When establishing a common environmental project, countries that benefit less may need to contribute more

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Abstract

Cooperation among multiple countries is essential for the effective establishment of common environmental projects, such as the eradication of invasive species and diseases and the development of green technologies. However, each country has the incentive to contribute less to the project and free-ride on the contribution of other countries. Therefore, a major question is how the contributions could be allocated among the countries, such that no country would have the incentive to reduce its contribution. Here we use a dynamic game model and consider a Markovian Nash equilibrium as a possible allocation of contributions. We prove that under general conditions, in each Nash equilibrium, among the countries that contribute, those that have smaller benefits from the project contribute more. Moreover, there are multiple Nash equilibria, where those Nash equilibria in which fewer countries contribute are more efficient and result in a faster establishment of the project. These results imply that an inherent tradeoff exists among fairness, efficiency, and stability when establishing a common project.

Keywords: Bioeconomics, dynamic games, international agreements, invasive species, Nash equilibrium.

Introduction

Achieving a common environmental goal necessitates the prolonged cooperation of multiple countries. Climate change mitigation, for instance, necessitates a global endeavor to reduce the emissions of greenhouse gases (GHGs) [1-3], and the management of invasive species and diseases necessitates cooperation among multiple countries because the proliferation of these threats in some countries may lead to their outbreak in other countries [4-11]. Nevertheless, the benefits from these actions are often public goods, and their benefits are shared among all countries. Specifically, investments to reduce GHG emissions and control harmful species are under-provided because each country cares mainly for its own damages from the threat and cares less about the damages to other countries [12, 13]. In turn, there is no simple mechanism to enforce an international agreement. A major focus in the literature, including this paper, is on self-enforcing agreements, in which the contribution/investment of each country to the public project is voluntary [13, 14]: Each country that keeps its contribution does so for its own benefit, and a country that has fewer incentives can opt-out without getting punished. A major question is, therefore, how the contributions could be allocated among the countries over time, and how our society can achieve better outcomes from a global perspective.

One possible solution is that each country will control the harmful species or the GHG emissions that originate from its own area, but this solution might fail for several reasons. First, the research and development of new technologies, such as a new green technology that enables production with less emissions [15-17], or a new vaccine [18], is inherently global and is used by all the countries; therefore, it is unclear how the contributions should be allocated in these cases. Second, countries that are poorer or that suffer fewer damages from the environmental threat may decide not to contribute their part, which, in turn, imposes damages on the other countries. For example, a given country may decide not to treat an invasive species or a disease in its area, which may lead to its invasions in other countries and impose damages globally (e.g., the weakest-link problem) [5, 7]. In such a case, other countries may need to combine efforts to treat the harmful species from that country [5, 19].

In this paper, we focus on the establishment of a given environmental project, which could be the development of new green technology (Fig. 1), the development of a vaccine, or the eradication of a particular invasive species or disease from a focal area where its outbreak has occurred. We focus on voluntary contributions, where countries that do not contribute are not being punished. We assume that all the countries might benefit from the project, but some countries benefit more than others. For example, a green technology may benefit more those countries that suffer higher costs due to climate damages. In turn, climate damages vary among countries [20-22] and may depend on a country's (i) current temperatures (a cold country may have a lower cost due to climate change), (ii) size (a larger country with a larger economy may have a higher total cost), (iii) wealth (a wealthier country may assign higher a dollar value to the same product and thereby have a higher cost), and (iv) type of production (a country that relies more heavily on agriculture may have a higher cost). Therefore, a major question is how the benefits of a given country from the project affect its contribution in a self-enforcing agreement [23].

Although the dynamic contribution of public goods has been extensively studied [13-18, 24-26], we show here that a fundamental property of these games has been overlooked. Specifically, we show that positive feedback exists between the relative contribution of a given country and the incentives of that country to contribute further. Specifically, if a given country already contributes more than other countries, then this country would be more incentivized to make an even greater contribution. As an example, consider a project that could become complete within 10 years if a total investment of $\$100M$ ($\$10M$ per year) is made, or within 5 years if a total investment of $\$120M$ ($\$24M$ per year) is made. (A greater investment is often needed to complete the project faster due to diminishing returns, e.g., it is commonly more cost-effective to eradicate a harmful species slowly [11, 27]). Consider the strategy in which country 1 contributes $\$10M$ per year and country 2 does not contribute, and consequently, the project becomes complete after 10 years. Then, if country 1 considers deviating to complete the project within 5 years instead of 10 years, it only needs to add $\$20M$ in total to accelerate the progress. On the other hand, if country 2 would like to deviate to accelerate the progress, it needs to increase its annual contribution from $\$0$ to $\$14M$ over a period of 5 years, namely, to add $\$70M$ in total. Therefore, the country that already contributes is more incentivized to deviate and increase its contribution because it needs to add less money to accelerate the progress.

In turn, we show in this paper that this positive feedback leads to the existence of multiple Nash equilibria, each of which is characterized by a given set of countries that contribute at a given stage of the project while the other countries do not contribute at that stage. In particular, each of these Nash equilibria is characterized by an unfair allocation of contributions even among those countries that do contribute: at each stage of the project, the countries that have higher benefits from the remaining project contribute less than the other countries that contribute. Furthermore, we show that the allocations of contributions that are less fair (in which fewer countries contribute) are also the more efficient ones. Therefore, no single equilibrium allocation is clearly better than the others. Nevertheless, we also show that the identity of the countries that contribute may change over time (or at different stages of the project), and we show that this suggests a possible solution by letting different countries contribute during distinct time periods.

Model

We consider N countries, where each country, *i*, decides how much to contribute over time, $a_i(t)$, to the establishment of a common environmental project, where the stage of the project is given by $G(t)$ (Fig. 1). For example, $G(t)$ may characterize (i) the stage of development or implementation of a given green technology or (ii) the stage of a certain eradication project (a higher G implies a lower density of the harmful species). In turn, $G(t)$ increases over time at a rate that increases with the aggregate contribution of all countries:

$$\frac{dG}{dt} = h(G, A) \,, \tag{1}$$

where

$$A(t) = \sum_i a_i \tag{2}$$

is the instantaneous aggregate contribution of all countries at time t, and h is the speed at which the project is being developed, which is positive and increasing with $A(t)$. The project may also be subject to diminishing returns ($\partial^2 h/\partial A^2 < 0$) if a large contribution at a given time is less effective than spreading the same contribution over a longer period.

The objective of each country, i, is to maximize its net present value, V_i, that incorporates the benefit of the country from the public good and the costs due to its own contributions over time:

$$\mathcal{V}_i = \int_0^\infty [B_i(G) - a_i] e^{-\delta t} dt, \tag{3}$$

where B_i is the annual benefit to country i from the project, and $\delta > 0$ is the discount rate. Note that the benefits, B_i, may vary among countries. B_i increases with G and approaches its maximum when the project is established ($G = G_{\max}$). Depending on the specific project, B_i may increase gradually with G, or it may have a sharp increase if the project becomes beneficial only after a certain "breakthrough" has occurred [23].

In turn, we consider a dynamic game in which each country chooses a strategy that dictates how much it contributes as a function of the state of the system (Markovian strategy) [13, 26]. Consequently, we seek to find the Markovian Nash equilibria, in which, if each country adopts its equilibrium strategy, $a_i^*(G)$, then no country can benefit by unilaterally deviating (for all i, a_i^* maximizes V_i if $a_j = a_j^*$ for all $j \neq i$). (Note that, if the integral in Eq. (3) diverges for all strategies, such as may occur if $\delta = 0$, then the Nash equilibrium is defined as a set of strategies such that for any, $a_i' \neq a_i^*$, there exists a sufficiently large T such that $V_i(a_i^*) > V_i(a_i')$, where the integration is to T instead ∞ [26].)

Methods

Consider a Nash equilibrium, $\boldsymbol{a}^*$, and denote $G^*_{\max}$ as the asymptotic value of G given that this Nash equilibrium is adopted by all countries. (Note that $G^*_{\max}$ could equal $G_{\max}$, but more generally, countries might establish only a part of the project, and therefore, $G^*_{\max} \leq G_{\max}$; also note that G may approach $G^*_{\max}$ within a finite time, or it may approach it asymptotically.) Consider an initial state $G_0 < G^*_{\max}$. Since we consider Markovian strategies that depend only on the state G, this implies that G increases monotonically from G_0 to $G^*_{\max}$. In turn, the idea behind our analysis is that each country aims to minimize its net cost during the time until G approaches $G^*_{\max}$, where this net cost includes both the cost of the country's investment and the cost due to the lost benefits. Specifically the annual cost due to the fact that the project is incomplete and is still in a state $G < G^*_{\max}$ is given by

$$C_i(G) = B_i(G^*_{\max}) - B_i(G) \,. \tag{4}$$

In turn, increasing the contribution a_i results in a greater annual cost to country i, but it also accelerates the rate at which G increases.

The theoretical analysis of the model is given in Appendices A-D. In Appendix A we show that, in each state of the system, the Nash equilibrium of the game is also a Nash equilibrium of a particular static game in which each player aims to minimize her/his cost until the system approaches the next state. In turn, in Appendices B and C, we further analyze the system and we prove the main results, Theorems 1 and 2. In Appendix D, we derive the conditions for the existence of certain Nash equilibria. In turn, the theoretical analysis is accompanied by a numerical analysis that demonstrate the main results (Figs. 2-5). The algorithm includes background induction [11, 26, 28, 29] and an algorithm that we developed to find the Nash equilibria in a given state, as described in Appendix E.

Results

Among the countries that contribute, the less incentivized countries contribute more

Our first result shows that, if δ is sufficiently small, then in any given state of the system among the countries that contribute in that state (country *i* "contributes" if $a_i > 0$), the countries that contribute more are those that gain lower benefits from establishing the project (Figs. 2,3). Furthermore, if a given set of countries contribute until the project is complete, then among those countries, the countries that have the lower benefits contribute more (regardless of the value of δ). The result is stated formally in the following theorem (see proof in Appendix B).

Theorem 1. Consider the *N*-players dynamic game in which each player adopts a Markovian strategy, $a_i(G) \geq 0$ $(i = 1,2, \dots, N)$, where the utility of player *i*, $\mathcal{V}_i$ is given by Eq. 3 and the dynamics of G are given by Eqs. 1, 2. Assume that h is monotone increasing with A and that, for all *i*, B_i increases with G and is bounded from above. Consider Markovian Nash equilibrium and denote $a_i^*(G)$ as the strategy of player i at state G and $G_{\max}^*$ as the asymptotic value of G following that equilibrium. The following two statements must hold:

A. There exists $\delta_c > 0$ such that, if $\delta < \delta_c$, the following holds for all $G_0 < G_{\max}^*$ and all *i* and *j*: If $C_i(G_0) > C_j(G_0)$ and $a_j(G_0) > 0$, then $a_i^*(G_0) < a_j^*(G_0)$, where C_i is given by Eq. 4.
B. Consider two players, i and j, that contribute simultaneously ($a_i^*(G) > 0$ and $a_j^*(G) > 0$) for all $G < G_{\max}^*$. It follows that, for all $G_0 < G_{\max}^*$, $a_i^*(G_0) < a_j^*(G_0)$ if and only if $C_i(G_0) > C_j(G_0)$.

