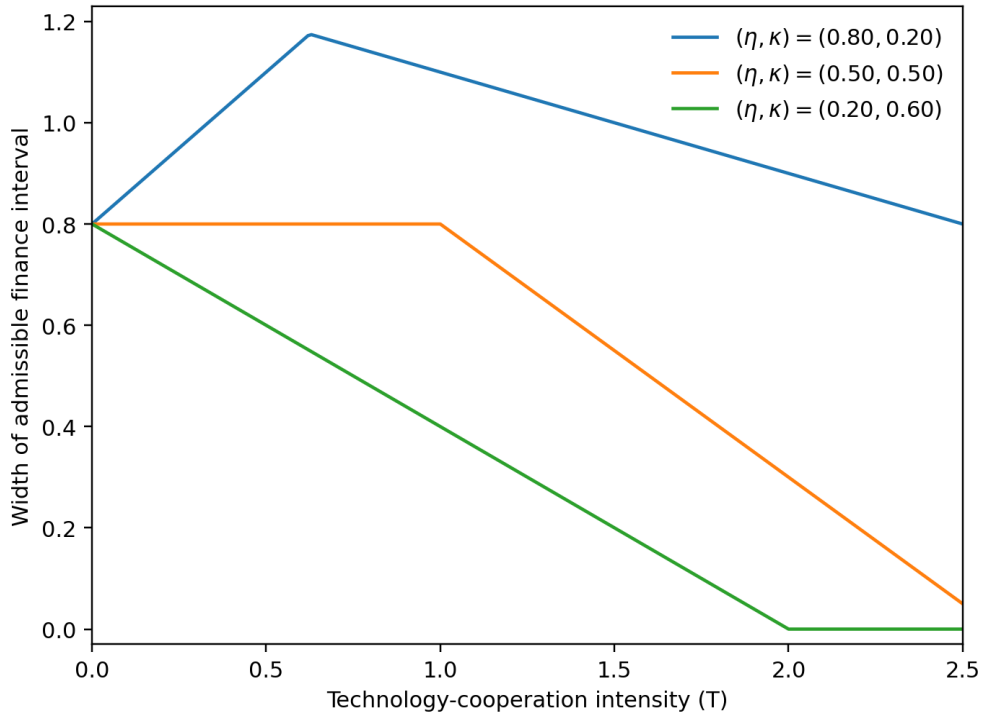


Fig. 4 Width of the cash-only negotiated-equity-constrained finance interval for $(\eta, \kappa) = (0.80, 0.20)$, $(0.50, 0.50)$, and $(0.20, 0.60)$, with $T \in [0, 2.5]$ and all other parameters at the common baseline

6.3.3 Existence and location of the active-lower-bound switch

For the cash-only rule ($\lambda = 0$), define $T^\dagger$ by $F_{\min}(T^\dagger) = F^J$. A positive economically relevant switch requires $\eta > 0$ and:

$$c_S - b_S - s_S - r_S - qp_S > F^J$$

so that:

$$T^\dagger = \frac{c_S - b_S - s_S - r_S - qp_S - F^J}{\eta} > 0$$

In addition, the admissible set must still exist at the switch:

$$F_{\max}(T^\dagger) > F^J$$

Under the common baseline, $T^\dagger = 0.625$ and $F_{\max}(T^\dagger) = 1.975 > 0.80$. Thus a genuine active-lower-bound switch occurs before provider feasibility is lost. For $T < T^\dagger$, recipient adequacy is the active lower constraint; for $T > T^\dagger$, the negotiated distributive benchmark is the active lower constraint. For technology intensities above the switching point, the negotiated distributive benchmark is the active lower constraint only while the admissible interval remains non-empty. The vertical marker in Fig. 2 displays this switch under the common baseline.

6.3.4 Technology recognition rules and the admissible finance interval

The generalized rule $F + \lambda\eta T \geq F^J$ makes the finance–technology interaction institutionally contingent rather than mechanically tied to a cash-only floor. Figure 5 compares $\lambda = 0, 0.5$, and 1 under the baseline $\eta = 0.80$ and $\kappa = 0.20$. A larger λ allows effective technology support to relax the negotiated distributive lower bound; when that technology-recognition constraint binds, the local slope becomes $\lambda\eta - \kappa$.

