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Marta Biancardi

marta.biancardi@uniba.it

University of Bari Aldo Moro

Giovanni Villani

University of Bari Aldo Moro

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Adaptation R&D, Knowledge Spillovers and Stable International Environmental Agreements

Marta Biancardi[1*†] and Giovanni Villani[1†]

[1*]Department of Economics and Finance, University of Bari, Largo Abbazia Santa Scolastica, Bari, Italy. Member of the National Research Group INdAM.

*Corresponding author(s). E-mail(s): marta.biancardi@uniba.it;
Contributing authors: giovanni.villani@uniba.it;
†These authors contributed equally to this work.

Abstract

The paper investigates how adaptation research and development (R&D) and knowledge spillovers affect the formation and stability of International Environmental Agreements (IEAs) in a dynamic framework. Adaptation is modeled as a knowledge-based public good generated through cooperative R&D, with knowledge fully shared within the coalition and only imperfectly spilling over to non-members. We formulate an infinite horizon differential game in which countries simultaneously choose emissions and adaptation investments, whereas pollution and adaptation knowledge evolve over time. The open-loop Nash equilibrium is characterized analytically, yielding explicit steady-state solutions for emissions, pollution, adaptation investments and knowledge stocks. The local dynamic properties of the equilibrium are then investigated through a stability analysis and its saddle-path properties are assessed numerically for the parameter configurations considered. Comparative statics reveal how coalition size, adaptation effectiveness, knowledge spillovers, environmental vulnerability, R&D costs and knowledge depreciation jointly influence the long-run equilibrium. The numerical analysis demonstrates that the model generates not only the conventional small stable coalitions commonly found in the IEA literature, but also intermediate self-enforcing coalitions and, under suitable parameter configurations, the grand coalition. Stable coalition size is shown to depend on the balance between the technological benefits of cooperative adaptation and

the incentives to free ride on shared knowledge. More effective adaptation technologies enlarge stable coalitions, whereas stronger knowledge spillovers, higher cooperative R&D costs and faster knowledge depreciation reduce participation incentives. The results highlight that adaptation policies may simultaneously strengthen international cooperation and generate moral hazard by weakening mitigation incentives. Overall, the paper shows that the interaction between adaptation knowledge and coalition formation substantially enlarges the range of self-enforcing international environmental agreements as well as the coexistence of medium and large coalitions compared with standard dynamic models.

Keywords: IEA, Adaptation R&D, Pollution Game, Open-loop Nash Equilibrium.

1 Introduction

Climate change is one of the major global challenges of our time. Since greenhouse gas emissions generate transboundary externalities, effective mitigation requires coordinated action among countries. International Environmental Agreements (IEAs) have therefore been regarded as the principal institutional framework for addressing global environmental problems. However, because participation is voluntary and no supranational authority can enforce compliance, countries face strong incentives to free ride on the abatement efforts of others. As a consequence, understanding the formation and stability of self-enforcing IEAs has become one of the central issues in environmental economics.

The economic literature has extensively investigated coalition formation in IEAs using non-cooperative game theory. The standard notion of coalition stability originates from the seminal contribution of [14], originally developed in the cartel literature and subsequently adapted to environmental agreements. According to this concept, a coalition is stable if no member has an incentive to leave the agreement (internal stability) and no outsider has an incentive to join it (external stability). Early contributions by [18], [13] and [2] showed that stable coalitions are typically small when countries interact strategically. Subsequent studies have confirmed this result under different strategic settings, while also showing that coalition size may increase under Stackelberg leadership rather than Cournot competition (see, among others, [15], [25] and [17]). Although coalition stability has been widely studied, much of the literature relies on static models that neglect the dynamic nature of pollution accumulation. Since greenhouse gases persist in the atmosphere for long periods, environmental damages depend on the evolution of the pollution stock rather than on contemporaneous emissions alone. Ignoring these dynamic interactions may therefore provide an incomplete representation of countries' strategic incentives. To overcome this limitation, several authors have employed differential games and optimal control techniques to investigate the formation and

stability of IEAs in dynamic environments. Important contributions include [5], [8], [11], [12], [24], [21], [26] and [27]. These studies explicitly account for pollution accumulation and show how dynamic incentives affect the sustainability of international cooperation.

Alongside mitigation policies, adaptation has progressively emerged as a second fundamental response to climate change. While mitigation aims to reduce greenhouse gas emissions, adaptation seeks to limit the damages generated by climate change by increasing countries' resilience. The interaction between mitigation and adaptation has recently attracted increasing attention in the IEA literature. [20], [4], [10], [22], [23], [3], [9], [7] and [19] study how adaptation influences countries' incentives to cooperate in international environmental agreements.

Most of these contributions distinguish between adaptation as a private good and adaptation as a public good. When adaptation consists of the implementation of specific technologies, its benefits mainly accrue to the investing country (see [4] and [20]). By contrast, when the focus shifts to the generation of adaptation knowledge through research and development (R&D), adaptation acquires important public-good characteristics because newly created knowledge can be shared across countries and may spill over beyond national borders (see [22] and [23]). Existing studies show that adaptation may increase coalition stability by reducing the costs associated with climate damages, but it may also generate moral hazard by weakening incentives to mitigate emissions (see [17], [3], [9], [10], [19], [22] and [23]). However, virtually all of this literature adopts static game-theoretic frameworks, thereby neglecting the dynamic interactions between pollution accumulation, knowledge accumulation, and adaptation investments. A recent contribution by [6] investigates the strategic impact of adaptation measures in a dynamic pollution game played in infinite horizon.

This paper contributes to the literature by bridging these two strands of research. Building on the dynamic pollution framework of [1], [6] and on the adaptation setting proposed by [23], we develop an infinite-horizon differential game in which countries simultaneously choose emissions and investments in adaptation R&D while pollution and adaptation knowledge accumulate over time. Adaptation knowledge is treated as a public good: members of an IEA fully share the knowledge generated through cooperative R&D, whereas non-signatories benefit only from partial spillovers. We analytically characterize the open-loop Nash equilibrium, derive explicit steady-state solutions for emissions, pollution, adaptation investments and knowledge stocks, and investigate the local dynamic properties of the equilibrium. The analysis further examines how coalition size, knowledge spillovers, adaptation effectiveness and R&D costs jointly affect environmental outcomes and the incentives to participate in self-enforcing IEAs.

The remainder of the paper is organized as follows. Section 2 presents the model. Section 3 derives the analytical solution of the differential game and characterizes the steady-state equilibrium together with its local dynamic

properties. Section 4 investigates the comparative statics of the equilibrium. Section 5 analyzes coalition stability through the membership game and proposes numerical and graphical simulations. Section 6 concludes.

2 The Model

Consider N countries ($h = 1 \cdots N$) that generate revenue with their production activities and, as a by-product, pollutant emissions.
Assuming that there is a monotonic increasing relationship between production and revenue and following [16] in which the relationship between the production of goods and emissions is proposed, revenue can be expressed directly as a function of emissions with a concave quadratic functional form:

$$R(e_h(t)) = \alpha e_h(t) - \frac{1}{2} e_h^2(t) \tag{1}$$

with $\alpha > 0$, parameter that represents the maximum emissions level and quantifies the economic gain derived from emissions. In fact, the marginal benefit of emission is $dR/de_h = \alpha - e_h$ so that the benefit $R(e_h)$ is monotonically increasing over $[0, \alpha]$ and $0 \leq e_h \leq \alpha$ in order to guarantee a non-negative marginal benefit. The marginal benefit of emissions diminishes with the amount of emissions, since $d^2R/de_h^2 < 0$; the concave functional form of revenue allows us to restrict the maximum level of benefits a country can obtain from emissions.
The emissions generated accumulate in the stock of common pollution $p(t)$ whose evolution is governed by the following differential equation:

$$\dot{p}(t) = E(t) - \delta p(t) \tag{2}$$

where

$$E(t) = \sum_{i=1}^{N} e_h(t) \tag{3}$$

are the total emissions, $0 \leq \delta \leq 1$ is the natural pollution decay rate and the initial level of pollution is $p(0) = p_0$.
The accumulated stock of pollution generates environmental damages that can be mitigated through adaptation investments. Adaptation refers to the development of knowledge, technologies and practices that reduce the welfare losses associated with pollution and increase resilience to climate change.
To improve its adaptation capacity, country h invests the effort k_h in research and development (R&D) activities that generate adaptation knowledge. This knowledge improves the country's ability to mitigate the damages associated with a polluted environment. The convex and increasing cost for the R&D effort is:

$$C(k_h(t)) = \frac{c_k}{2} k_h^2(t) \tag{4}$$

where $c_k > 0$ is the cost parameter.
The resulting stock of adaptation knowledge is denoted by K_h and evolves

according to:

$$\dot{K}_h(t) = I_h(k(t)) - \Phi K_h(t)$$

where $I_h(k)$ denotes the effective flow of newly created adaptation knowledge and Φ is the rate of depreciation of accumulated knowledge due to the use of obsolete techniques.