End of Theorem 1

Multiple Nash equilibria coexist

Our results also show that multiple Nash equilibria may coexist, where the entire contribution in each equilibrium is made by a certain set of countries. To begin with, consider the cases in which the same countries contribute simultaneously at all times (or until *G* approaches its maximum). Even then, there exists multiple Nash equilibria, each of which comprises a different set of countries that contribute (Figs. 2, 3A, 3B). For example, our numerical results show that a Nash equilibrium in which the four most incentivized countries contribute (Fig. 2A) may coexist (same parameter values) with a Nash equilibrium in which only two or three of these countries contribute (Fig. 2B,C) and, similarly, a Nash equilibrium in which the nine most incentivized countries contribute (Fig. 2D) may coexist with Nash equilibria where fewer countries contribute (Fig. 2E,F). Also, there are multiple Nash equilibria in which only two or three countries contribute, but the identity of the countries that contribute vary from one equilibrium to another.

Nevertheless, the existence of a Nash equilibrium in which a particular set of countries contribute simultaneously depends on the discount rate as well as on the relative costs of these countries (Figs. 3,4, Appendix D). In particular, if δ is sufficiently small, it worth for a single country to contribute alone. Bus if δ is greater than a certain threshold, there exists a Nash equilibrium in which no country contributes, and the other Nash equilibria dictate the contribution of several countries (Fig. 5). Similarly, the larger the value of δ, the larger the number of countries that have to contribute in a Nash equilibrium (and solutions in which fewer countries contribute may become unstable) (Fig. 5, and see also [11, 19]). Also, a country cannot contribute if its benefits from the project are much lower than those of the most incentivized country (Fig. 4B, Appendix D). For example, in the special case where h is linear and $\delta = 0$, we show in Appendix D that, for any state, G_0, a given set of $n \geq 2$ countries could be those that contribute in Nash equilibrium if and only if $C_1 \leq (n-1)\langle C \rangle / n$, where C_1 is the largest cost and $\langle C \rangle$ is the average cost of the countries that contribute at $G = G_0$. If this condition is satisfied, then, in the Nash equilibrium, where $G = G_0$, $\overline{\boldsymbol{a}} = ((1/(n-1))\Lambda - I)\overline{\boldsymbol{C}}$, where $\overline{\boldsymbol{a}}$ is the vector of the strategies of the countries that contribute, $\overline{\boldsymbol{C}}$ is the vector of their costs, Λ is the all-ones $n \times n$ matrix, and I is the $n \times n$ identity matrix.

Furthermore, in addition to all the Nash equilibria in which the same countries contribute at all times, there exist iterative Nash equilibria in which different countries contribute at different times (Fig. 3). Specifically, these equilibria differ in the timing at which the different countries start, pause and resume their contributions (Fig. 3A). For example, there exists a Nash equilibrium in which countries 2 and 4 contribute until the technology is partially developed, e.g., $G = 0.7G_{\max}$, and countries 1, 3 and 5 contribute thereafter, until the technology is fully developed, $G = G_{\max}$ (Fig. 3C). This iterative solution coexists with the solutions in which the same countries contribute simultaneously at all times (Fig. 3A, B).

The solution is more efficient if fewer countries contribute

Another result is that the more efficient solutions, in which the aggregate contribution is larger, are those where fewer countries contribute. Specifically, if a country opts-out and no longer contributes, then the new Nash equilibrium is more efficient. This result is shown in the following theorem (see proof in Appendix C) and is demonstrated in Fig. 3.

Theorem 2. Consider the *N*-players dynamic game in which each player adopts a Markovian strategy, $a_i(G) \geq 0$ ($i = 1,2, \ldots, N$), where the utility of player *i*, $\mathcal{V}_i$ is given by Eq. 3 and the dynamics of G are given by Eqs. 1, 2. Assume that h is monotone increasing with A ($\partial h / \partial A > 0$) and is subject to diminishing returns ($\partial^2 h / \partial A^2 < 0$).

Consider two coexisting Markovian Nash equilibria, 1 and 2, and assume that G approaches the same value in both. Assume that in a given state, $G = G_0$, the set of players contributing in equilibrium 2 is a subset of the set of players contributing in equilibrium 1 (a player "contributes" if $a_i(G_0) > 0$). It follows that, if δ is sufficiently small ($\delta < \delta_c$ for a certain $\delta_c > 0$), then the aggregate contribution, $A(G_0)$, in equilibrium 2 is greater than the aggregate contribution in equilibrium 1.

End of Theorem 2

Note that the efficiencies of all the Nash equilibria depend critically on the diminishing returns [11]. In particular, without diminishing returns (h is a linear function), the optimal solution dictates that G approaches $G_{\max}$ as fast as possible (bang-bang strategy), whereas in Nash equilibrium, approaching $G_{\max}$ may take a long time, because each country "waits" for the other countries to contribute (Fig. 3). But if the diminishing returns are higher, the optimal solution dictates lower values of A and becomes more similar to the Nash equilibria. Consequently, the efficiency of the Nash equilibria increases with the diminishing returns (see also [11]).

Discussion

We showed that, in any Nash equilibrium, among the countries that contribute to the public project, those countries that gain the lower benefits are those that contribute more. The mechanism underlying this counterintuitive phenomenon is that, if a given country makes a large portion of the contribution to the project, this incentivizes that country to increase its contribution even further. Namely, there is a positive feedback between the contribution of a given country and its incentives to contribute (Figs. 4,6). To understand the mechanism underlying this feedback, consider a project that, sooner or later, is going to be completed by the countries. Then, the incentives of the countries to contribute further is due to their benefit from accelerating the project's completion. If the contribution of a given country increases, the annual cost to that country increases, and therefore, its incentives to accelerate the progress increases. In other words, if the country already intends to contribute a significant amount, then increasing its present contribution would accelerate the increase in G without significantly increasing the country's net contribution. In contrast, if a country relies mostly on the contributions of other countries, increasing its present contribution would translate in full into a cost for that country. In turn, the disproportional contributions emerge because, in equilibrium, the marginal benefits of all the countries that contribute have to be the same, and due to the positive feedback mechanism, this could only happen if the countries that receive smaller benefits contribute more (Figs. 4A, 6A).

Nevertheless, in stark contrast to our results, various previous studies have concluded that the contribution to public goods would increase with the country's benefits from these goods [24-26]. One reason is that some previous studies considered models or scenarios that do not incorporate feedback between the state of the system and the strategy. For example, several authors asked how much each country invests in the short-term reduction of GHG emissions, where the benefits a country receives from its present investment do not necessarily depend on its portion of the future investments [13, 14, 30-32].

Another reason is that most previous studies assumed that there are diminishing returns on the contribution of every single country [24-26]; namely, a country's marginal cost of investment increases with the total investment of that country. (Note that in our model the diminishing returns are only on the aggregate contribution, A.) These diminishing returns per country's investment may occur, for example, if a country can afford to invest a certain amount without much effect on its welfare, whereas investing larger amounts results in a larger marginal effect on its welfare [33]. In turn, these diminishing returns imply that it is less beneficial for a given country to increase its contribution above some level; consequently, they may inhibit the effect of the positive feedback and necessitates investments by a larger number of countries. In contrast, the diminishing returns on the aggregate contribution that we did consider in the model do not have the same effect and do not inhibit the positive feedback mechanism. The diminishing returns on the aggregate investment may result from limitations on the project's implementation that do not relate to the identity of the countries that contribute. For example, the eradication of harmful species is inherently constrained by biological factors that make it inefficient to eradicate too fast [11, 34]. In turn, the diminishing returns per country's investment could be incorporated into our model by allowing more general forms of the response function, (e,g., $h(a_1, a_2) = a_1^\gamma + a_2^\gamma$ with $\gamma < 1$), or a more general form of the cost due to the investment (e.g., $a_i \to a_i + a_i^2$ in Eq. 3). Incorporating sufficiently large diminishing returns into our model results in a Nash equilibrium in which, as in numerous previous studies [24-26], the contributions increase with the benefits (Fig. 4C).

We also demonstrated the coexistence of multiple Nash equilibria, each of which comprises a different set of countries that contribute, or different times at which the different countries contribute (Figs. 2, 3). The multiple Nash equilibria already appear in each time step (Fig. 2), and consequently, in the dynamic game, even more Nash equilibria are possible as the identities of the countries that contribute may change over time (Fig. 3). Note that the existence of multiple Nash equilibria in dynamic games is a well-known phenomenon, but the underlying mechanism that is more common in the literature is that punishments can be used by the agents to enforce different sets of strategies (e.g., the folk theorems) [13, 26, 32]. In our model, however, we do not consider punishment mechanisms as we consider Markovian Nash equilibria, in which the actions of the agents at a given time do not depend on their prior actions. Instead, the mechanism underlying the emergence of multiple Nash equilibria in our model is the positive feedback, in which the more a given country contributes, the more it is incentivized to contribute even further.

When establishing a common project, the countries could agree to contribute according to any of the Nash equilibria. Specifically, such an agreement would be self-enforcing as no country would have the incentive to deviate [13-16, 30-32]. However, it is unclear which of the Nash equilibria should be preferred. Specifically, even the simplest case in which the same countries contribute at all times exhibits cases in which no Nash equilibrium is Pareto-superior to any other Nash equilibrium, namely, switching from one Nash equilibrium to another is beneficial for some countries but deleterious for others (Figs. 2, 3). This is because each Nash equilibrium comprises a different set of countries that contribute, and each country would prefer an equilibrium in which it does not contribute. Furthermore, we showed in Theorem 2 that those Nash equilibria in which fewer countries contribute at any given time are the more efficient ones. Namely, the efficient solutions, in which the aggregate contributions are higher and the project becomes complete faster, are also the less fair solutions. This tradeoff between efficiency and fairness makes it even harder to form an efficient, self-enforcing agreement. Nevertheless, the iterative solutions, in which the identities of the countries that contribute change over time, may suggest a solution to the conflict between efficiency and fairness. Specifically, these iterative solutions can be more efficient if fewer countries contribute at any given time, and can be fair if various countries contribute, each during a distinct time period.