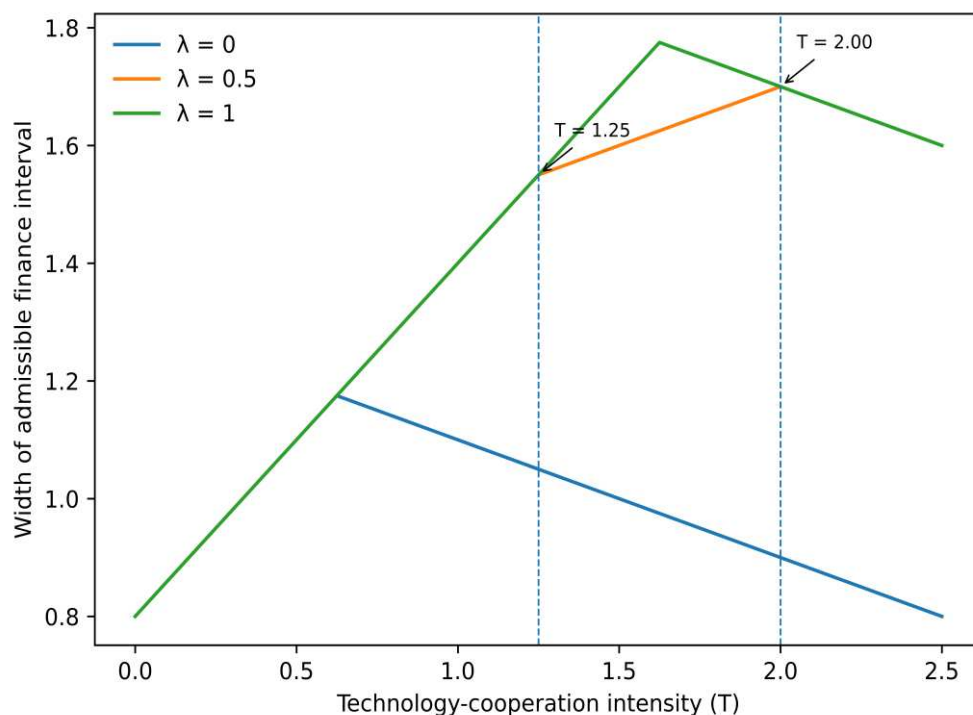


Fig. 5 Width of the negotiated-equity-constrained finance interval under alternative technology-recognition rules $\lambda=0, 0.5$, and 1, using the common baseline. For $\lambda=0.5$, the kinks at $T=1.25$ and $T=2.00$ mark switches from the recipient-adequacy lower bound to the technology-recognition lower bound and then to the zero lower bound

6.3.5 Reproducibility and interpretation

The figures are generated from the equations reported in Sections 3–6.2 and the common parameter table above. Their purpose is to verify sign changes, constraint switching, and local nullcline-threshold movement, not to claim empirical magnitudes. Any empirical application would require external identification or calibration of the payoff components and the binding constraint.

7 Institutional interpretation and discussion

7.1 Institutional interpretation in the Paris regime

Table 6 provides an institutional interpretation of the model channels. These correspondences test external consistency; they do not treat the reduced-form parameters as direct measures of treaty provisions.

Table 6. Institutional interpretation of model channels in current climate governance

Model channel	Institutional analogue	Model role	Scope / limitation
F	Decision 1/CMA.6 (NCQG)	Relaxes recipient participation but tightens provider participation	Cooperation-linked mitigation/transition finance only; excludes unconditional adaptation and loss-and-damage finance
T, η, κ	Paris Agreement Art. 10; Technology Mechanism; Decision 18/CMA.7	Technology effectiveness and provider net cost	Reduced-form channel; does not model IP bargaining or project-level heterogeneity
q	Paris Agreement Art. 13; BTRs and technical expert review	Improves observation and institutional feedback	Maps to observability and credibility, not to an Article 13 sanction
s_D, s_S, h_D	Climate clubs, sectoral alliances, standards partnerships	Creates positive cooperative synergies and can shift thresholds	Does not represent all climate-club architectures or trade-law effects
F^J	Paris Agreement Art. 2.2; negotiated CBDR-RC/equity principles	Defines a finance-equivalent negotiated distributive benchmark	Reduced-form negotiated criterion; not a unique or official monetary measure of climate justice
λ	No direct treaty analogue; negotiated eligibility, accounting, and valuation rule	Separates effective recipient value from recognized distributive credit	Model-specific institutional parameter, not an observed Paris Agreement accounting rule