Following [22], we assume that the accumulated pollution stock reduces each country's welfare through environmental damages. The extent of these damages depends on both the pollution stock and the country's adaptation capacity and is captured by the following damage function:

$$D(p(t), K_h(t)) = \frac{1}{2}\beta p^2(t) - \theta F(K_h(t))p(t) \tag{5}$$

The first term is the damage caused by global emissions, with β denoting the country's natural vulnerability to climate change. The second term states the benefit from adaptation that reduces the damage and depends on the parameter $\theta > 0$ which denotes the effectiveness of adaptation on the available knowledge given by the function:

$$F(K_h(t)) = \frac{K_h(t)}{\bar{K}} \tag{6}$$

where $\bar{K} > 0$ measures the amount of knowledge required to achieve a given level of adaptation capacity. Consequently, $F(K_h)$ increases with K_h, while larger values of $\bar{K}$ imply that a greater stock of knowledge is needed to achieve the same adaptation capacity.

Finally, the net benefit of the country h is defined as follows:

$$\begin{aligned} W_h(t) =& R(e_h(t)) - C(k_h(t)) - D(p(t), K_h(t)) \\ =& \alpha e_h(t) - \frac{1}{2}e_h^2(t) - \frac{c_k}{2}k_h^2(t) - \frac{1}{2}\beta p^2(t) + \theta F(K_h(t))p(t) \end{aligned} \tag{7}$$

2.1 The coalition formation

We assume that a subset of m countries, indexed by $i = 1, \ldots, m$, forms an International Environmental Agreement (IEA). These countries, hereafter referred to as cooperators, coordinate their decisions by maximizing the joint payoff of the coalition rather than their individual payoffs. As part of the agreement, coalition members fully share the adaptation knowledge generated through their R&D activities. The remaining $N - m$ countries, indexed by $j = m+1, \ldots, N$, are defectors. They act non-cooperatively, maximizing their own individual payoffs, do not participate in the coalition's knowledge-sharing arrangement, and therefore benefit only from exogenous knowledge spillovers. The effective flow of adaptation knowledge available to each country, denoted by $I(k_h)$, depends on its membership status. We assume that adaptation knowledge is only partially appropriable. Consequently, knowledge generated

through R&D can be transferred across countries through two distinct channels: intentional knowledge sharing and unintentional knowledge spillovers. Intentional knowledge sharing takes place exclusively among coalition members. By joining the IEA, cooperators commit to fully sharing the adaptation knowledge they produce, so that each member has complete access to the knowledge created within the coalition. By contrast, countries outside the agreement do not participate in this cooperative exchange. Because knowledge is not perfectly appropriable, part of the knowledge generated by each country also diffuses unintentionally across national borders. These spillovers occur both from coalition members to defectors and among defectors themselves, although they are only partial. As a result, non-signatory countries can benefit from the knowledge created elsewhere without contributing to the cooperative R&D effort.

Let $e_i(t)$ and $k_i(t)$ the emission level and the investment in adaptation technologies of a representative signatory and $e_j(t)$ and $k_j(t)$ those of a non-signatory country, we have:

$$E(t) = \sum_{i=1}^{m} e_i(t) + \sum_{j=m+1}^{N} e_j(t) \tag{8}$$

the total emission level. The flow of knowledge is:

$$I_i(k(t)) = \sum_{i=1}^{m} k_i(t) + \gamma \sum_{j=m+1}^{N} k_j(t)$$

for a signatory country that fully shares its adaptation knowledge and:

$$I_j(k(t)) = k_j(t) + \gamma \left(\sum_{i=1}^{m} k_i(t) + \sum_{\substack{z=m+1 \\ z \neq j}}^{N} k_z(t) \right)$$

for a non-signatory country that benefits only from its own R&D effort and from spillovers generated by other countries.

We capture the unintentional spillover by introducing a parameter $0 \leq \gamma \leq 1$; when $\gamma = 0$, there is no spillover, instead $\gamma = 1$ means perfect spillover. A higher value of γ implies a lower appropriability of adaptation knowledge.

Finally, we assume that R&D costs are homogeneous within each group; the symmetry assumption implies $c_i = c_c$ for all signatories and $c_j = c_d$ for all non-signatories.

3 The Emission Differential game

We consider a two-stage game in which countries make decisions sequentially across two stages. In the first stage (the membership game) each country

decides whether or not to join an IEA and in the second stage (the emission differential game) each country determines its emissions and investment in R&D. Given the sequential nature of the game, we use a backward induction approach to determine the open-loop Nash equilibrium. Suppose that, as outcome of the first-stage game, a coalition of size m is formed and $N-m$ are defectors, in the second-stage, the countries solve a profit maximization problem formulated as follows:

$$W^c = \sum_{i=1}^{m} W_i^c = \sum_{i=1}^{m} \int_0^{+\infty} \left[\alpha e_i(t) - \frac{1}{2} e_i^2(t) - \frac{c_c}{2} k_i^2(t) - \frac{1}{2} \beta p^2(t) + \theta F(K_i(t)) p(t) \right] e^{-\rho t} \, dt \tag{9}$$

$$W_j^d = \int_0^{+\infty} \left[\alpha e_j(t) - \frac{1}{2} e_j^2(t) - \frac{c_d}{2} k_j^2(t) - \frac{1}{2} \beta p^2(t) + \theta F(K_j(t)) p(t) \right] e^{-\rho t} \, dt \tag{10}$$

with the dynamic constraints:

$$\dot{p}(t) = \sum_{i=1}^{m} e_i(t) + \sum_{j=m+1}^{N} e_j(t) - \delta p(t) \qquad p(0) = p_0 \tag{11}$$

$$\dot{K}_i(t) = I_i(k(t)) - \Phi K_i(t) \qquad K_i(0) = K_{i,0} \tag{12}$$

$$\dot{K}_j(t) = I_j(k(t)) - \Phi K_j(t) \qquad K_j(0) = K_{j,0} \tag{13}$$

where $p(t)$, $K_i(t)$, $K_j(t)$ are the state variables and $e_i(t)$, $k_i(t)$, $e_j(t)$, $k_j(t)$ are the control variables of a cooperator and of a defector and ρ is the discount rate.