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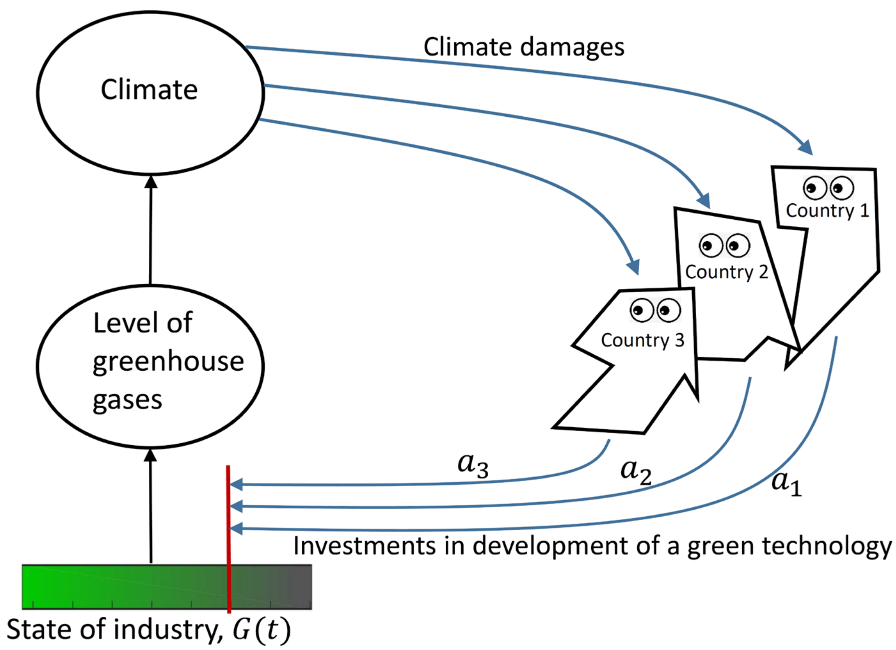


Figure 1: Illustration of the model in a special case of climate change mitigation. The state of the technology used worldwide, $G(t)$, determines the amount of greenhouse gases (GHG; e.g., CO_2) emitted to the atmosphere. In turn, GHG causes the temperature to increase over time, and the higher temperatures may cause damages in all the countries. Each country may decide how much to invest in the development and establishment of greener technologies, a_i, which increase G and result in a benefit to all the countries due to lower future GHG emmissions.

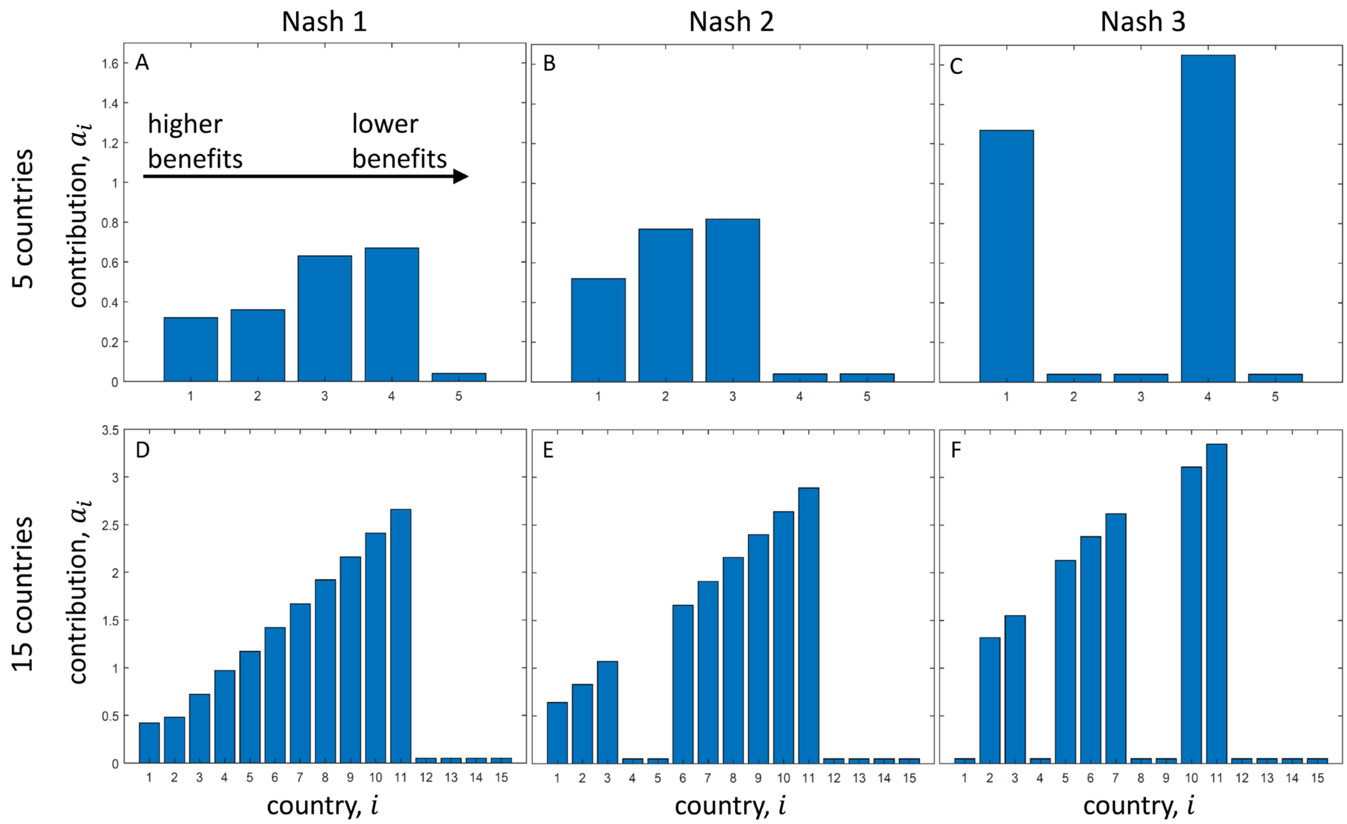


Figure 2: There exist multiple Nash equilibria, all of which exhibit contributions that are not monotone with the incentives of the countries. Each panel shows a Nash equilibrium, where the bars show the contribution of the countries to the common project at a given state, $a_i(G_0)$. In each panel, the countries are shown from those with the highest benefits from the common project (left) to those with the lowest benefits from the project (right). In each Nash equilibrium, the contribution is made by several countries that gain sufficiently large benefits from the project, but in a reversed order in which the countries that have more benefits contribute less. Also note that the coexisting Nash equilibria differ in the identities of the countries that contribute. Specifically, panels A, B, and C each shows a distinct Nash equilibrium that correspond to a case where $N = 5$ countries could potentially contribute, while panels D, E, and F each shows a distinct Nash equilibrium that corresponds to a case in which $N = 15$ countries could contribute.

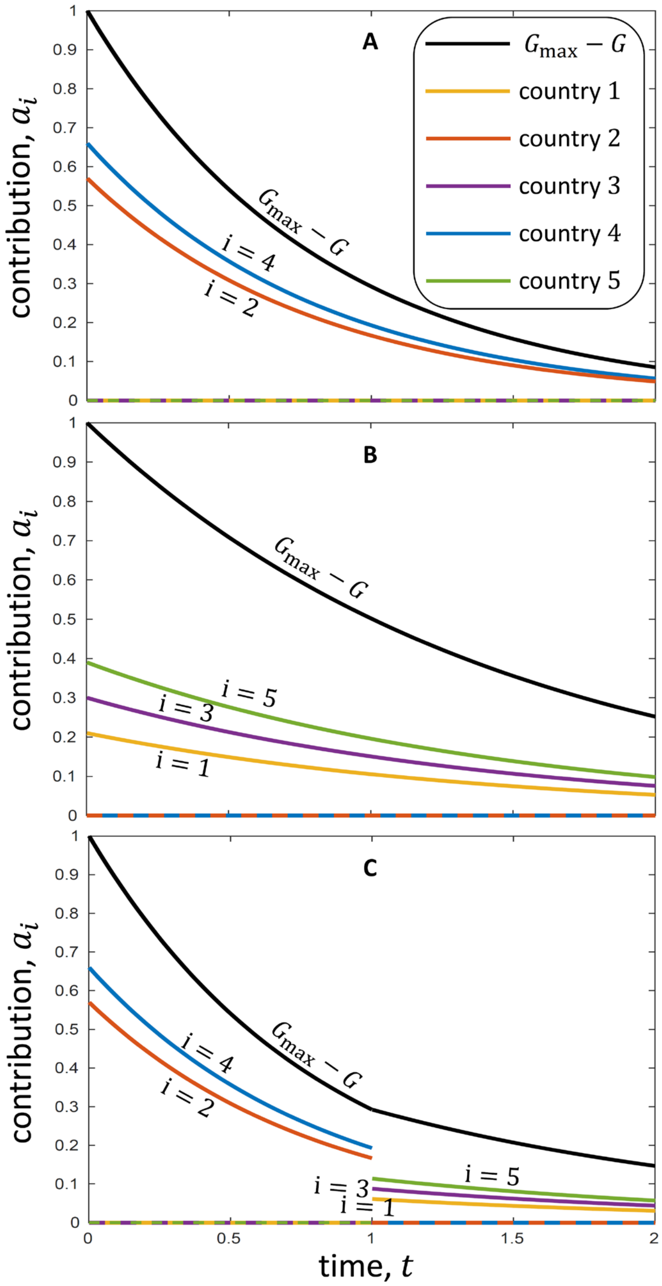


Figure 3: The Nash equilibria may differ in the timings at which different countries contribute. Demonstrated are three Nash equilibria that coexist in a given project. **(A, B)** In some Nash equilibria, the same countries contribute at all times. **(C)** In other Nash equilibria, the identities of the countries that contribute switch at certain times. The countries are ordered according to the benefits, from the most incentivized country (country 1) to the least incentivized one (country 5). Note that, at any given time, the less incentivized country among the contributing countries contribute more than the other countries. Also, note that the aggregate contribution is larger when fewer countries contribute.