Decision 1/CMA.6 provides a contemporary institutional analogue for the finance channel, but the NCQG is a collective goal rather than the bilateral conditional transfer represented in the model. Its numerical goal therefore does not equal the model's participation thresholds or distributive benchmark. Decision 18/CMA.7 supports treating technology as an independent cooperation channel. Article 13 maps to information and credibility infrastructure, not to a supranational sanction. The recognition parameter λ has no direct treaty analogue; it represents a negotiated eligibility, accounting, and valuation rule for recognizing effective technology support toward the distributive benchmark.

The climate-club interpretation is deliberately positive rather than punitive. Recent research in this journal emphasizes sectoral alliances, standards, metrics, and development partnerships alongside carbon-price cooperation (von Luepke et al., 2024). Proposition 3 should therefore be read conditionally: if a pioneer arrangement raises initial participation or creates positive cooperative synergies, the model shows how the corresponding state or local nullcline threshold can shift. Coalition membership itself is not endogenized.

7.2 Negotiated distribution, incentive compatibility, and institutional feasibility

The analysis distinguishes three questions. What distributive support requirement do the parties negotiate? Does the resulting package satisfy recipient and provider participation constraints? If it does, can cooperative strategies become self-reinforcing under payoff-monotonic learning? The model addresses these questions sequentially and makes no claim that satisfying the benchmark establishes the broader legitimacy of the agreement.

Ecological interdependence motivates the search for high cooperation, but it does not determine how support should be distributed. The negotiated benchmark constrains the support package, while recipient and provider participation bounds constrain the same package strategically. Institutional feasibility requires their intersection to be non-empty.

7.3 Conditional policy implications

Because the model is analytical rather than estimated, its policy implications are conditional on which constraint binds and on whether the system remains in the stated local regime.

First, if the recipient-adequacy threshold is empirically identified as the active lower bound, the model predicts that higher technology effectiveness η , lower provider net technology cost κ , or lower recipient transition cost increases the width of the admissible finance interval, conditional on remaining in the same local coordination regime. These changes can arise through absorptive-capacity investment, complementary infrastructure, joint R&D, interoperability, and risk sharing.

Second, if the negotiated distributive benchmark is the active lower constraint, technology support cannot be evaluated independently of the recognition rule. Under cash-only recognition ($\lambda=0$), additional technology tightens the provider margin without relaxing the benchmark. With positive recognition, the relevant condition is $\lambda\eta > \kappa$. Negotiators therefore affect feasibility through the eligibility, verification, and valuation of non-cash support as well as through its physical effectiveness.

Third, transparency can improve credible observation and widen the participation set without converting Article 13 into a punitive mechanism. The model predicts larger effects when observed weak cooperation carries meaningful reputational, investor, financing, or club-related opportunity costs.

Fourth, pioneer coalitions should be evaluated through both state and local-threshold channels. If an open sectoral arrangement raises initial participation or creates standards, common demand, technology access, finance, or other cooperative synergies, it can lower the relevant local participation-growth threshold. The model does not imply that stronger exclusion is always beneficial; exclusion can also reduce political acceptance or weaken provider and recipient participation conditions.

Fifth, provider-side domestic green benefits matter because higher m_D makes unilateral cooperation more attractive even before wider participation rises. Energy security, innovation, health co-benefits, and green industrial development can therefore reduce the coordination problem at its source.

7.4 Scope and limitations

The two strategic types suppress substantial within-group variation among advanced economies, emerging economies, least developed countries, small island states, fossil-fuel

exporters, and vulnerable high-income states. Strategies are binary although actual mitigation and support are continuous. Finance, technology, transparency, the negotiated benchmark, and the recognition rule are exogenous institutional parameters rather than outcomes of a prior bargaining stage. Climate damages, adaptation, loss and damage, and domestic political turnover remain outside the formal model.

The binary structure isolates participation margins, binding-constraint switches, and local threshold effects in closed form. A continuous-strategy model could instead study cooperation intensity, while a three-type or continuous-type model could represent variation in capability and vulnerability.