3.1 The Open-loop Nash Equilibrium

In order to use the Maximum principle, let us define the current value of the Hamiltonian H in the standard way. Let:

$$\begin{aligned} H^c = & \sum_{i=1}^{m} \left[\alpha e_i - \frac{1}{2} e_i^2 - \frac{c_c}{2} k_i^2 - \frac{1}{2} \beta p^2 + \theta \frac{K_i}{\bar{K}} p \right] + \\ & + \lambda_c \left[\sum_{i=1}^{m} e_i + \sum_{j=m+1}^{N} e_j - \delta p \right] + \sum_{i=1}^{m} \mu_i^c \left[\sum_{r=1}^{m} k_r + \gamma \sum_{j=m+1}^{N} k_j - \Phi K_i \right] \end{aligned} \tag{14}$$

the Hamiltonian of the coalition and

$$H_j^d = \left[\alpha e_j - \frac{1}{2}e_j^2 - \frac{c_d}{2}k_j^2 - \frac{1}{2}\beta p^2 + \theta\frac{K_j}{\bar{K}}p\right] + \\ + \lambda_j\left[\sum_{i=1}^{m} e_i + \sum_{l=m+1}^{N} e_l - \delta p\right] + \mu_j^d\left[k_j + \gamma\left(\sum_{i=1}^{m} k_i + \sum_{\substack{z=m+1 \\ z\neq j}}^{N} k_z\right) - \Phi K_j\right] \tag{15}$$

the Hamiltonian of a defector and λ_c, λ_j, μ_i^c and μ_j^d are the adjoint variables. Assuming interior solutions, we have the first order necessary conditions:

$$\frac{\partial H^c}{\partial e_i} = 0 \iff e_i = \alpha + \lambda_c \qquad i = 1, .., m \tag{16}$$

$$\frac{\partial H_j^d}{\partial e_j} = 0 \iff e_j = \alpha + \lambda_j \qquad j = m+1, .., N \tag{17}$$

$$\frac{\partial H^c}{\partial k_r} = 0 \iff k_r = \frac{\sum_{i=1}^{m}\mu_i^c}{c_c} \qquad r = 1, .., m \tag{18}$$

$$\frac{\partial H_j^d}{\partial k_j} = 0 \iff k_j = \frac{\mu_d^j}{c_d} \qquad j = m+1, .., N \tag{19}$$

Note that the second derivatives of H with respect to e and k are $\frac{\partial^2 H}{\partial e_i^2} = -1 < 0$, $\frac{\partial^2 H}{\partial e_j^2} = -1 < 0$, $\frac{\partial^2 H}{\partial k_r^2} = -c_c < 0$, $\frac{\partial^2 H}{\partial k_j^2} = -c_d < 0$ so that the second order conditions for the maximum of functions are satisfied.

The adjoint equations are:

$$\dot{\lambda}_c = (\rho + \delta)\lambda_c + \beta m p - \frac{\theta}{\bar{K}}\sum_{i=1}^{m} K_i \tag{20}$$

$$\dot{\lambda}_j = (\rho + \delta)\lambda_j + \beta p - \frac{\theta}{\bar{K}}K_j \qquad j = 1 + m, .., N \tag{21}$$

$$\dot{\mu}_i^c = (\rho + \Phi)\mu_i^c - \frac{\theta}{\bar{K}}p \qquad i = 1, .., m \tag{22}$$

$$\dot{\mu}_j^d = (\rho + \Phi)\mu_j^d - \frac{\theta}{\bar{K}}p \qquad j = m+1, .., N \tag{23}$$

and the transversality conditions are:

$$\lim_{t\to\infty} e^{-\rho t}\lambda_c(t)p(t) = 0, \quad \lim_{t\to\infty} e^{-\rho t}\mu_i^c(t)K_i(t) = 0 \qquad i = 1, .., m \tag{24}$$

$$\lim_{t\to\infty} e^{-\rho t}\lambda_j(t)p(t) = 0, \lim_{t\to\infty} e^{-\rho t}\mu_j^d(t)K_j(t) = 0 \qquad j = m+1,..,N \tag{25}$$

The open-loop equilibrium is obtained by solving the system of necessary conditions for the 2N control variables.
Since all countries belonging to the same group are assumed to be identical, they face the same production technology, the same environmental damage function, the same discount rate and identical R&D costs within the group. Moreover, they are subject to the same pollution stock and differ only according to their membership status. Therefore, all signatories adopt identical emission and adaptation strategies, while all non-signatories also behave identically. This symmetry considerably simplifies the analysis, reducing the original 2N-player differential game to four optimality conditions describing the behavior of a representative signatory and a representative non-signatory. Under this symmetry assumption $e_i = e_c$, $e_j = e_d$, $k_r = k_c$, $k_j = k_d$, $\mu_i^c = \mu_c$, $\mu_j^d = \mu_d$, $K_i = K_c$, $K_j = K_d$, we can rewrite:

$$e_c = \alpha + \lambda_c \tag{26}$$

$$e_d = \alpha + \lambda_d \tag{27}$$

$$k_c = \frac{m\mu_c}{c_c} \tag{28}$$

$$k_d = \frac{\mu_d}{c_d} \tag{29}$$

Equations (26) - (29) give us:

$$\lambda_c = e_c - \alpha \Longrightarrow \dot{\lambda}_c = \dot{e}_c \tag{30}$$

$$\lambda_d = e_d - \alpha \Longrightarrow \dot{\lambda}_d = \dot{e}_d \tag{31}$$

$$c_c k_c = m\mu_c \Longrightarrow \dot{\mu}_c = \frac{c_c \dot{k}_c}{m} \tag{32}$$

$$c_d k_d = \mu_d \Longrightarrow \dot{\mu}_d = c_d \dot{k}_d \tag{33}$$

Let:

$$\Omega = \rho + \delta, \quad \Psi = \rho + \Phi, \quad \xi = \frac{\theta}{\bar{K}}$$

Substituting the first-order conditions (30) - (33) into the adjoint equations (20) - (23) yields a closed seven-dimensional dynamical system describing the joint evolution of emissions, adaptation effort, pollution stock and adaptation knowledge:

$$
\begin{aligned}
\dot{e}_c =& \Omega\, e_c + m\beta p - \xi m K_c - \alpha\Omega \\
\dot{e}_d =& \Omega\, e_d + \beta p - \xi K_d - \alpha\Omega \\
\dot{p} =& m e_c + (N-m) e_d - \delta p \\
\dot{k}_c =& -\frac{m\xi}{c_c} p + \Psi k_c \\
\dot{k}_d =& -\frac{\xi}{c_d} p + \Psi k_d \\
\dot{K}_c =& m k_c + \gamma(N-m) k_d - \Phi K_c \\
\dot{K}_d =& \gamma m k_c + [1 + \gamma(N-m-1)] k_d - \Phi K_d
\end{aligned}
\tag{34}
$$

with the given initial conditions $p(0) = p_0$, $K_c(0) = K_{c,0}$ and $K_d(0) = K_{d,0}$. Taking into account that at the steady state $\dot{e}_c = \dot{e}_d = \dot{p} = \dot{k}_c = \dot{k}_d = \dot{K}_c = \dot{K}_d = 0$ the system (34) can be used to find the stationary equilibrium.

Let:

$$
\frac{\beta\Phi\Psi}{\xi^2} > \frac{\frac{m^2\left(m^2+\gamma(N-m)\right)}{c_c} + \frac{(N-m)\left(1+\gamma(m^2+N-m-1)\right)}{c_d}}{m^2 + N - m + \frac{\delta\Omega}{\beta}} \tag{35}
$$

Proposition 1 *For any given coalition size m, under condition (35) and for parameter configurations ensuring an interior solution, the differential game (9) - (13) admits a unique stationary equilibrium given by:*

$$
p^* = \frac{N\alpha\Omega}{\delta\Omega + \beta\left[m^2 + (N-m)\right] - \frac{\xi^2}{\Phi\Psi}\left[\frac{m^2(m^2+\gamma(N-m))}{c_c} + \frac{(N-m)(\gamma m^2+1+\gamma(N-m-1))}{c_d}\right]} \tag{36}
$$

$$
e_c^* = \alpha + \frac{m}{\Omega}\left[\frac{\xi^2}{\Phi\Psi}\left(\frac{m^2}{c_c} + \frac{\gamma(N-m)}{c_d}\right) - \beta\right] p^* \tag{37}
$$

$$
e_d^* = \alpha + \frac{1}{\Omega}\left[\frac{\xi^2}{\Phi\Psi}\left(\frac{1}{c_d} + \gamma\left(\frac{m^2}{c_c} + \frac{N-m-1}{c_d}\right)\right) - \beta\right] p^* \tag{38}
$$

$$k_c^* = \frac{m\xi}{c_c \Psi}\, p^* \tag{39}$$

$$k_d^* = \frac{\xi}{c_d \Psi}\, p^* \tag{40}$$

$$K_c^* = \frac{\xi}{\Phi\Psi}\left(\frac{m^2}{c_c} + \frac{\gamma(N-m)}{c_d}\right) p^* \tag{41}$$

$$K_d^* = \frac{\xi}{\Phi\Psi}\left[\frac{1}{c_d} + \gamma\left(\frac{m^2}{c_c} + \frac{N-m-1}{c_d}\right)\right] p^* \tag{42}$$