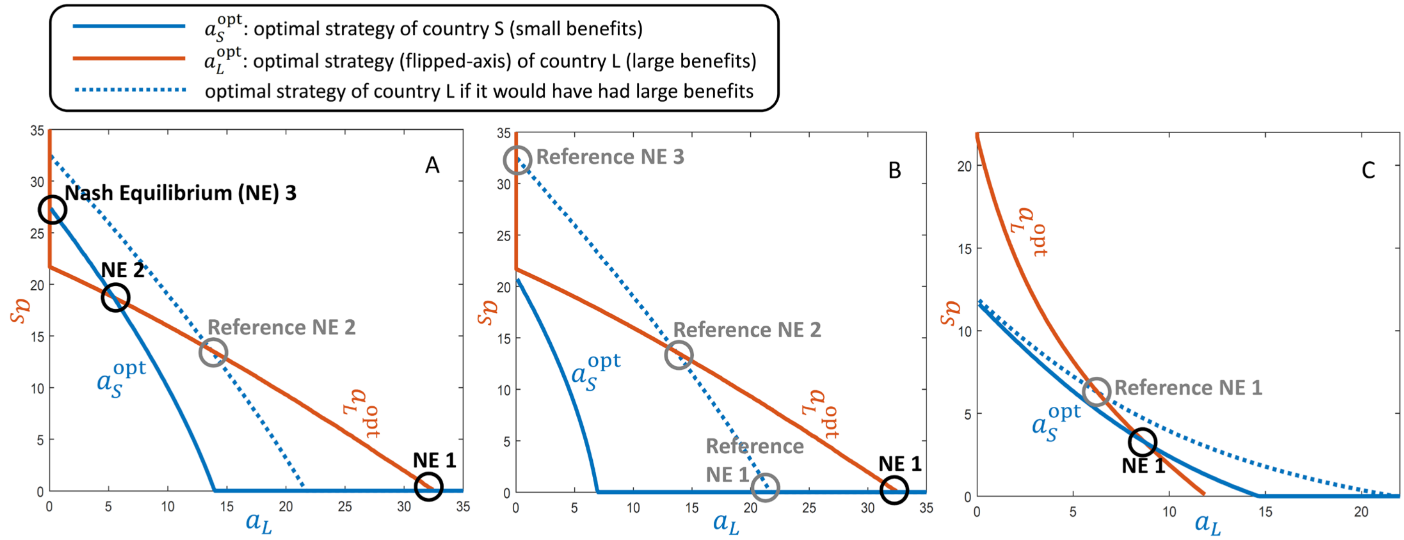


Figure 4: Countries contribute amounts that are disproportional to their incentives. We consider two countries: country S with small benefits and country L with large benefits from the common environmental project. In each panel, we plot the optimal contribution of one country at a given state as a function of the contribution of the other country, (a_S^{opt}- solid, blue line; a_L^{opt}- on flipped-axis - solid, red line). We also plot, as a reference, a mirror image of a_L^{opt} (dashed, blue-line), characterizing the optimal contribution of a hypothetical country that is identical to country L. Each intersection of the two solid lines corresponds to a Nash equilibrium that comprises a pair of contributions, one by country S and one by country L, in which no country has an incentive to unilaterally change its strategy. (The Nash equilibrium is given by the coordinates where the x-axis and y-axis show the contributions of country L and country S, respectively.) Similarly, each intersection of the dashed blue line and the solid red line corresponds to a Nash equilibrium of two identical countries with high incentives. The three panels differ in the parameter values. **(A)** There exists a Nash equilibrium in which both countries contribute (NE 2), but then, country S contributes more than country S. Note that country S contributes less for every given contribution of country L (the solid blue line is below the dashed blue line). But due to the positive feedback between the investment and the incentives to invest, the blue line is above the red line near the y-axis, and consequently, the Nash equilibrium dictates larger contribution of country S. **(B)** Country S has much lower incentives than country L, and it cannot stably contribute in Nash equilibrium. **(C)** We assume a different version of the model in which there are diminishing returns on the per-country investment, $h = h(a_1, a_2)$. The red line is above the blue line near the y-axis, which implies that there exists a single Nash equilibrium, in which both countries contribute, and country L contributes more than country S.

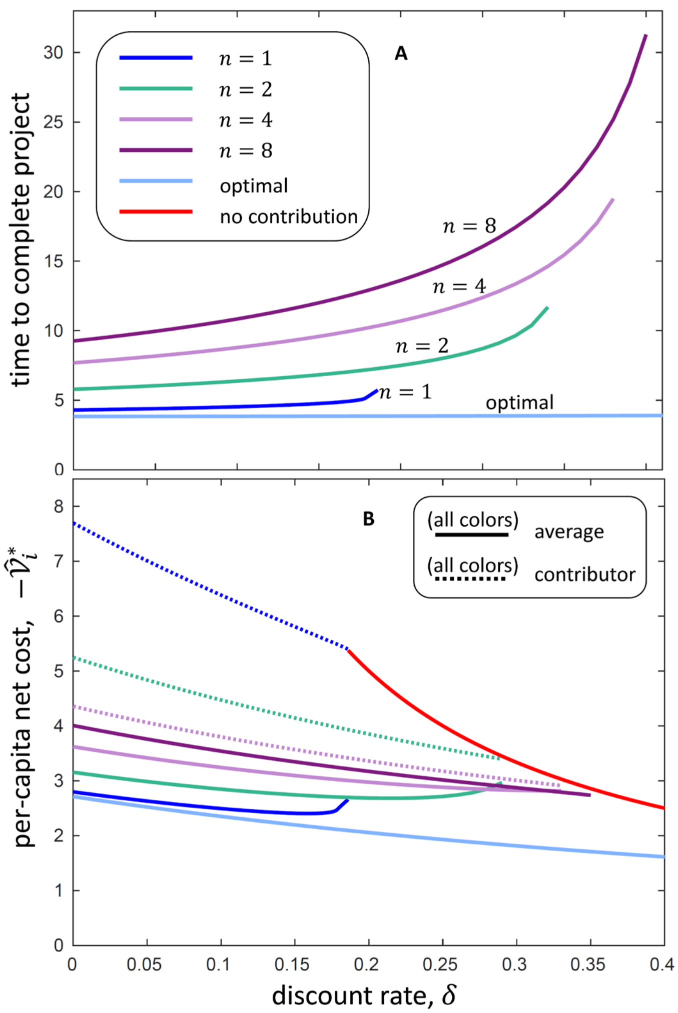


Figure 5: The project is being established faster if fewer countries contribute (see Theorem 2). Demonstrated are several Nash equilibria, in each of which n identical countries contribute simultaneously at all times until the project is complete ($G = G_{\max}$). Each Nash equilibrium is demonstrated as a function of δ for those values of δ for which it exists. (Note that each Nash equilibrium exists until δ approaches some threshold value, and this threshold value is lower if n is smaller.) **(A)** Demonstrated are the total times that it takes to approach $G_{\max}$ as a function of the discount rate for the four Nash equilibria in which $n = 1, 2, 4$, and 8, as well as for the optimal solution that maximizes the total social welfare of all the $N = 8$ countries. **(B)** Demonstrated are the total net costs, $-\hat{\mathcal{V}}_i^*$, which incorporate both C_i and a_i over time, as a function of δ for the same four Nash equilibria. Dotted lines show the costs per county that contributes, and solid lines show the average costs per country (including the countries that contribute and those that do not). The red line shows the Nash equilibrium in which no country contributes (and G remains zero). Note that, in accordance with Theorem 2, for a sufficiently small δ, the project is becomes complete faster and the average net cost is lower if n is smaller.

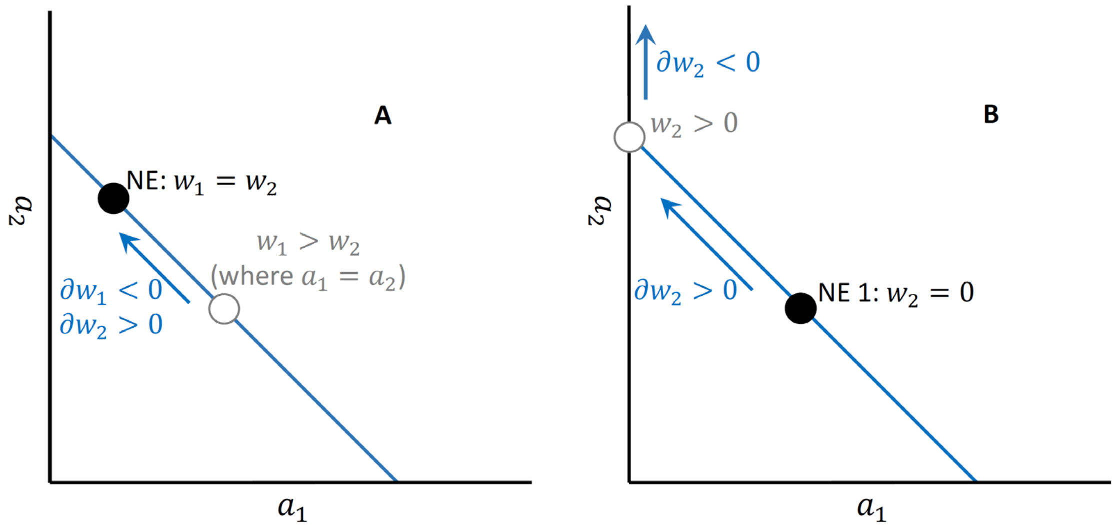
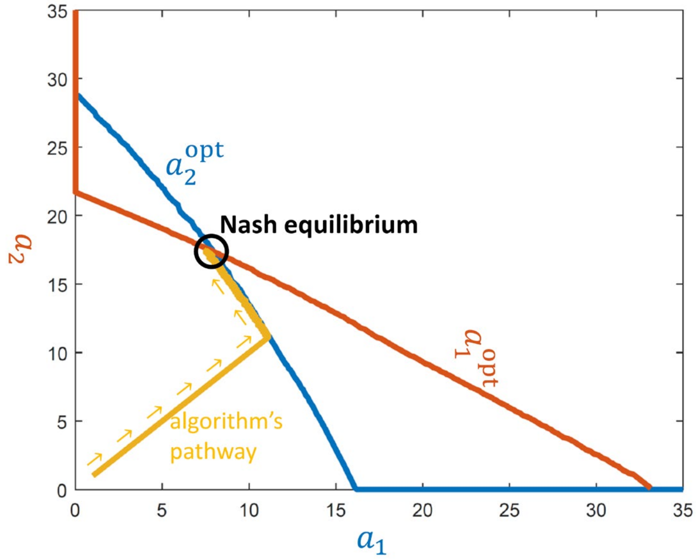


Figure 6: The mathematical ideas behind the proof of Theorems 1 and 2 are demonstrated for the case of two players. The blue curve is a curve on which $a_1 + a_2$ is a constant. Specifically, it satisfies $a_1 + a_2 = a_1^* + a_2^*$, where (a_1^*, a_2^*) is a Nash equilibrium in which both countries contribute. (The Nash equilibrium resides on this curve.) Also, we denote $w_i = \partial \mathcal{V}_i / \partial a_i$ $(i = 1{,}2)$, characterizing the marginal benefit of country i from increasing its contribution (or the "incentives" of country i to increase its contribution). In turn, when moving leftward along the blue curve, w_1 decreases while w_2 increases. (This is due to the positive feedback mechanism that implies that each country becomes more incentivized if its relative contribution is larger.) This gives rise to the following two phenomena. **(A)** If player 1 has higher benefits from the public good, it follows that $w_1 > w_2$ if $a_1 = a_2$. In particular, $w_1 > w_2$ must hold at the middle point of the blue curve. In turn, in Nash equilibrium, $w_1 = w_2$ must hold. Since w_1 decreases while w_2 increases when moving leftward along the blue curve, it follows that $a_2^* > a_1^*$ must hold in a Nash equilibriun. **(B)** In the Nash equilibriun in which only one player contribute, $(0, a_2^{**})$, the aggregate contribution is grater than in the Nash equilibrium in which both players contribute, namely, $a_2^{**} > a_1^* + a_2^*$. This is because, when moving leftward along the blue curve, w_2 increases. Therefore, when $a_1 = 0$ and $a_2 = a_1^* + a_2^*$, $w_2 > 0$. In turn $dw_2/da_2 < 0$ if $w_2 > 0$. Also, in Nash equilibrium, $w_2 = 0$. Therefore, $a_2^{**} > a_1^* + a_2^*$.