Future work can endogenize the distributive benchmark and recognition parameter through bargaining over responsibility, capability, need, and eligible support; add a pre-stage in which finance and technology are jointly chosen; and introduce multiple country types. A climate-state variable or mitigation-effectiveness constraint could connect strategy prevalence to emissions and damages. These extensions would distinguish cooperation persistence from ecological effectiveness and permit calibration with NDCs, biennial transparency reports, finance flows, technology projects, and green-trade exposure.

8 Conclusion

International climate cooperation combines a collective-action problem with disagreement over the distribution and recognition of support. Finance, technology, transparency, and pioneer coalitions alter participation through different margins, so their institutional roles should not be collapsed into a single enforcement parameter.

The model shows that low and high cooperation can coexist as locally stable outcomes when unilateral action is unattractive but mutual cooperation generates strategic complementarities. A negotiated-equity-compatible configuration exists only when the distributive benchmark, recipient adequacy, and provider participation are jointly feasible. The main result is a binding-constraint switch. Technology widens the admissible finance interval under $\eta > \kappa$ when recipient adequacy binds, but under $\lambda\eta > \kappa$ when the negotiated recognition constraint binds. The institutional treatment of effective technology support is therefore part of the cooperation mechanism, not a neutral accounting detail. Pioneer arrangements can also promote cooperation when they raise initial participation or create positive synergies that lower local growth thresholds.

The framework links a negotiated distributive requirement to two-sided participation incentives and dynamic strategy prevalence. It does not equate the benchmark with comprehensive justice or legitimacy. Its narrower conclusion is that durable differentiated cooperation requires a support package that both strategic groups will sustain and an institutional recognition rule that preserves a non-empty feasible set as cooperation evolves.

Statements and Declarations

Funding: The authors did not receive support from any organization for the submitted work.

Competing interests: The authors have no relevant financial or non-financial interests to disclose.

Data availability: No datasets were generated or analyzed during the current study. The model, assumptions, analytical derivations, and numerical illustrations are fully described in the manuscript.

Ethics approval: Not applicable. This study does not involve human participants, animals, or identifiable personal data.

Consent to participate: Not applicable. This study does not involve human participants.

Consent for publication: Not applicable. This study does not contain individually identifiable personal data or images.

Author contributions: E.Z.: Supervision, conceptualization, theoretical guidance, and writing—review and editing. L.T.: Conceptualization, methodology, formal analysis, mathematical modeling, investigation, visualization, and writing—original draft. J.Z.: Validation, literature verification, data and reference checking, and writing—review and editing.

References

- Apra, I. L., Donnini, C., & Sacco, A. (2026). From individual welfare to global equity: Reforming international environmental agreements. *Journal of Global Optimization*. Advance online publication. <https://doi.org/10.1007/s10898-026-01628-3>
- Barkai, K. R., & Winkler, H. (2025). Developing a framework for assessing equity in national contributions to the global goal on adaptation. *International Environmental Agreements: Politics, Law and Economics*, 25, 79–106. <https://doi.org/10.1007/s10784-024-09660-y>
- Barrett, S. (1994). Self-enforcing international environmental agreements. *Oxford Economic Papers*, 46(Supplement 1), 878–894. https://doi.org/10.1093/oeq/46.Supplement_1.878
- Bergsvik, R., Gupta, A., Weikmans, R., et al. (2024). Is transparency furthering clarity in multilateral climate governance? The case of climate finance. *International Environmental Agreements: Politics, Law and Economics*, 24, 565–588. <https://doi.org/10.1007/s10784-024-09652-y>
- Biancardi, M., & Villani, G. (2015). The effects of R&D investments in international environmental agreements with asymmetric countries. *Chaos, Solitons & Fractals*, 79, 30–39. <https://doi.org/10.1016/j.chaos.2015.07.026>
- Carraro, C., & Siniscalco, D. (1993). Strategies for the international protection of the environment. *Journal of Public Economics*, 52(3), 309–328. [https://doi.org/10.1016/0047-2727\(93\)90037-T](https://doi.org/10.1016/0047-2727(93)90037-T)
- Distefano, T., & D'Alessandro, S. (2021). A new two-nested-game approach: Linking micro- and macro-scales in international environmental agreements. *International Environmental Agreements: Politics, Law and Economics*, 21, 493–516. <https://doi.org/10.1007/s10784-021-09526-7>