To investigate the dynamic properties of the stationary equilibrium, we consider the Jacobian matrix of system (34), evaluated at the steady state. Ordering the variables as the vector $(e_c, e_d, p, k_c, k_d, K_c, K_d)$, the Jacobian is:

$$J = \begin{pmatrix} \Omega & 0 & m\beta & 0 & 0 & -m\xi & 0 \\ 0 & \Omega & \beta & 0 & 0 & 0 & -\xi \\ m & (N-m) & -\delta & 0 & 0 & 0 & 0 \\ 0 & 0 & -\dfrac{m\xi}{c_c} & \Psi & 0 & 0 & 0 \\ 0 & 0 & -\dfrac{\xi}{c_d} & 0 & \Psi & 0 & 0 \\ 0 & 0 & 0 & m & \gamma(N-m) & -\Phi & 0 \\ 0 & 0 & 0 & \gamma m & [1+\gamma(N-m-1)] & 0 & -\Phi \end{pmatrix} \tag{43}$$

Since system (34) is linear affine, the Jacobian is constant and does not depend on the particular steady-state values. Its characteristic polynomial can be written as:

$$P(\bar{\lambda}) = (\bar{\lambda} - \Omega)(\bar{\lambda} - \Psi)(\bar{\lambda} + \Phi) Q_4(\bar{\lambda}),$$

where

$$Q_4(\bar{\lambda})$$

is a fourth-degree polynomial whose coefficients depend on the structural parameters of the model. Therefore, three eigenvalues can be immediately identified:

$$\bar{\lambda}_1 = \Omega = \rho + \delta > 0, \qquad \bar{\lambda}_2 = \Psi = \rho + \Phi > 0, \qquad \bar{\lambda}_3 = -\Phi < 0.$$

It follows that the stationary equilibrium cannot be locally asymptotically stable, since the system always possesses at least two eigenvalues with positive real parts. At the same time, the negative eigenvalue $-\Phi$ implies the existence of at least one stable direction. The steady state exhibits saddle-path stability whenever exactly three eigenvalues of the Jacobian have negative real

parts, matching the number of predetermined state variables p, K_c and K_d. Since the signs of the four roots of Q_4 cannot be characterized analytically in general, this condition is verified numerically for the parameter configurations considered below.

In the context of an infinite-horizon differential game, this result can be interpreted in the following way. Pollution and adaptation knowledge are predetermined state variables, whereas emissions and R&D investments are choice variables that may adjust at the initial instant. Therefore, convergence to the steady state does not require all eigenvalues to have negative real parts. The relevant equilibrium trajectory is selected by the initial conditions of the state variables together with the transversality conditions and must lie on the stable manifold associated with the stationary equilibrium.

A complete analytical classification of the four roots of $Q_4(\bar{\lambda})$ is not available because their signs depend on the interaction among coalition size, knowledge spillovers, adaptation effectiveness and R&D costs. For this reason, the dimension of the stable manifold is evaluated numerically for the parameter configurations used in the simulations.

Proposition 1 characterizes the unique stationary equilibrium of the differential game. The steady-state values depend on the interaction between coalition size, knowledge spillovers, adaptation effectiveness and R&D costs. The expressions highlight that adaptation and pollution are jointly determined, generating feedback effects between mitigation incentives and knowledge accumulation. By analyzing the expressions obtained at steady state, the following observations can be made.

Remark 1 Consider the difference between the steady-state knowledge stocks of signatories and non-signatories:

$$K_c^* > K_d^* \iff m^2 c_d > c_c$$

- A sufficiently large coalition or relatively low R&D costs for signatories generate a knowledge advantage for coalition members.
- Conversely, non-signatories may enjoy a larger stock of adaptation knowledge than signatories. This situation may arise when the coalition is small or when cooperative R&D activities are relatively expensive.

In perfect spillovers ($\gamma = 1$), both groups have access to the same amount of knowledge and

$$K_c^* = K_d^*$$

- Stronger spillovers reduce the knowledge advantage associated with coalition membership and tend to equalize adaptation capacities across countries.

- Therefore, stronger knowledge spillovers erode the knowledge advantage associated with coalition membership, making adaptation capacities increasingly similar across countries and strengthening incentives to free ride on the efforts of signatories.

Remark 2 Consider the difference between the steady-state R&D investments of signatories and non-signatories:

$$k_c^* > k_d^* \iff mc_d > c_c$$

- Signatories invest more in adaptation R&D whenever the size of the coalition and the relative efficiency of cooperative research activities are sufficiently large.
- Conversely, when cooperative R&D is relatively costly, non-signatories may invest more than coalition members.

Considering the ratio between the steady-state R&D investments of signatories and non-signatories:

$$\frac{k_c^*}{k_d^*} = \frac{mc_d}{c_c}$$

- This ratio depends exclusively on the size of the coalition and on the relative R&D costs faced by signatories and non-signatories.
- This result highlights that differences in adaptation investments are driven solely by the organizational structure of cooperation and by the relative efficiency of research activities.
- A larger coalition increases incentives to invest in adaptation technologies, while higher R&D costs for signatories reduce their investment effort relative to that of outsiders.

Remark 3 Consider the difference between the steady-state emissions of signatories and non-signatories:

$$e_c^* \gtrless e_d^*$$

- No clear ranking emerges for equilibrium emissions, signatories may emit either more or less than non-signatories.
- Cooperation simultaneously strengthens environmental awareness and increases adaptation capacity.
- While the former tends to reduce emissions, the latter may weaken mitigation incentives by lowering the effective damages associated with pollution.

Cooperation does not necessarily lead to lower individual emissions. By reducing the damages associated with pollution, adaptation may generate a moral hazard effect that offsets, or even dominates, the incentives for emission abatement arising from cooperation.

4 Comparative Statics

Table 1 shows some results for a sensitive analysis of the steady state.

Table 1: Comparative statics of the equilibrium values.

	$\partial/\partial m$	$\partial/\partial\gamma$	$\partial/\partial\theta$
p^*	$\gtrless 0$	> 0	> 0
e_c^*	$\gtrless 0$	$\gtrless 0$	$\gtrless 0$
e_d^*	$\gtrless 0$	$\gtrless 0$	$\gtrless 0$
K_c^*	$\gtrless 0$	> 0	> 0
K_d^*	$\gtrless 0$	> 0	> 0
k_c^*	$\gtrless 0$	> 0	> 0
k_d^*	$\gtrless 0$	> 0	> 0

The following observations can be made.

Effect of coalition size. The effect of coalition size on steady-state equilibrium is generally ambiguous. An increase in the number of signatories affects environmental outcomes through two opposing channels. On the one hand, a larger coalition internalizes a greater share of the environmental externality, strengthening incentives for pollution control and environmental protection. On the other hand, coalition enlargement promotes the production and diffusion of adaptation knowledge, improving countries' ability to cope with environmental damages and potentially weakening incentives for mitigation.
As a consequence, the impact of coalition size on steady-state pollution stock, emissions, adaptation investments, and knowledge accumulation depends on the relative strength of these two effects.
For emissions, stronger environmental cooperation tends to reduce pollution through greater internalization of environmental damages, whereas improved adaptation capacity lowers the effective costs of pollution and may induce a moral hazard effect that increases emissions. Therefore, the signs of $\partial e_c^*/\partial m$ and $\partial e_d^*/\partial m$ are generally indeterminate. A larger coalition also stimulates the creation and dissemination of adaptation knowledge by expanding the pool of cooperating countries and increasing collective R&D activities. This direct effect tends to raise the stock of knowledge available to both signatories and non-signatories. However, coalition enlargement also affects the steady-state pollution stock, which in turn influences equilibrium R&D efforts and knowledge accumulation. Consequently, the signs of $\partial K_c^*/\partial m$ and $\partial K_d^*/\partial m$ are generally ambiguous. The effect on adaptation investments differs between coalition members and outsiders. For signatories, coalition enlargement generates a direct incentive to invest more in adaptation technologies because the benefits from collective knowledge creation are fully shared within the agreement. For non-signatories, instead, adaptation effort is affected only indirectly through changes in the steady-state pollution stock. Hence, the sign of

$\partial k_d^*/\partial m$ coincides with that of $\partial p^*/\partial m$, while the sign of $\partial k_c^*/\partial m$ reflects both the direct cooperative effect and the indirect environmental feedback effect.