Supplementary Figure S1: Our algorithm goes along the optimal manifolds to find the Nash equilibrium in which a given set of countries contribute. The algorithm is demonstrated here for 2 countries. a_2^{opt} is the optimal strategy of country 2 as a function of a_1, while a_1^{opt} is the optimal strategy of country 1 as a function of a_2 (plotted on a flipped-axis; see also Fig. 4). The algorithm starts from assigning low values to a_1 and a_2. Then, the algorithm increases the values a_1 and a_2 until it approaches one of the optimal curves. Finally, it continues along that curve until it approaches the other curve, where the Nash equilibrium is found.

Appendices

When establishing a common environmental project, countries that benefit less may need to contribute more

Contents

Appendix A: Reduction of the dynamic game to a series of static games

In this appendix, we analyze the solution to the dynamic game described in the main text and we show that, at each state of the system, the solution is also given by a solution to an equivalent static game. The key idea is that the state of the system, G, increases monotonically over time until it approaches its asymptotic state, $G = G^*_{max}$. Therefore, if the present state of the system is $G_0 < G^*_{max}$, then either the system remains at $G = G_0$ forever, or the next state of the system is $G_0 + dG$ (namely, the system remains between G_0 and $G_0 + dG$ until it approaches $G_0 + dG$). Consequently, when the system is at state G_0, the optimization problem of player i is how to approach the state $G_0 + dG$ in the optimal fashion where the strategies of the other players at $G = G_0$ are given. These considerations give rise to Lemma 1, which we prove in two different ways. The first proof reflects directly the logic of the backward-induction process described here. The second proof is shorter and makes a use of the Hamilton-Jacobi-Bellman equation.

Before we state the lemma, note that adding a constant to the utility functions does not change the Nash equilibria. Therefore, instead of the utility function $\mathcal{V}_i$, we may consider the following utility function:

$$\hat{\mathcal{V}}_i(\boldsymbol{a}, G_0) = -\int_0^\infty \left(C_i(G) + a_i(G)\right) e^{-\delta t} dt \tag{S1}$$

with $G = G_0$ when $t = 0$, where

$$C_i(G) = B(G^*_{max}) - B_i(G). \tag{S2}$$

Specifically, note that $B(G^*_{max})$ is a constant, and therefore, the game in which the utilities are given by $\hat{\mathcal{V}}_i$ is equivalent to the game where utilities are given by $\hat{\mathcal{V}}_i$. Moreover, note that C_i has the intuitive interpretation as it is the cost due to the the fact that the state G is still lower than G^*_{max}. Also, note that the integrand of $\hat{\mathcal{V}}_i$ approaches zero as $t \to \infty$.

Lemma 1. Consider the N-players dynamic game in which each player adopts a Markovian strategy, where the utility of player i, $\mathcal{V}_i$, is given by Eq. 3 (main text), and the dynamics of G are given by Eqs. 1, 2 (main text). Assume that h is positive and monotone increasing with A. Consider a Markovian Nash equilibrium of this game, $\boldsymbol{a}^*$. Denote $\boldsymbol{a}^*(G_0) = (a_1^*(G_0), a_2^*(G_0), ..., a_m^*(G_0))$ as the equilibrium strategies where $G = G_0$, and denote G^*_{max} as the asymptotic value of G following the equilibrium $\boldsymbol{a}^*$ ($G \to G^*_{max}$ as $t \to \infty$).

It follows that, for any $G_0 \leq G^*_{max}$, $\boldsymbol{a}^*(G_0)$ is also a Nash equilibrium of the static game in which the utilities are given by

$$u_i = -\frac{C_i(G_0) + a_i(G_0) + \delta\hat{\mathcal{V}}_i^*(G_0)}{h(A(G_0), G_0)}, \tag{S3}$$

where C_i is given by Eq. (S2), $A(G_0) = \sum_i a_i(G_0)$, and $\hat{\mathcal{V}}_i^*(G_0) = \hat{\mathcal{V}}_i(\boldsymbol{a}^*, G_0)$. More generally, if $h(A, G_0)$ is not positive for all A, then u_i is given by Eq. (S3) if $h(A) > 0$ and approaches minus infinity otherwise.

Furthermore, denote $\boldsymbol{a}^*(\delta)$ as a set of Nash equilibria, each of which corresponds to a different value of $\delta > 0$, and denote $\hat{\mathcal{V}}_i^*(G_0, \delta)$ as $\hat{\mathcal{V}}_i(G_0)$ where $\boldsymbol{a} = \boldsymbol{a}^*(\delta)$. It follows that

$$\lim_{\delta \to 0} \delta\hat{\mathcal{V}}_i^*(G_0, \delta) = 0. \tag{S4}$$

In particular, if $\delta = 0$, $\boldsymbol{a}^*(G_0)$ is also a Nash equilibrium of the static game

$$u_i = -\frac{C_i(G_0) + a_i(G_0)}{h(G_0, A)}. \tag{S5}$$

Proof of Lemma 1 using a backward induction approach.

First part. The assumption that $G_0 < G^*_{max}$, together with the assumption that the strategies are Markovian (a_i depends only on G), imply that, in equilibrium, G increases monotonically until it approaches G^*_{max}. Therefore, when we consider the solution at a given state, $G_0 < G^*_{max}$, we may restrict attention to cases where G increases, i.e., $h(A) > 0$. Namely, even if $h(A) \leq 0$ for some values of A, the assumption that $G_0 < G^*_{max}$ implies that, in equilibrium, $h(A) > 0$. Furthermore, since G increases monotonically, we may consider a backward induction approach in which the players need to chose a strategy at a given state G_0, where the equilibrium utilities of the players at the next state, $G_0 + dG$, are known and are given by $\hat{\mathcal{V}}_i^*(G_0 + dG)$. Specifically, since we consider G as a continuous variable, we consider dG as infinitesimally small. (Note that a similar derivation would apply if G is discrete each player is committed to use a given strategy between G and $G + \Delta G$).

Specifically, the strategies of the players between G_0 and $G_0 + dG$ determine the time that it takes to the system to approach $G_0 + dG$, which we denote as Δt. In turn, it follows that the utilities at state $G = G_0$, given that $\boldsymbol{a} = \boldsymbol{a}^*$ if $G \geq G_0 + dG$, are given by

$$\hat{\mathcal{V}}_i(G_0) = -(C_i(G_0) + a_i(G_0))\Delta t + \hat{\mathcal{V}}_i^*(G_0 + dG)\exp(-\delta\Delta t). \tag{S6}$$

Namely, the strategy $a_i(G_0)$ of player i affects her/his utility in two different ways. First, the player suffers a cost $C_i(G_0) + a_i(G_0)$ during a period Δt (where both the cost and the Δt depend on the strategy of the player). Second, the system approaches the state $G_0 + dG$ only after a delay, Δt, and therefore, a greater Δt implies a greater discount on the utility at the next state of the system.

In particular, note that Eq. 2 implies that

$$\Delta t = dG/h(A), \tag{S7}$$

where $h(A) = h(A(G_0), G_0)$. Substitution of Eq. (S6) into Eq. (S7) implies

$$\hat{\mathcal{V}}_i(G_0) = -\frac{C_i(G_0) + a_i(G_0)}{h(A)}dG + \hat{\mathcal{V}}_i^*(G_0 + dG)\exp\left(-\frac{\delta}{h(A)}dG\right). \tag{S8}$$

In turn, note that dG is infinitesimally small, and we can write Eq. (S8) as

$$\hat{\mathcal{V}}_i = \hat{\mathcal{V}}_i^*(G_0 + dG) - \frac{C_i(G_0) + a_i(G_0) + \delta\hat{\mathcal{V}}_i^*(G_0)}{h(A)}dG + \mathcal{O}(dG^2) \tag{S9}$$

Finally, note that $\hat{\mathcal{V}}_i^*(G + dG)$ is a constant that does not depend on the strategies of the players at $G = G_0$. It follows that the equilibrium strategies at $G = G_0$ must also be the equilibrium strategies of the static game in which the utilities are given by the second term in the right hand side of Eq. (S9). In other words, the utilities are given by Eq. (S3), which complete the proof of the first part of the lemma.

Second part. To show that $\delta\hat{\mathcal{V}}_i^*(G_0, \delta) \to 0$ as $\delta \to 0$, we need to show that, for each ϵ, there exists δ_c such that $\delta\hat{\mathcal{V}}_i^* < \epsilon$ for all $\delta < \delta_c$. First, note that $(C_i + a_i^*) \to 0$ as $t \to \infty$, as follows directly from the definition of C_i. In particular, this implies that there exists $t_1 < \infty$, such that $C_i + a_i^* < \epsilon/2$ for all $t > t_1$. In turn, this implies that

$$V_i^a \equiv \int_{t_1}^{\infty} (C_i + a_i^*) e^{-\delta t} dt < \frac{1}{2}\frac{\epsilon}{\delta}.$$

Also, note that

$$V_i^b = \int_0^{t_1} (C_i + a_i^*) e^{-\delta t} dt \le \max\{C_1 + a_1^*\} t_1,$$

and therefore, if

$$\delta_c \equiv \frac{1}{2}\frac{\epsilon}{\max\{C_1 + a_1^*\} t_1},$$

then $V_i^b < \frac{1}{2}\frac{\epsilon}{\delta}$ for all $\delta < \delta_c$. In turn, $\hat{\mathcal{V}}_i^* = V_i^a + V_i^b$, and therefore, $\hat{\mathcal{V}}_i^* < \epsilon/\delta$ (or $\delta\hat{\mathcal{V}}_i^* < \epsilon$) for all $\delta < \delta_c$, which completes the proof of Lemma 1. □

Alternative proof of the first part of Lemma 1 using the Hamilton-Jacobi-Bellman equation.