- Donnini, C., & Sacco, A. (2024). Social equity in international environmental agreements. *Journal of Global Optimization*, 90, 261–291. <https://doi.org/10.1007/s10898-024-01368-2>
- Eichner, T., & Schopf, M. (2025). Self-enforcing environmental agreements with the optimal intensity of cooperation. *Environmental and Resource Economics*, 88, 249–278. <https://doi.org/10.1007/s10640-024-00927-1>
- Hagen, A., Altamirano-Cabrera, J.-C., & Weikard, H.-P. (2021). National political pressure groups and the stability of international environmental agreements. *International Environmental Agreements: Politics, Law and Economics*, 21, 405–425. <https://doi.org/10.1007/s10784-020-09520-5>
- Hannam, P. M., Vasconcelos, V. V., Levin, S. A., & Pacheco, J. M. (2017). Incomplete cooperation and co-benefits: Deepening climate cooperation with a proliferation of small agreements. *Climatic Change*, 144, 65–79. <https://doi.org/10.1007/s10584-015-1511-2>
- Herrera, O., Alcaraz, O., & Sureda, B. (2025). Analysis of fairness and ambition considerations in nationally determined contributions. *International Environmental Agreements: Politics, Law and Economics*, 25, 359–378. <https://doi.org/10.1007/s10784-025-09670-4>
- Hofbauer, J., & Sigmund, K. (1998). *Evolutionary Games and Population Dynamics*. Cambridge University Press.
- Kerr, S., Lippert, S., & Lou, E. Y. (2025). Transfers in climate action teams. *Economic Theory*, 80, 595–618. <https://doi.org/10.1007/s00199-024-01600-w>
- Klinsky, S., Roberts, T., Huq, S., et al. (2017). Why equity is fundamental in climate change policy research. *Global Environmental Change*, 44, 170–173. <https://doi.org/10.1016/j.gloenvcha.2016.08.002>
- Li, Q., & Fujita, T. (2021). Transfers in international environmental agreements under heterogeneity. *Applied Economics*, 53(33), 3899–3910. <https://doi.org/10.1080/00036846.2020.1861209>
- Luqman, M., Soytaş, U., Li, Y., & Ahmad, N. (2022). Rewards and penalties in an evolutionary game theoretic model of international environmental agreements. *Economic Research-Ekonomska Istraživanja*, 35(1), 602–621. <https://doi.org/10.1080/1331677X.2021.1931907>
- McGinty, M. (2010). International environmental agreements as evolutionary games. *Environmental and Resource Economics*, 45(2), 251–269. <https://doi.org/10.1007/s10640-009-9314-4>
- Nordhaus, W. (2015). Climate clubs: Overcoming free-riding in international climate policy. *American Economic Review*, 105(4), 1339–1370. <https://doi.org/10.1257/aer.15000001>
- Okada, A. (2023). A dynamic climate negotiation game achieving full cooperation. *Journal of Economic Behavior & Organization*, 214, 657–669. <https://doi.org/10.1016/j.jebo.2023.08.019>
- Pouw, N. R. M., Weikard, H.-P., & Howarth, R. B. (2022). Economic analysis of international environmental agreements: Lessons learnt 2000–2020. *International Environmental Agreements: Politics, Law and Economics*, 22, 279–294. <https://doi.org/10.1007/s10784-022-09576-5>
- Sandholm, W. H. (2010). *Population Games and Evolutionary Dynamics*. MIT Press.
- UNFCCC. (2024). Decision 1/CMA.6: New collective quantified goal on climate finance. FCCC/PA/CMA/2024/17/Add.1.
- UNFCCC. (2026). Report of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on its seventh session, held in Belém from 10 to 25 November 2025. Addendum. Part two: Action taken by the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement. Decision 18/CMA.7: Belém Technology Implementation Programme. FCCC/PA/CMA/2025/19/Add.2.