Effect of spillovers. An increase in knowledge spillovers has important consequences for the steady-state equilibrium. Stronger spillovers facilitate the diffusion of adaptation knowledge across countries, allowing both signatories and non-signatories to benefit from research activities undertaken elsewhere. As a result, the steady-state stock of adaptation knowledge increases for both groups, reflecting the public-good nature of adaptation technologies. At the same time, higher spillovers reduce the profitability of R&D investments and strengthen free-riding incentives. Non-signatory countries can benefit from the knowledge generated by coalition members without fully contributing to its production, while signatories can also exploit knowledge created outside the coalition. Although knowledge diffusion improves adaptation capacity throughout the economy, it weakens the incentives to internalize the environmental externality. Consequently, stronger spillovers increase the steady-state pollution stock. The greater availability of adaptation knowledge reduces the effective damages associated with pollution and may induce countries to rely more on adaptation and less on mitigation. Therefore, while spillovers enhance adaptation capacity, they may also undermine the effectiveness of international environmental cooperation. The effect of spillovers on equilibrium emissions is generally ambiguous. On the one hand, improved adaptation capacity lowers the perceived costs of pollution and tends to increase emissions. On the other hand, spillovers affect the long-run pollution stock and the strategic interaction between coalition members and outsiders. As a result, both signatories' and non-signatories' emissions may either increase or decrease depending on which effect dominates. Finally, the effect of spillovers on equilibrium adaptation investments operates through their impact on the steady-state pollution stock. Since equilibrium R&D efforts are proportional to long-run pollution, stronger spillovers increase adaptation investments whenever they raise the steady-state pollution stock.

Effect of adaptation effectiveness. An increase in the effectiveness of adaptation has significant implications for the steady-state equilibrium. More effective adaptation reduces the damages associated with a given level of pollution, increasing countries' ability to cope with environmental degradation. As a consequence, the incentive to undertake mitigation efforts is weakened and countries rely more heavily on adaptation measures. This adaptation-induced moral hazard effect leads to an increase in the steady-state pollution stock. Therefore, while more effective adaptation enhances resilience to climate change, it may also reduce environmental quality by weakening incentives for emission abatement. The result highlights the existence of a trade-off between adaptation and mitigation policies. The effect of adaptation effectiveness on equilibrium emissions is generally ambiguous. On the one hand, lower perceived environmental damage tends to increase emissions by reducing

incentives for mitigation. On the other hand, changes in the pollution stock and adaptation capacity modify the strategic interaction among countries. Consequently, both signatories' and non-signatories' emissions may either increase or decrease depending on the relative strength of these effects.

Effect of R&D costs. With respect to the R&D costs, focusing on the direct own-cost effects on knowledge accumulation, we obtain:

$$\frac{\partial K_c^*}{\partial c_c} < 0, \quad \frac{\partial K_d^*}{\partial c_d} < 0$$

The effects of the costs on the knowledge show that an increase in R&D costs reduces the steady-state stock of adaptation knowledge available to both signatories and non-signatories. Higher research costs discourage investments in adaptation technologies, lowering knowledge accumulation directly. Lower knowledge accumulation weakens adaptation capacity and decreases the long-run pollution stock, further reducing the amount of effective knowledge available in equilibrium. Therefore, both groups are adversely affected by higher R&D costs, regardless of whether the cost increase occurs within or outside the coalition.

5 The Membership Game

We assume that in the first stage, countries play a simultaneous open membership game negotiating an IEA, that is played in the initial moment. The strategies for each country are to sign or not to sign the agreement and any player is free to join the agreement. Each country chooses simultaneously one of the two possible strategies and the agreement is formed by all players who choose to sign. We assume that the signature of the agreement is binding on signatories so cooperators stay in the agreement during the second stage of the game, against non-signatories.

One of the earliest definitions of a self-enforcing agreement used in the literature of IEAs is the stability concept proposed by [14]. Initially, it was initially applied in a context of static emission game, here, the static definition is extended for a dynamic game.

Definition 1 A coalition of size m is said to be stable if it is internally stable, i.e.

$$W_i^c(m) \geq W_j^d(m-1)$$

and externally stable, i.e.

$$W_i^c(m+1) \leq W_j^d(m)$$

The first condition says that any signatory country is at least as well off staying in the the IEA as quitting, assuming that all other countries do not change their membership decision. The second inequality, similarly affirms that any non-signatory is at least as well off remaining a non-signatory than joining the

IEA, assuming that all others countries do not change their membership decision. A self-enforcing IEA can therefore be interpreted as a Nash equilibrium of the simultaneous open-membership game. It has been shown that under fairly general conditions stable coalitions exist, however, this does not satisfactorily address the problem of protecting international commons because, as has been demonstrated in the environmental literature (see, for example, [13] and [18]), stable coalitions are generally formed by $m < N - m$ players, where m is a small number, regardless of $N - m$. The main obstacle to coalition enlargement is that the expanded agreement may fail to be self-enforcing.

The welfare functions do not admit tractable analytical expressions after substituting the equilibrium paths. Therefore, the internal and external stability conditions are evaluated numerically. For each coalition size, the equilibrium trajectory is selected from the stable manifold associated with the stationary equilibrium. The discounted payoffs of a representative signatory and a representative non-signatory are then computed by numerical integration of the corresponding equilibrium trajectories, and the stable coalition is identified by evaluating the internal and external stability conditions.

The fixed parameter values are reported in Table 2, while Table 3 lists the parameters varied in the numerical analysis.

Table 2: Fixed Parameter values

Parameters	Description	Value
N	Number of countries	10
α	Revenue parameter	1
c_d	defector's parameter	1
ρ	Discount rate	0.03229
δ	Natural decay	0.31713
$\bar{K}$	Knowledge parameter	1
p_0	Initial level of pollution	5
$K_{c,0}$	Initial level of cooperator's knowledge	2
$K_{d,0}$	Initial level of defector's knowledge	2

Table 3: Variable Parameter values

Parameters	Description
θ	Adaptive capacity
γ	Unintentional spillover
β	environmental vulnerability
c_c	cooperator's cost parameter
Φ	depreciation of accumulated knowledge

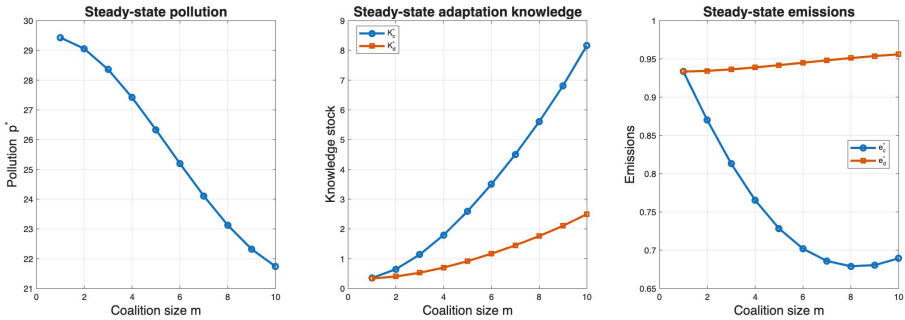


Fig. 1: Steady-state outcomes as coalition size varies.

The figure reports the steady-state pollution stock, the adaptation knowledge stocks of signatories and non-signatories, and their individual emissions for different coalition sizes. All remaining parameters are fixed at the benchmark calibration. As the coalition expands, pollution decreases and adaptation knowledge increases, particularly for signatories. At the same time, signatories reduce their emissions, whereas non-signatories slightly increase theirs, reflecting strategic free-riding on the environmental and technological efforts of coalition members.

Figure 1 illustrates how coalition enlargement affects the long-run equilibrium under the benchmark calibration. The steady-state pollution stock decreases monotonically with coalition size, indicating that the stronger internalization of environmental damages dominates the adaptation-induced moral hazard effect in this parameter configuration. At the same time, both signatories and non-signatories accumulate more adaptation knowledge, although the increase is substantially larger for coalition members because they fully share the knowledge generated through cooperative R&D.