In Nash equilibrium, each player adopts a strategy that maximizes his/her strategy given the strategy of the other players, and therefore, $\hat{\mathcal{V}}_i^*$ must satisfy the Hamilton-Jacobi-Bellman equation [26, 28]. Specifically, from Eqs. 1-3, it follows that the Hamilton-Jacobi-Bellman equation is given by

$$-\frac{\partial \hat{\mathcal{V}}_i^*}{\partial t} = h(A(G), G)\frac{\partial \hat{\mathcal{V}}_i^*}{\partial G} - \delta\hat{\mathcal{V}}_i(G) - C_i(G) - a_i^*(G), \tag{S10}$$

where this equation applies to both $\mathcal{V}_i^*$ and the equivalent $\hat{\mathcal{V}}_i^*$ (Eq. (S1)). Next, note that the game is time-invariant as both the strategies and the utilities do not depend explicitly on time. This follows directly from the fact that, for all t_1 and t_2, $\hat{\mathcal{V}}_i(G_0, t_1) = \hat{\mathcal{V}}_i(G_0, t_2)$, which, in turn, follows directly from Eq. (S1) together with the assumption that the strategies are Markovian and depend only on the state G. It follows that $\partial \hat{\mathcal{V}}_i^*/\partial t = 0$ and therefore, it follows from Eq (S10) that

$$\frac{\partial \hat{\mathcal{V}}_i^*(G)}{\partial G} = \frac{C_i(G) + a_i + \delta \hat{\mathcal{V}}_i^*(G)}{h(A(G), G)}. \tag{S11}$$

In turn, it follows from the definition of $\hat{\mathcal{V}}_i$ that $\hat{\mathcal{V}}_i^*(G_{max}^*) = 0$. Therefore, for all $G < G_{max}^*$, the strategy a_i that maximizes $\hat{\mathcal{V}}_i(G)$ is also the strategy that minimizes $\partial \hat{\mathcal{V}}_i^*(G)/\partial G$ (where the strategies of the other players are given). Namely, in Nash equilibrium, each player choses a strategy that minimizes the right-hand-side of Eq. (S11), which is also the strategy that maximizes u_i (Eq. (S3)), which completes the proof of the first part of Lemma 1. □

Appendix B: Proof of Theorem 1

In this Appendix, we prove Theorem 1. We begin with Lemma 2, which is used to prove both Part A and Part B of the theorem. Then, we present Lemma 3, which is used for the proof of Part B. We also use Lemma 1 from Appendix A for the proof.

Lemma 2 Consider the two-players static game in which each player i, $i = 1, 2$, adopts a strategy $a_i \geq 0$ and has a utility given by

$$u_i = -\frac{C_i + a_i}{h(F + a_1 + a_2)}, \tag{S12}$$

where $h(x) > 0$ and $h'(x) \geq 0$ for all $x > 0$.

Consider that a Nash equilibrium of the game is given by (a_1^*, a_2^*). If the equilibrium strategies of both players are strictly positive, $a_1^* > 0$ and $a_2^* > 0$, it follows that

$$a_1^* + C_1 = a_2^* + C_2. \tag{S13}$$

Specifically, note that Eq. (S13) implies that $a_2^* > a_1^*$ if and only if $C_1 > C_2$, and it also implies that

$$u_1(a_1^*, a_2^*) = u_2(a_1^*, a_2^*) \tag{S14}$$

Proof of Lemma 2 Since $a_i \in [0, \infty)$, and since $a_i^* > 0$ in Nash equilibrium (in which each player adopts a strictly positive strategy that maximizes her/his utility when the strategy of the other player is given), it follows that

$$\frac{\partial u_i(a_1^*, a_2^*)}{\partial a_i} = 0. \tag{S15}$$

In turn, from Eq. (S12), it follows that

$$\frac{\partial u_i}{\partial a_i} = -\frac{h(A) - (C_i + a_i)h'(A)}{h^2(A)}, \tag{S16}$$

where $A = F + a_1 + a_2$. Substitution of Eq. (S16) into Eq. (S15) implies that

$$h(A^*) - (C_i + a_i^*)h'(A^*) = 0 \tag{S17}$$

or

$$C_i + a_i^* = \frac{h(A^*)}{h'(A^*)}, \tag{S18}$$

where $A^* = F + a_1^* + a_2^*$. Specifically, note that Eq. (S18) applies to both $i = 1$ and $i = 2$, and therefore,

$$C_1 + a_1^* = C_2 + a_2^*, \tag{S19}$$

which completes the proof of Lemma 2. □

Lemma 3 Consider the N-players dynamic game in which each player adopts a Markovian strategy, $a_i(G) \geq 0$, the utility of player i, $\mathcal{V}_i$, is given by Eq. 3, and the dynamics of G are given by Eqs. 1, 2. Assume that h is non-negative and monotone increasing with A for all G. Consider a Nash equilibrium, $\boldsymbol{a^*}$. Denote G^*_{max} as the asymptotic state of G, and denote as $\hat{\mathcal{V}}^*_i(G)$ as the value of $\hat{\mathcal{V}}_i(\boldsymbol{a}, G)$ (Eq. S1) where $\boldsymbol{a} = \boldsymbol{a^*}$.

It follows that, if $a_i^*(G) > 0$ and $a_j^*(G) > 0$ for all $G_0 < G < G^*_{max}$ (both players contribute until the project approaches its asymptotic level), then

$$\hat{\mathcal{V}}^*_i(G) = \hat{\mathcal{V}}^*_j(G) \tag{S20}$$

for all $G_0 \leq G \leq G^*_{max}$.

Proof of Lemma 3. Note that the assumptions of Lemma 3 also satisfy the assumption of Lemmas 1 and 2. From Lemma 1, it follows that for all $G_0 \leq G_1 \leq G^*_{max}$, the Nash equilibrium at the state $G = G_1$ is also a Nash equilibrium of the static game in which the utilities are given by

$$u_i = \frac{\tilde{C}_i(G_1) + a_i(G_1)}{h(A(G_1), G_1)}, \tag{S21}$$

where

$$\tilde{C}_i(G_1) = C_i(G_1) + \delta\hat{\mathcal{V}}_i^*(G_1). \tag{S22}$$

Accordingly, Lemma 2 implies that if both $a_1^*(G_1) > 0$ and $a_2^*(G_1) > 0$, then

$$a_1^*(G_1) + \tilde{C}_1(G_1) = a_2^*(G_1) + \tilde{C}_2(G_1). \tag{S23}$$

In turn, note that if $\hat{\mathcal{V}}_i^*(G_1) = \hat{\mathcal{V}}_j^*(G_1)$, then $a_1^*(G_1) + \tilde{C}_1(G_1) = a_2^*(G_1) + \tilde{C}_2(G_1)$ implies that $a_1^*(G_1) + C_1(G_1) = a_2^*(G_1) + C_2(G_1)$. Also, note that $\hat{\mathcal{V}}_i^*(G_{max}^*) = \hat{\mathcal{V}}_j^*(G_{max}^*)$, and therefore, if $a_1^*(G) + C_1(G) = a_2^*(G) + C_2(G)$ for all $G_1 < G < G_{max}^*$, it follows from Eq. (S1) that $\hat{\mathcal{V}}_i^*(G_1) = \hat{\mathcal{V}}_j^*(G_1)$ Therefore, it follows from backward induction that $\hat{\mathcal{V}}_i^*(G_1) = \hat{\mathcal{V}}_j^*(G_1)$ for all $G_0 < G_1 < G_{max}^*$, which completes the proof of Lemma 3. □.

Proof of Theorem 1. According to Lemma 1, we only need to show that the theorem holds for the static game in which the utilities are given by

$$u_i = -\frac{\tilde{C}_i + a_i}{h(A)} \tag{S24}$$

if $h(A) > 0$ and u_i approaches minus infinity otherwise, where

$$\tilde{C}_i = C_i(G_0) - \delta\hat{\mathcal{V}}_i^*(G_0), \tag{S25}$$

and $h(A) = h(A(G_0), G_0)$. In turn, from Lemma 2, it follows that, for all i and j, if both a_i^* and a_j^* are strictly positive and $\tilde{C}_i > \tilde{C}_j$, then $a_j^* > a_i^*$ (Eq. (S24) is a special case of Eq. (S12) where $F = A - a_i - a_j$).

To complete the proof of the theorem, it remains to show that, under the conditions specified in part A and part B, $C_i < C_j$ implies that $\tilde{C}_i < \tilde{C}_j$. Specifically, note that Lemma 1 also implies that

$$\lim_{\delta \to 0} \delta\hat{\mathcal{V}}_i^* = 0.$$

Therefore, for sufficiently small δ, $\tilde{C}_i < \tilde{C}_j$ if $C_i < C_j$, which completes the proof of part A. In turn, note that according to Lemma 3, if both players i and j contribute at all times until $G = G_{max}^*$, then $\hat{\mathcal{V}}_i^* = \hat{\mathcal{V}}_j^*$. This implies that $\tilde{C}_i > \tilde{C}_j$ if and only if $C_i > C_j$, which completes the proof of part B of the theorem. □

Appendix C: Proof of Theorem 2

In this Appendix, we prove Theorem 2. We begin with proving two lemmas and we also use Lemma 1 from Appendix A for the proof. Fig. 6B demonstrates a graphical illustration of the proofs of Lemmas 4 and 5.

Lemma 4. Consider the optimization problem in which a single player needs to chose $a \geq 0$ that maximizes $u(F, a)$ where F is given. Denote

$$w(a, F) = \frac{\partial u(a, F)}{\partial a} \tag{S26}$$

and assume that the following two conditions hold for all a and F:

(1) w increases if a increases while the sum $a + F$ remains unchanged. Namely, if $a_1 + F_1 = a_2 + F_2$ and $a_1 > a_2$, then $w(a_1, F_1) > w_2(a_2, F_2)$.

(2) If $w(a, F) > 0$, then $\dfrac{\partial w(a, F)}{\partial a} < 0$.

Denote $a^*(F)$ the value of a that maximizes $u(a, F)$ for a given value of F. It follows that, if $a^* > 0$, then the value of the sum $(a^*(F) + F)$ increases as F decreases.