- United Nations. (2015). Paris Agreement. United Nations Framework Convention on Climate Change.
- Urpelainen, J. (2013). Can strategic technology development improve climate cooperation? A game-theoretic analysis. *Mitigation and Adaptation Strategies for Global Change*, 18, 785–800. <https://doi.org/10.1007/s11027-012-9388-0>
- Villani, G., & Biancardi, M. (2019). An evolutionary game approach in international environmental agreements with R&D investments. *Computational Economics*, 54(3), 1027–1042. <https://doi.org/10.1007/s10614-018-9860-3>
- von Luepke, H., Neuhoﬀ, K., & Marchewitz, C. (2024). Bridges over troubled waters: Climate clubs, alliances, and partnerships as safeguards for eﬀective international cooperation? *International Environmental Agreements: Politics, Law and Economics*, 24, 289–308. <https://doi.org/10.1007/s10784-024-09639-9>
- Weibull, J. W. (1995). *Evolutionary Game Theory*. MIT Press.

Appendix A. Proof sketches

Proof of Lemma 1. At $E_4=(1,1)$, the Jacobian is diagonal with eigenvalues $-(\alpha_D+\beta_D)$ and $-(\alpha_S+\beta_S)$. Hence E_4 is locally asymptotically stable if and only if $\alpha_D+\beta_D>0$ and $\alpha_S+\beta_S>0$.

Proof of Proposition 1. Under $\alpha_D < 0$, $\alpha_S < 0$, $\alpha_D + \beta_D > 0$, and $\alpha_S + \beta_S > 0$, the latter two inequalities imply $\beta_D > 0$ and $\beta_S > 0$. The interior equilibrium is $E_5 = (-\alpha_S/\beta_S, -\alpha_D/\beta_D)$. At E_5 , the diagonal terms of the Jacobian are zero and

$$\det(J) = -\beta_D\beta_Sx^*(1-x^*)y^*(1-y^*) < 0.$$

Hence the eigenvalues have opposite signs and E_5 is a saddle point. E_1 and E_4 are both locally stable, and the stable manifold of the saddle separates their basins of attraction.

Proof of Proposition 2. As defined in Section 5.4, let the generalized lower bound be the maximum of the non-negativity bound, the recipient-adequacy threshold, and the negotiated technology-recognition threshold. Define the admissible-interval width as zero whenever the provider ceiling does not exceed that lower bound, and otherwise as their difference. All derivatives below are local to regions in which the interval is non-empty and the stated lower constraint is the unique active lower bound.

When the recipient-participation lower bound is the unique active lower bound, its derivative with respect to technology intensity is $-\eta$, whereas the provider ceiling changes at rate $-\kappa$; hence the local derivative of the admissible-interval width is $\eta-\kappa$.

$$\frac{\partial W_\lambda^J}{\partial T} = \eta - \kappa.$$

When the negotiated technology-recognition lower bound is the unique active lower bound, its derivative with respect to technology intensity is $-\lambda\eta$, so

$$\frac{\partial W_\lambda^J}{\partial T} = \lambda\eta - \kappa.$$

When zero is the unique lower bound under the generalized credit rule, the local derivative is $-\kappa$. At equality of lower constraints, the width is continuous but generally non-differentiable.

Proof of Proposition 3. Within the coordination regime, $x^* = -\alpha_S/\beta_S$ and $y^* = -\alpha_D/\beta_D$. Since $\partial\beta_S/\partial F = 1$ and $\partial\beta_S/\partial T = \eta$,

$$\frac{\partial x^*}{\partial F} = \frac{\alpha_S}{\beta_S^2} < 0, \quad \frac{\partial x^*}{\partial T} = \frac{\eta \alpha_S}{\beta_S^2} < 0.$$

Since $\partial \beta_D / \partial F = -1$ and $\partial \beta_D / \partial T = -\kappa$,

$$\frac{\partial y^*}{\partial F} = -\frac{\alpha_D}{\beta_D^2} > 0, \quad \frac{\partial y^*}{\partial T} = -\frac{\kappa \alpha_D}{\beta_D^2} > 0.$$

Finally, $\partial \beta_D / \partial h_D = 1$ implies

$$\frac{\partial y^*}{\partial h_D} = \frac{\alpha_D}{\beta_D^2} < 0.$$

The same logic applies to the additional cooperative synergies: $\partial x^* / \partial s_S = \alpha_S / \beta_S^2 < 0$ and $\partial y^* / \partial s_D = \alpha_D / \beta_D^2 < 0$.

Thus increases in recipient-side and provider-side synergies lower the corresponding local nullcline thresholds.