The emission responses of the two groups differ markedly. Signatories progressively reduce their steady-state emissions as the coalition expands, reflecting the increasing share of environmental damages internalized by the agreement. By contrast, non-signatories slightly increase their emissions. This response reveals a strategic free-riding effect: outsiders benefit from lower aggregate pollution and from knowledge spillovers generated by coalition members, while avoiding the full costs of environmental cooperation. Consequently, the environmental improvement associated with coalition enlargement is driven primarily by the mitigation efforts of signatories.

Regarding the stability of coalitions, the total number of countries considered is $N = 10$ so the number of cooperators can vary between $2 \leq m \leq 10$.

In Tables 4 - 8 we show how parameters such as: adaptive capacity θ, unintentional spillover γ, environmental vulnerability β, cooperator's cost c_c, depreciation of accumulated knowledge Φ are varied to assess their effect on the stable coalition size.

Table 4: Stable coalitions as adaptive capacity θ varies and $\gamma = 0.30$, $c_c = 0.80$, $\beta = 0.0008$, $\Phi = 0.5$.

Adaptive capacity θ	Stable coalitions	Stability regime
$0 \leq \theta \leq 3.14 \times 10^{-4}$	$m = 2$	Small coalition
$3.14 \times 10^{-4} < \theta \leq 6.70 \times 10^{-4}$	$m = 3$	Small coalition
$6.70 \times 10^{-4} < \theta \leq 8.16 \times 10^{-4}$	$m = 4$	Intermediate coalition
$8.16 \times 10^{-4} < \theta \leq 8.37 \times 10^{-4}$	$m = 5$	Intermediate coalition
$8.37 \times 10^{-4} < \theta \leq 8.79 \times 10^{-4}$	$m = 5, 10$	Intermediate and Grand coalition
$8.79 \times 10^{-4} < \theta \leq 8.97 \times 10^{-4}$	$m = 6, 10$	Intermediate and Grand coalition
$\theta > 8.97 \times 10^{-4}$	$m = 10$	Grand coalition

Table 4 illustrates the effect of adaptation effectiveness on the stability of international environmental agreements. When adaptation technologies are only weakly effective, the unique self-enforcing agreement consists of two countries. In this case, the benefits associated with cooperative R&D are too limited to compensate for the incentives to free ride on the adaptation efforts of coalition members. As adaptation effectiveness increases, larger coalitions and the grand coalition become stable. More productive adaptation knowledge raises the value of cooperation because signatories benefit from a larger stock of shared knowledge that substantially reduces environmental damages. Consequently, the incentives to remain inside the agreement strengthen and coalition size increases from two to three, four and eventually five members. When adaptation effectiveness becomes sufficiently high, the grand coalition emerges as the unique stable agreement. At this point, the gains from fully shared adaptation knowledge dominate the incentives to free ride, making universal participation self-enforcing.

Table 5: Stable coalitions as unintentional spillover γ varies and $\beta = 0.0008$, $c_c = 0.80$, $\theta = 0.0008$, $\Phi = 0.5$.

Unintentional spillover γ	Stable coalitions	Stability regime
$0.00 \leq \gamma \leq 0.16$	$m = 10$	Grand coalition
$0.16 < \gamma \leq 0.19$	$m = 6, 10$	Intermediate and Grand coalition
$0.19 < \gamma \leq 0.20$	$m = 5, 10$	Intermediate and Grand coalition
$0.20 < \gamma \leq 0.27$	$m = 5$	Intermediate coalition
$0.27 < \gamma \leq 0.45$	$m = 4$	Intermediate coalition
$0.45 < \gamma \leq 0.83$	$m = 3$	Small coalition
$0.83 < \gamma \leq 1.00$	$m = 2$	Small coalition

Table 5 shows how the diffusion of adaptation knowledge affects coalition formation. When knowledge spillovers are negligible, outsiders cannot benefit from the adaptation investments undertaken by coalition members. Consequently, participation becomes relatively attractive and the grand coalition is the unique stable outcome. As spillovers increase, outsiders receive a progressively larger share of adaptation knowledge without contributing to its production. This strengthens free-riding incentives and gradually reduces the size of the stable coalition. The equilibrium coalition decreases from the grand

coalition to five and four members, and eventually converges to the traditional small-coalition outcome. Therefore, although knowledge spillovers improve the diffusion of adaptation technologies, they simultaneously undermine the incentives to participate in cooperative environmental agreements.

Table 6: Stable coalitions as environmental vulnerability β varies and $\gamma = 0.30$, $c_c = 0.80$, $\theta = 0.0008$, $\Phi = 0.5$.

Environmental vulnerability β	Stable coalitions	Stability regime
$0 \leq \beta \leq 7.01 \times 10^{-4}$	$m = 10$	Grand coalition
$7.01 \times 10^{-4} < \beta \leq 7.21 \times 10^{-4}$	$m = 6, 10$	Intermediate and Grand coalition
$7.21 \times 10^{-4} < \beta \leq 7.59 \times 10^{-4}$	$m = 5, 10$	Intermediate and Grand coalition
$7.59 \times 10^{-4} < \beta \leq 7.83 \times 10^{-4}$	$m = 5$	Intermediate coalition
$7.83 \times 10^{-4} < \beta < 9.44 \times 10^{-4}$	$m = 4$	Intermediate coalition
$9.44 \times 10^{-4} < \beta < 1.52 \times 10^{-3}$	$m = 3$	Small coalition
$1.52 \times 10^{-3} < \beta \leq 5.19 \times 10^{-3}$	$m = 2$	Small coalition

Table 6 reports the impact of environmental vulnerability on coalition stability. Under the adopted calibration, higher environmental vulnerability reduces the stable coalition size. For relatively low levels of vulnerability, the grand coalition is stable because environmental damages are limited and countries primarily value the benefits associated with cooperative adaptation. As vulnerability increases, countries internalize a larger share of environmental damages when they join the agreement. This increases the relative attractiveness of remaining outside the coalition and free riding on the mitigation and adaptation efforts of signatories. Consequently, the stable coalition shrinks progressively from six to five, four and three members. For sufficiently high vulnerability, only a two-country coalition remains self-enforcing. The simulations therefore suggest that greater environmental damages do not necessarily promote broader cooperation once adaptation incentives and free-riding opportunities are simultaneously taken into account.

Table 7: Stable coalitions as cooperator's cost c_c varies and $\gamma = 0.30$, $\beta = 0.0008$, $\theta = 0.0008$, $\Phi = 0.5$.

cooperator's cost c_c	Stable coalitions	Stability regime
$0.1300 \leq c_c \leq 0.6373$	$m = 10$	Grand coalition
$0.6373 < c_c \leq 0.6640$	$m = 6, 10$	Intermediate and Grand coalition
$0.6640 < c_c \leq 0.7316$	$m = 5, 10$	Intermediate and Grand coalition
$0.7316 < c_c \leq 0.7695$	$m = 5$	Intermediate coalition
$0.7695 < c_c \leq 1.1049$	$m = 4$	Intermediate coalition
$1.1049 < c_c \leq 3.0090$	$m = 3$	Small coalition
$c_c > 3.0090$	$m = 2$	Small coalition

Table 7 investigates how the cost of cooperative research influences coalition formation. When cooperative R&D is inexpensive, countries have strong incentives to participate in joint adaptation activities and the grand coalition is stable. As cooperative research becomes more costly, the technological

advantage associated with membership gradually disappears. The reduction in adaptation investments weakens the benefits of cooperation, making defections increasingly attractive. Consequently, the stable coalition becomes progressively smaller, moving from six to five and four members before converging to the conventional small-coalition equilibrium. These results highlight the crucial role of cooperative R&D efficiency in sustaining broad environmental agreements. Table 8 illustrates the effect of knowledge depreciation on coali-

Table 8: Stable coalitions as depreciation of accumulated knowledge Φ varies and $\gamma = 0.30$, $\beta = 0.0008$, $\theta = 0.0008$, $c_c = 0.80$.