Proof of Lemma 4. Assume that $a_1^* > 0$ maximizes $u_1(a) = u(a, F_1)$, and $a_2^* > 0$ maximizes $u_2 = u(a, F_2)$, where $F_2 < F_1$. It follows that

$$w_1 = \frac{du_1(a_1^*)}{da} = 0, \tag{S27}$$

$$w_2 = \frac{du_2(a_2^*)}{da} = 0. \tag{S28}$$

Also, consider $a_2^0 > 0$ that satisfies

$$F_2 + a_2^0 = F_1 + a_1^*. \tag{S29}$$

The assumption that $F_2 < F_1$ implies that $a_2^0 > a_1^*$. Therefore, it follows from condition (1) that

$$w_2(a_2^0) > w_1(a_1^*), \tag{S30}$$

and since $w_1(a_1^*) = 0$, it follows that

$$w_2(a_2^0) > 0. \tag{S31}$$

In turn, it follows from condition (2) that $w_2(a) > 0$ for all $0 \leq a \leq a_0$. Therefore, $w(a_2) = 0$ implies that $a_2^* > a_2^0$. Then, Eq. (S29) implies that

$$F_2 + a_2^* > F_1 + a_1^*. \tag{S32}$$

Finally, note that Eq. (S32) holds for all F_1 and F_2 that satisfy $F_2 < F_1$, which completes the proof of Lemma 4. □

Lemma 5. Consider an N-players static game in which each player, $i = 1, 2, ..., N$, chooses a strategy $a_i \geq 0$ and has a utility function given by u_i. Denote A as the aggregate contribution,

$$A = \sum_i a_i \tag{S33}$$

and

$$w_i = \frac{\partial u_i}{\partial a_i}. \tag{S34}$$

Assume that the utility satisfies the following two conditions for all sets of strategies, $\{a_1, a_2, ..., a_N\}$, and for all i:

(1) w_i increases if the contributions change such that a_i increases while A remains unchanged.

(2) If $w_i > 0,$ then $\dfrac{\partial w_i}{\partial a_i} < 0.$

Also, assume that the following two Nash equilibria exist: equilibrium 1, in which $a_i > 0$ if and only if $i = 1, 2, ..., n$, and equilibrium 2, in which $a_i > 0$ if and only if $i = 2, 3, ..., n$ (and $a_1 = 0$). Then, it follows that A is greater in equilibrium 2.

Proof of Lemma 5. Denote A^{*1} and A^{*2} the aggregate contributions in equilibria 1 and 2, respectively. Denote a_i^{*1} the strategy of player i in equilibrium 1 and a_i^{*2} the strategy of player i in equilibrium 2. Also, denote $A_{-i}^{*1} = A^{*1} - a_i^{*1}$ and $A_{-i}^{*2} = A^{*2} - a_i^{*2}$.

Assume that, in contrast to the lemma, $A^{*2} \leq A^{*1}$. It follows that there exists i such that

$$A_{-i}^{*2} < A_{-i}^{*1}. \tag{S35}$$

In turn, from Lemma 3 (where a_i plays the role of a and A_{-i}^{*1} plays the role of F), it follows that

$$A_{-i}^{*2} + a_i^{*2} > A_{-i}^{*1} + a_i^{*1}, \tag{S36}$$

which is equivalent to $A^{*2} > A^{*1}$, and we reached a contradiction. This implies that $A^{*2} > A^{*1}$ must hold, which completes the proof of Lemma 5. □

Proof of Theorem 2. According to Lemma 1, the results of Theorem 2 hold if they hold for the static game in which the utilities are given by

$$u_i = -\frac{\tilde{C}_i(G_0) + a_i(G_0)}{h(G_0, A)}, \tag{S37}$$

where

$$\tilde{C}_i = C_i(G_0) + \delta \hat{\mathcal{V}}_i^*.$$

We begin with a proof for the non-discounted case ($\delta = 0$), and then, we extend the proof to the more general case.

Non-discounted case

According to Lemma 1, $\delta \hat{\mathcal{V}}_i^* \to 0$ as $\delta \to 0$, and therefore, in the non-discounted case, $\tilde{C}_i = C_i(G_0)$. Moreover, note that $C_i(G_0)$ has the same value in both equilibria, which follows directly from the assumption that G_{max}^* is the same in both. Therefore, both equilibria are equilibria of the same static game where $G = G_0$, and therefore, the results of the theorem follow from the results of Lemma 5. It remains to show that conditions (1) and (2) of Lemma 5 hold for all u_i and all a_i. It follows from Eq. (S37) that

$$\frac{\partial u_i}{\partial a_i} = -\frac{h(A) - (C_i + a_i)h'(A)}{h^2(A)} = -\frac{h(A) - C_i h'(A)}{h^2(A)} + a_i \frac{h'(A)}{h^2(A)}. \tag{S38}$$

Condition (1) follows directly from Eq. (S38) because $h'(A) > 0$ and $h^2(A) > 0$, and therefore, $\partial u_i/\partial a_i$ increases if the strategies change such that a_i increases while A remains unchanged.

Next, note that

$$\frac{\partial^2 u_i}{\partial a_i^2} = \frac{a_i h'' h^2 + 2hh'(h - (C_i + a)h')}{h^4}, \tag{S39}$$

where we use h to denote $h(A)$. In turn, note that $a_i h'' h^2 \leq 0$ follows from the assumptions that $a_i > 0$, $h > 0$, and $h'' \leq 0$. In turn, note that $\partial u_i/\partial a_i > 0$ implies that $(h - (C_i + a_i)h') < 0$. It follows that, if $\partial u_i/\partial a_i > 0$, then the numerator is negative while the denominator is positive, which implies that $\partial^2 u_i/\partial a_i^2 < 0$. Namely, condition (2) of Lemma 5 also holds.

Discounted case

Denote K the set of players that contribute in a given Nash equilibrium: $a_i^* > 0$ if $i \in K$ and $a_i^* = 0$ otherwise. From Eq. (S38), it follows that for each $i \in K$,

$$\tilde{C}_i = \frac{h(A^*)}{h'(A^*)} - a_i^*. \tag{S40}$$

(Note that $\hat{\mathcal{V}}_i^* \leq 0$ does not depend to $a_i(G_0)$.) In turn, the assumption that $h'' < 0$ implies that

$$\frac{d}{da_i}\left(\frac{h(A)}{h'(A)} - a_i\right) = \frac{h'^2(A) - h(A)h''(A)}{h'^2(A)} - 1 = -\frac{h(A)h''(A)}{h'^2(A)} > 0. \tag{S41}$$

Namely, $h(A^*)/h'(A^*) - a_i^*$ increases with a_i^*, which implies that the solution to Eq. (S40) is unique. In turn, this implies that the Nash equilibrium in which the set of players that contribute is given by K is unique. Moreover, it implies that for each $i \in K$, a_i^* changes continuously with δ, and the existence of that Nash equilibrium for a given $\delta = \delta'$ implies its existence for all $0 < \delta < \delta'$.

Denote $A^{*1}(\delta)$ and $A^{*2}(\delta)$ the values of A^{*1} and A^{*2}, respectively, for a given value of δ. Specifically, we have seen in the proof for the non-discounted case that $A^{*2}(0) > A^{*1}(0)$, and therefore, $\Delta \equiv A^{*2}(0) - A^{*1}(0) > 0$. Also, since a_i^* changes continuously with δ, $A^{*1}(\delta)$ and $A^{*2}(\delta)$ are continuous functions of δ. Specifically, $A^{*1}(\delta) \to A^{*1}(0)$ and $A^{*2}(\delta) \to A^{*2}(0)$ as $\delta \to 0$. Therefore, there exists δ_c such that $(A^{*2}(\delta) - A^{*2}(0) - (A^{*1}(\delta) - A^{*1}(0))) < \Delta$ for all $\delta < \delta_c$. This implies that $A^{*1}(\delta) < A^{*2}(\delta)$ for all $\delta < \delta_c$, which completes the proof of Theorem 2. $\square$

Appendix D: Existence of cooperative Nash equilibria

In Appendices A-C, we discuss the properties of Nash equilibria in which several players contribute simultaneously. In this Appendix, we analyze which of these Nash equilibria may coexist and how it depends on the parameters. In particular, we consider a set of players, K, and we examine the conditions for the existence of a Nash equilibrium in which only these players contribute at a given state G. For example, $K = \{2, 3, 5\}$ implies that only players 2, 3 and 5 contribute, namely, $a_i^* > 0$ if and only if $i = 2, 3, 5$ (and $a_i^* = 0$ otherwise).

Role of the discount rate

The existence of a given Nash equilibrium in which only players in K contribute depends on the discount rate, δ, as demonstrated in Fig. 5. In particular, if δ is sufficiently small, then it worth for a single agent to contribute even if no other agent contributes. However, if δ is greater than some threshold, then the solution in which no agent contributes becomes stable and a contribution by a single agent is no longer a Nash equilibrium (see also [11, 19]). Similarly, as δ further increases, fewer Nash equilibria exist and those that still exist include more countries that contribute simultaneously. To obtain some analytic insights, consider the simple case in which h does not depend on G, $h(0) = 0$, $h'(x) > 0$, and $h''(x) < 0$ for all x. Also, assume that players are identical, and the benefits are given by $B_i(G) = \beta G$ if $G < G_{max}$ and $B_i = \beta G_{max}$ otherwise. In this case, a Nash equilibrium in which only one agent contributes for all $G < G_{max}$ exists if and only if $\delta < \beta h'(0)$. More generally, a necessary condition for the existence of any Nash equilibrium in which K is not empty is that δ is below a certain threshold, where the particular threshold depends on K.

Role of the relative costs: general case

In the rest of this Appendix, we restrict attention to the case in which δ is sufficiently small, and we examine how the heterogeneity among the players determine which Nash equilibria exist. We restrict attention to a given state of the system, $G_0 < G^*_{max}$. For simplicity, we omit the notation

G_0 from all the functions and we use the notation C_i for $\tilde{C}_i(G_0)$, $h(A)$ for $h(A(G_0), G_0)$, a_i for $a_i(G_0)$, and A^* for the aggregate contribution, A, where $G = G_0$ in a given Nash equilibrium.

We have seen in the proof of Lemma 2 that, in Nash equilibrium, a_i^* satisfies

$$C_i + a_i^* = \frac{h(A^*)}{h'(A^*)} \tag{S42}$$

for all $i \in K$ (and $a_i^* = 0$ for all $i \notin K$). (Note that Eq. (S42) is an implicit formula as a_i^* appears in both sides of the equation as it is also a component of A^*.) In turn, this implies three necessary conditions for the existence of a Nash equilibrium in which only agents in K contribute:

(1) For all $i \in K$, the solution in Eq. (S42) maximizes the utility (we only saw that $\partial u_i/\partial a_i = 0$ if and only if Eq. (S42) holds, but we still did not examine the second derivative) .

(2) For all $i \in K$, there exists a solution to Eq. (S42) in which $a_i^* > 0$.

(3) For all $i \notin K$, $a_i = 0$ maximizes u_i.

Note that conditions (2) and (3) are demonstrated in Fig. 4A,B for the case of two players. In particular, Fig. 4A shows a case in which the costs C_i are sufficiently close, and a Nash equilibrium in which both players contribute exists. Fig. 4B shows a case in which the difference between the costs is larger, and only the player with the larger C_i may contribute in a Nash equilibrium. In what follows, we derive general necessary conditions for conditions (1)-(3).

<u>condition (1)</u>

A sufficient condition for condition (1) is that

$$\frac{\partial^2 u_i(\boldsymbol{a}^*)}{\partial a_i^2} < 0. \tag{S43}$$

In turn, it follows from Eq. (S3) that

$$\begin{aligned} \frac{\partial^2 u_i(\boldsymbol{a}^*)}{\partial a_i^2} &= -\frac{[h'(A^*) - h'(A^*) - a_i^* h''(A^*)]h^2(A^*) - 2h(A^*)h'(A^*)[h(A^*) - (C_i + a_i^*)h'(A^*)]}{h^4(A^*)} \\ &= \frac{a_i^* h''(A^*)h^2(A^*) + 2h^2(A^*)h'(A^*) - 2h(A^*)h'^2(A^*)(C_i + a_i^*)}{h^4(A^*)}. \end{aligned} \tag{S44}$$

After the substitution of $C_i - a_i^* = h(A^*)/h'(A^*)$ (Eq. (S42)), Eq. (S44) becomes

$$\frac{\partial^2 u_i(\boldsymbol{a}^*)}{\partial a_i^2} = \frac{a_i^* h''(A^*)}{h^2(A^*)}. \tag{S45}$$

Therefore, a sufficient condition for condition (1) is that $h''(A^*) < 0$. Further analysis is needed if $h''(A^*) = 0$.

<u>condition (2)</u>

To further examine conditions (2) and (3), we assume that $h''(x) < 0$ for all x, and we examine which other assumptions are necessary in that case. In particular, $h'' < 0$ implies that

$$\frac{d}{da_i}\left(\frac{h(A)}{h'(A)} - a_i\right) = \frac{h'^2(A) - h(A)h''(A)}{h'^2(A)} - 1 = -\frac{h(A)h''(A)}{h'^2(A)} > 0. \tag{S46}$$

Namely, $h(A)/h'(A) - a_i$ increases with a_i. This implies that the Nash equilibrium, if exists, in unique. Also, it follows from Eq. (S42) that a necessary condition for condition (2) is that, for all $i \in K$,

$$C_i > \frac{h(A_{-i}^*)}{h'(A_{-i}^*)}, \tag{S47}$$

where $A_{-i}^* = A^* - a_i^*$. In particular, note that $h(x)$ increases with x and $h'(x)$ decreases with x (since we assume that $h''(x) < 0$), and therefore, $h(x)/h'(x)$ increases with x. Consequently, Eq. (S47) implies that C_i must be sufficiently large and/or the contribution of the other players in equilibrium must be sufficiently small.

<u>condition (3)</u>

The analysis of condition (2) also shows that, in the case where $h'' < 0$, condition (3) holds if and only if

$$C_i \leq \frac{h(A_{-i})}{h'(A_{-i})}, \tag{S48}$$

for all $i \notin K$. In particular, if $i \notin K$, then $a_i^* = 0$ and $A_{-i}^* = A^*$. Also, it is sufficient that the condition holds for the player with the largest C_i among the players that do not contribute. Denote

$$C_m = \max_{i \notin K}\{C_i\}. \tag{S49}$$

Then, a necessary condition to condition (3) is that

$$C_m \leq \frac{h(A^*)}{h'(A^*)} \tag{S50}$$

Equivalently, for a given $i \in K$, if follows from Eq. () that condition (3) holds if and only if

$$a_i^* \geq C_m - C_i \tag{S51}$$

In conclusion, a unique Nash equilibrium in which a given set of players contribute exists if the discount rate, δ, is sufficiently small, there are diminishing returns on investment, $h'' < 0$, and the cost (C_i) of the players that contribute is sufficiently large compared to the players with the largest costs (Eqs. (S47,S50)).

Role of the relative costs: no diminishing returns

To gain a better insight, we analyze here the special case in which there are no diminishing returns, namely, $h(A)$ is linear and is given by

$$h(A) = \alpha A, \tag{S52}$$

where α is a constant. In this special case, $h'' = 0$, and therefore, Eq. (S43) is not satisfied. However, as we will see, there still exist cooperative Nash equilibria in which the players are indifferent between keeping their contribution and deviating from it. The analysis of these Nash equilibria is meaningful because, with the presence of some small diminishing returns, $h'' \lesssim 0$, these Nash equilibria become more stable in the sense that the players are worse off deviating. In turn, the linear case (Eq. (S52)) is easier to analyze and enables us to gain some analytic insights.

Substitution of Eq. (S52) into Eq. (S3) implies

$$u_i = -\frac{C_i + a_i}{\alpha A}. \tag{S53}$$

Note that the strategies do not change if the utilities are multiplied by a constant, and therefore, the equilibrium strategies do not depend on α and we can set $\alpha = 1$ without loss of generality.

Consider a Nash equilibrium in which the set of players that contribute is given by K ($a_i^* > 0$ if $i \in K$ and $a_i^* = 0$ otherwise). Specifically, where $h(A) = \alpha A$, Eq. (S42) becomes

$$C_i + a_i^* = A \tag{S54}$$

if $i \in K$. Namely, for all $i \in K$,

$$C_i = \sum_{j \neq i} a_j. \tag{S55}$$

Specifically, this defines a set of n linear equations where n is the number of players that contribute ($n = |K|$). This set of equation can be written in the matrix form

$$\bar{\boldsymbol{C}} = M \bar{\boldsymbol{a}}, \tag{S56}$$

where $\bar{\boldsymbol{C}}$ is the vertical vector of all the costs (C_i) of the players that contribute ($i \in K$), $\bar{\boldsymbol{a}}$ is the vertical vector of the strategies (a_i) of these players, and M is the $n \times n$ matrix given by

$$M = \mathbb{1} - I, \tag{S57}$$

where $\mathbb{1}$ is the $n \times n$ matrix in which all the elements equal 1 and I is the $n \times n$ identity matrix. In turn, note that M is a regular matrix if $n \geq 2$, and therefore, the inverse matrix, M^{-1}, exists, and

$$\bar{\boldsymbol{a}} = M^{-1} \bar{\boldsymbol{C}}. \tag{S58}$$

In particular, note that

$$M^{-1} = \frac{1}{n-1} \mathbb{1} - I. \tag{S59}$$

It follows that

$$a_i = \frac{1}{n-1} \langle C \rangle_K - C_i, \tag{S60}$$

where $\langle C \rangle_K$ is the average value of all the costs (C_i) of the countries that contribute.

Finally, we need to find the conditions under which the solution given by Eq. S60 is a valid Nash equilibrium. Namely, we need to show that conditions (1), (2) and (3) hold. From Eq. (S44), if follows that if $a_j = a_j^*$ for all $j \neq i$, then $u_i(a_i)$ does not depend on a_i, and therefore, condition (1) holds (although in its marginal form).

In turn, condition (2) states that $a_i \geq 0$ for all $i \in K$, which implies that

$$C_i \leq \frac{n}{n-1} \langle C \rangle_K \tag{S61}$$

for all the countries that contribute. In turn, condition (3) implies that

$$C_j \leq A \tag{S62}$$

for all the countries that do not contribute. However, Eq. S60 implies that

$$A = \frac{n}{n-1} \langle C \rangle_K \,, \tag{S63}$$

and therefore, Eq. S61 coincides with Eq. S62 (conditions (2) and (3) coincide), where the condition must hold for all i, regardless of whether country i contributes. Therefore, a necessary and sufficient condition that the solution in Eq. S60 is valid is that

$$C_1 \leq \frac{n}{n-1} \langle C \rangle_K \,, \tag{S64}$$

where C_1 is the largest cost, regardless of whether country 1 participates or not. Note that $\langle C \rangle_K$ is the average cost among the participating countries only, and therefore, the condition implies that the average cost has to be sufficiently close to the largest cost.

Appendix E: Numerical methods

To calculate the Markovian Nash equilibrium for all G, we used a standard backward induction approach, in which a static game is solved in each time step. Specifically, since G can only increase over time, we could simplify the algorithm further by repeatedly solving the problem of how to move from some $G_0 - \Delta$ to G_0, starting with $G_0 = G_{\max}$, where Δ defines the resolution and can be chosen to be arbitrarily small. Specifically, that utilities of each static games are given by Eq. S3, as shown in Lemma 1, Appendix A. Therefore, the challenge is to find, for a given set of n countries, whether a Nash equilibrium exists in which these are the countries that contribute, and, if yes, to find that Nash equilibrium.

One method to find and analyze the Nash equilibrium graphically for 2 countries is to calculate, for every given contribution by country 2, the optimal contribution by country 1, $a_1^{\text{opt}}(a_2)$. Similarly, we calculate the function $a_2^{\text{opt}}(a_1)$. Then, plotting $a_1^{\text{opt}}(a_2)$ and plotting $a_1^{\text{opt}}(a_2)$ on a flipped axis (Fig. 4) provides a graphical way to find and to analyze the Nash equilibria (Fig. 4). Specifically, a Nash equilibrium appears at each intersection of these two lines. However, when $N \geq 3$, this method becomes harder to visualize. Specifically, each of the functions $a_i(a_{j\neq i})$ define an $(N-1)$-dimensional manifold in an N-dimensional space. Another difficulty arises as there are multiple Nash equilibria, and general algorithms for finding a Nash equilibrium may fall on any of these.

Therefore, we developed an algorithm that goes along the $(n-1)$-dimensional manifolds until it converges at the Nash equilibrium in which a given set of n countries contribute, or until the algorithm indicates that no such Nash equilibrium exists (Fig. S1). Specifically, the algorithm starts with assigning a small contribution to each country. Then, at each time step, the algorithm checks for each country, i, whether increasing a_i by ϵ increases $\mathcal{V}_i$. If the answer is yes, a_i is increased by ϵ ($a_i \to a_i + \epsilon$). If the answer is no, a_j is decreased by 2ϵ for all the other countries ($a_j \to a_j - 2\epsilon$ for all $j \neq i$). Fig. S1 demonstrates how this algorithm goes through the optimal manifolds until it approaches the Nash equilibrium. In turn, if at some point, for any i, $a_i \leq 0$, this indicates that there is no solution where all the n countries contribute. Otherwise, the algorithm terminates at a candidate Nash equilibrium. It only remains to verify that, for the remaining $N - n$ countries, $a_j = 0$ is the optimal strategy (and it is sufficient to verify that for the country with the largest benefits). Simulating this algorithm repeatedly with different subsets of countries enables us to find the various Nash equilibria (Figs. 2, 3).