Depreciation of accumulated knowledge Φ	Stable coalitions	Stability regime
$0.1883 \leq \Phi \leq 0.4431$	$m = 10$	Grand coalition
$0.4431 < \Phi \leq 0.4524$	$m = 6, 10$	Intermediate and Grand coalition
$0.4524 < \Phi \leq 0.4769$	$m = 5, 10$	Intermediate and Grand coalition
$0.4769 < \Phi \leq 0.4894$	$m = 5$	Intermediate coalition
$0.4894 < \Phi \leq 0.6012$	$m = 4$	Intermediate coalition
$0.6012 < \Phi \leq 1.3094$	$m = 3$	Small coalition
$\Phi > 1.3094$	$m = 2$	Small coalition

tion stability. When adaptation knowledge depreciates slowly, the benefits generated by cooperative research persist over time and the grand coalition is stable. As the depreciation rate increases, the stock of accumulated knowledge declines more rapidly, reducing the long-run value of cooperative R&D. The technological advantage of coalition membership therefore becomes weaker and the stable coalition progressively decreases from five to four and then three members. For sufficiently high depreciation rates, only the two-country coalition remains stable. Hence, the durability of adaptation knowledge is an important determinant of the sustainability of international environmental cooperation.

Overall, the numerical simulations reveal a consistent pattern across all parameter variations. Factors that increase the private benefits associated with cooperative adaptation, such as higher adaptation effectiveness, lower cooperative R&D costs or slower knowledge depreciation, tend to support broader international environmental agreements. Conversely, parameters that strengthen free-riding incentives, including larger knowledge spillovers, higher cooperative R&D costs and greater environmental vulnerability under the adopted calibration, systematically reduce the size of the stable coalition. The results therefore suggest that coalition stability is determined by the balance between two opposing forces. On the one hand, cooperative adaptation increases the benefits from membership through knowledge sharing. On the other hand, the possibility of exploiting the efforts of signatories without contributing to their costs generates incentives to remain outside the agreement. The stable coalition size emerges from the interaction between these two mechanisms.

The following figure shows that it is possible to obtain different stable coalition between two parameters. Panels (a)–(d) report the size of the self-enforcing coalition obtained from the numerical solution of the membership game. Each colored region identifies the coalition satisfying both internal and external stability. Panel (a) varies the cooperative and non-cooperative R&D costs; panel (b) varies adaptation effectiveness and environmental vulnerability; panel (c) varies knowledge spillovers and knowledge depreciation; panel (d) varies knowledge spillovers and environmental vulnerability. All remaining parameters are fixed at the benchmark calibration reported in Table 2.

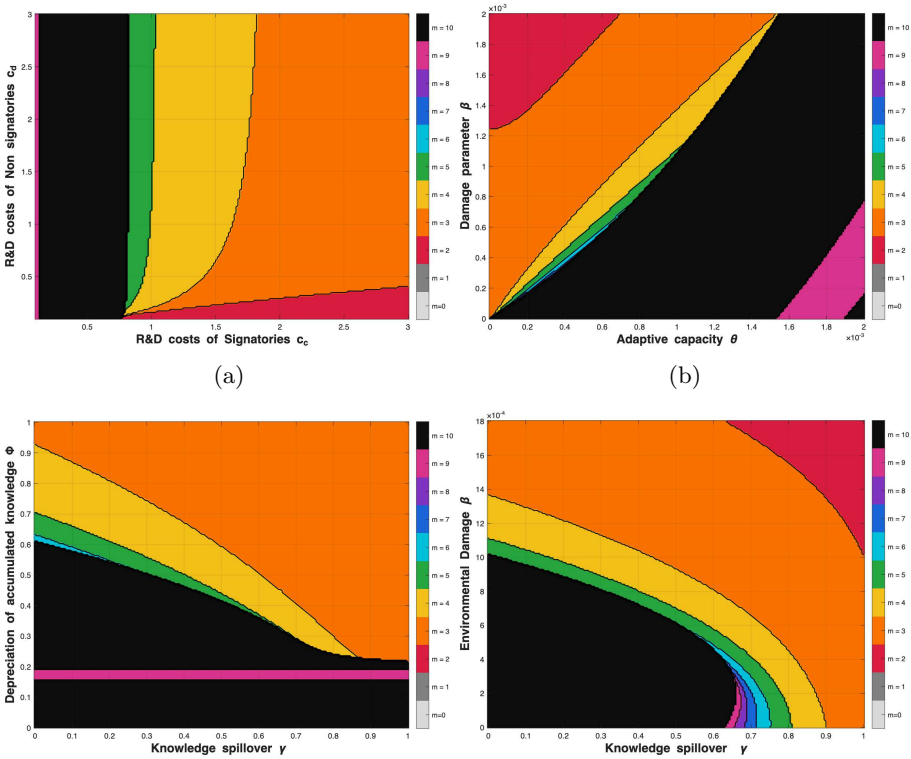


Fig. 2: Stable coalition regions under alternative parameter combinations

Figure 2 complements the threshold values reported in Tables 4–8 by illustrating the stability regions in the parameter space. Rather than focusing on isolated parameter values, the figures identify the combinations of structural parameters that support different self-enforcing coalition sizes. The graphical representation highlights how the interaction between two parameters modifies the incentives to participate in an International Environmental Agreement and reveals the boundaries separating alternative stability regimes.

Panel (a) illustrates how the relative costs of cooperative and non-cooperative R&D determine coalition stability. When cooperative research is relatively inexpensive compared to independent research, countries have strong incentives to participate in joint adaptation activities, making the grand coalition the unique stable outcome. As the cost advantage of cooperative R&D decreases, the technological benefits associated with membership become progressively weaker and the stable coalition shrinks from six to five and four members before converging to the conventional two-country coalition. The figure shows that coalition stability depends primarily on the relative efficiency of research activities rather than on their absolute cost levels.
Panel (b) shows the interaction between adaptation effectiveness and environmental vulnerability. The figure reveals a clear trade-off between adaptation and environmental damages. Higher adaptation effectiveness increases the value of shared knowledge and enlarges the stable coalition, whereas greater environmental vulnerability strengthens the incentives to free ride under the adopted calibration, thereby reducing coalition size. The resulting stability regions indicate that broad international cooperation is sustainable only when adaptation technologies are sufficiently productive relative to the environmental damages generated by pollution. Among the four panels, this figure most clearly illustrates the balance between the benefits of cooperative adaptation and the incentives for free riding.
Panel (c) illustrates the joint effect of knowledge spillovers and knowledge depreciation. The largest coalitions are observed when adaptation knowledge is both durable and largely appropriable. As either spillovers or depreciation increase, the long-run value of cooperative R&D declines because knowledge becomes either more rapidly obsolete or more easily accessible to outsiders. Consequently, the technological advantage associated with coalition membership diminishes and the stable coalition becomes progressively smaller. The figure therefore highlights that the sustainability of broad international cooperation requires both persistent and sufficiently exclusive adaptation knowledge.
Panel (d) combines knowledge spillovers and environmental vulnerability. The figure shows that these two mechanisms reinforce one another in reducing coalition size. Higher spillovers strengthen free-riding incentives by allowing outsiders to benefit from adaptation knowledge without participating in its production, while greater environmental vulnerability increases the relative cost borne by coalition members under the adopted calibration. As a result, the region supporting the grand coalition gradually disappears and is replaced by intermediate and eventually small stable coalitions. This panel emphasizes that broad cooperation is sustainable only when knowledge spillovers remain sufficiently limited and environmental vulnerability is moderate.

Taken together, the four panels reveal a remarkably consistent pattern. Parameters that increase the private benefits associated with cooperative adaptation, such as higher adaptation effectiveness, lower cooperative R&D

costs and slower knowledge depreciation, enlarge the stable coalition. Conversely, parameters that increase free-riding incentives, including stronger knowledge spillovers, higher cooperative research costs and, under the adopted calibration, greater environmental vulnerability, reduce coalition size. The stability regions therefore illustrate that self-enforcing international environmental agreements are determined by the balance between the technological benefits of knowledge sharing and the strategic incentives to free ride.

6 Conclusions

The paper investigates the formation and stability of International Environmental Agreements within an infinite-horizon differential game where countries simultaneously choose emissions and investments in adaptation research and development. Unlike most of the existing literature, adaptation is modeled as a knowledge-based public good generated through cooperative R&D activities. Coalition members fully share the knowledge they produce, whereas non-signatories benefit only from partial knowledge spillovers. This framework makes it possible to analyze the joint dynamics of pollution accumulation, knowledge accumulation and strategic coalition formation.

The analytical analysis provides explicit expressions for the stationary equilibrium and shows that adaptation, emissions and pollution are jointly determined through a system of dynamic feedback effects. On the one hand, adaptation knowledge reduces the damages generated by pollution and increases countries' resilience to climate change. On the other hand, by lowering the effective cost of environmental degradation, adaptation may weaken incentives for mitigation and generate an adaptation-induced moral hazard effect. Consequently, adaptation and mitigation emerge as complementary but potentially conflicting policy instruments.

The numerical analysis extends these theoretical findings by investigating how the main structural parameters influence the formation of self-enforcing environmental agreements. The simulations reveal that coalition stability is determined by the interaction between adaptation effectiveness, knowledge spillovers, environmental vulnerability, cooperative R&D costs and knowledge depreciation. Parameters that increase the private benefits associated with cooperative adaptation, such as more effective adaptation technologies, lower cooperative R&D costs and slower knowledge depreciation, generally support broader international cooperation. Conversely, stronger knowledge spillovers, higher cooperative R&D costs and, under the adopted calibration, greater environmental vulnerability strengthen free-riding incentives and reduce the size of the stable coalition.

A particularly relevant result emerging from the numerical analysis is that the model is capable of generating not only the conventional small stable coalitions commonly found in the IEA literature, but also intermediate self-enforcing coalitions and, under suitable parameter configurations, the grand coalition.

Furthermore, there are cases in which the stability of intermediate coalitions coexists with the stability of the grand coalition. Stable coalition sizes evolve gradually as the underlying economic environment changes, rather than switching directly from very small agreements to full cooperation. This finding suggests that the interaction between adaptation knowledge and coalition incentives substantially enlarges the range of feasible self-enforcing agreements compared with standard models of environmental cooperation.

From an economic perspective, the simulations highlight that coalition stability is governed by the balance between two opposing mechanisms. Cooperative adaptation increases the benefits of membership through knowledge creation and sharing, whereas the public-good nature of knowledge simultaneously creates incentives for countries to free ride on the research efforts of coalition members. The equilibrium coalition size therefore reflects the relative strength of these two forces rather than the effect of any single parameter considered in isolation.

The policy implications are equally important. Policies aimed at promoting adaptation should not focus exclusively on increasing technological effectiveness. Broad and stable international cooperation also requires institutional arrangements capable of preserving sufficient appropriability of adaptation knowledge and maintaining incentives for countries to participate in cooperative R&D. Otherwise, excessive knowledge diffusion may undermine participation even though it improves adaptation capacity. The results therefore suggest that adaptation policies should be complemented by appropriate mechanisms that preserve cooperation incentives while limiting the strategic advantages associated with free riding.

Overall, the analysis suggests that adaptation policies may contribute not only to reducing climate damages but also to enlarging the set of self-enforcing international environmental agreements, provided that the institutional framework preserves sufficient incentives for countries to cooperate.

Although the analysis provides a comprehensive characterization of coalition stability under symmetric countries, several extensions deserve further investigation. Future research could consider heterogeneous countries differing in environmental vulnerability, adaptation technologies or R&D productivity, endogenous transfers among coalition members, alternative information structures such as feedback strategies, and stochastic pollution dynamics. These extensions would allow the interaction between adaptation, technological cooperation and international environmental agreements to be analyzed in even richer institutional environments.

Declarations

Conflict of interest. The authors declare that they have no conflict of interest.

References

[1] V. Baris and G. Zaccour, The strategic impact of adaptation in a transboundary pollution dynamic game, Environmental Modeling & Assessment, 23 (2018), 653-669.

[2] S. Barrett, Self-enforcing international environmental agreements, Oxford Economic Papers, 46 (1994), 878-894.

[3] B. Bayramoglu, M. Finus and J. Jacques, Climate agreements in a mitigation adaptation game, Journal of Public Economics, 165 (2018), 101-113.

[4] H. Benchekroun, W. Marrouch and A. Chaudhuri, Adaptation technology and free-riding incentives in international environmental agreements, Economics of International Environmental Agreements, edited by M. Özgür Kayalica, Selim Ça ğatay, and Hakan Mihçi, Chapter 11 (2017).

[5] M.E. Biancardi, International environmental agreement: A dynamical model of emissions reduction, Nonlinear Dynamics in Economics, Finance and Social Sciences, Eds. Springer, (2010), 73-93.

[6] M. Biancardi and L. Maddalena, Adaptation measures and stable international environmental agreements in a pollution dynamic game, Decisions in Economics and Finance, 48(1) (2025), 223-240.

[7] M. Biancardi and G. Villani, Stability of International Environmental Agreements: Effects of Mitigation and Adaptation Policies. Computational Economics, 67 (2026), 1511–1531.

[8] M. Biancardi and G. Villani, International environmental agreements with asymmetric countries, Computational Economics, 36 (2010), 69-92.

[9] M. Borrero and S.J. Rubio, An adaptation-mitigation game: does adaptation promote participation in international environmental agreements?, International Environmental Agreements, 22 (2022), 439-479.

[10] M. Breton and L. Sbragia, The impact of adaptation on the stability of international environmental agreements, Environmental and Resource Economics, 74 (2019), 697-725.

[11] M. Breton, L. Sbragia and G. Zaccour, A dynamic model for international environmental agreements, Environmental and Resource Economics, 45 (2010), 25-48.

[12] E. Calvio and S. J. Rubio, Dynamic Models of International Environmental Agreements: A Differential Game Approach, The International Review

of Environmental and Resource Economics, 6 (2012).

[13] C. Carraro and D. Siniscalco, Strategies for the international protection of the environment, Journal of Public Economics, 52 (1993), 309-328.

[14] C. d'Aspremont, A. Jacquemin, J. Gabszewicz and J. A. Weymark, On the stability of collusive price leadership, Canadian Journal of Economics, 16 (1983), 17-25.

[15] E. Diamantoudi and E. Sartzetakis, Stable international environmental agreements: An analytical approach, Journal of Public Economic Theory, 8 (2006), 247-263.

[16] E.J. Dockner and N.V. Long, International pollution control: cooperative versus noncooperative strategies, Journal of Environmental Economics and Management, 25(1) (1993), 13-29.

[17] M. Finus, F. Furini and A. V. Rohrer, The efficacy of international environmental agreements when adaptation matters: Nash-Cournot vs Stackelberg leadership, Journal of Environmental Economics and Management, 109(C) (2021).

[18] M. Hoel, International environmental conventions: The case of uniform reductions of emissions, Environmental and Resource Economics, 2 (1992), 141-159.

[19] L. Hongxiu and A. Rus. Horatiu, Climate change adaptation and international mitigation agreements with heterogeneous countries, Journal of the Association of Environmental and Resource Economists, 6 (2019), 503-530.

[20] I. Lazkano, W. Marrouch and B. Nkuiya, Adaptation to climate change: How does heterogeneity in adaptation costs affect climate coalitions? Environment and Development Economics, 21 (2016), 812-838.

[21] S. Marsiglio and N. Masoudi, Social norms and international environmental agreements: A natural solution to environmental problems?, Energy Economics, 153 (2026).

[22] N. Masoudi and G. Zaccour, Adapting to climate change: is cooperation good for the environment?, Economics Letters, 153 (2017), 1-5.

[23] N. Masoudi and G. Zaccour, Adaptation and international environmental agreements, Environmental and Resource Economics, 71 (2018), 1-21.

[24] S. J. Rubio and B. Casino, Self-enforcing international environmental agreements with a stock pollutant, Spanish Economic Review, 7 (2005), 89-109.

[25] S. J. Rubio and A. Ulph, Self-enforcing international environmental agreements revisited, Oxford Economic Papers, 58 (2006), 233-263.

[26] S. J. Rubio and A. Ulph, An infinite-horizon model of dynamic membership of international environmental agreements, Journal of Environmental Economics and Management, 54 (2007), 296-310.

[27] A. de Zeeuw, Dynamic effects on the stability of international environmental agreements, Journal of Environmental Economics and Management, 55 (2008), 163-174.