Green R&D Clubs

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Abstract

Provision of global public goods necessitates coordination and cooperation between countries. This is particularly difficult in view of the fact that public goods allow for free riding. Moreover, if the costs of contributing is high the incentive to free ride on others' contributions becomes even more severe. A necessary part of the solution to sustain global cooperation is cost-reducing innovation. But the most risky and premature technologies often require heavy start-up costs. This model considers a scenario where the chance of ending up as the single developer that harvest all the revenue of a breakthrough technology is too small to tempt investments. When countries have no incentive to undertake unilateral innovation projects, we find they should conduct research jointly. We consider an environmental agreement that includes R&D cooperation, where countries cooperate both in the technology market and in abatement. A club has a higher chance of developing a successful technology and members share the sales revenues from licensing the innovation to non-members. We show that a green R&D club can sustain a higher number of members and thus more abatement than a one-dimensional IEA that focus on abatement-cooperation only.

Key words: Climate change, Research & Development, Technology cooperation, International cooperation, Self-enforcing international environmental agreements

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1 Introduction

Today's global economy face two related challenges. The main challenge is to combat climate change and overcome the damaging free rider incentives that prevents optimal contributions. A related issue is the low levels of investments in green R&D. In order to increase abatement levels we need to reduce abatement costs, which depends on the development of new cost-reducing technology. But R&D in premature technologies requires heavy start-up costs with small chances of success. In addition there are small chances of extracting sufficient revenue in the case of success. These factors are discouraging investments in green R&D.

In this paper we will consider a scenario where there are severe under-investments in abatement technologies and a Prisoners Dilemma situation in abatement contributions. We are interested to see whether this un-satisfying outcome can be improved by introducing a two-dimensional cooperation arrangement: A green R&D club. By combining the two present challenges we find that there exist possible Pareto improvements.

To date we do not know whether the nationally determined contributions (NDCs) made by the individual countries to the Paris agreement will be carried out. The current rate in global green house gas (GHG) emissions are not promising; global emissions increased from 2017 to 2018, inspite of the Paris Agreement ratified in 2016. Moreover, even if the NDCs are fulfilled, global temperatures are set to increase much more than the 1.5 degree target.

The results from 25 years of climate change negotiations are in line with the theoretic literature on international environmental agreements (IEAs). This literature has repeatedly stated that classical climate agreements, focusing mainly on emission reduction, cannot be expected to achieve much, see Hoel (1992), Carraro and Siniscalco (1993) and Barrett (1994). The free rider incentive prevents cooperation. The treaty that emerges from the negotiations have only two member countries, and abatement levels are very close to the non-cooperative outcome.

In this paper we analyze to what extent an R&D and climate club can hope to attract participation from more than two countries and whether such a club is likely to increase global abatement significantly. Our setup follows the classical framework by Barrett (1994) but adds an intermediate stage: the investment stage, where countries choose whether to invest in R&D in order to develop an improved technology.

In a classical IEA the investments in technology are unilateral if it is an option at all. In a club, on the other hand, the investment decision becomes cooperative in addition to collectively deciding abatement levels. In static IEAs the threat of leaving the coalition is inadequate. One less member only implies marginally less abatement. In our paper the potential threat of defection is larger. When leaving the club as the pivotal member, the club breaks down and the technology will not be invented. The R&D and climate club can sustain a higher level of members which commit to a higher abatement level.

The R&D is directed towards an cost-reducing abatement technology associated with so called breakthrough technologies (see Barrett (2006); Hoel and de Zeeuw (2010)). Examples in this category are carbon capture and storage (CCS) and fusion energy production (see for instance the May issue of The Economist (2019)). Innovation in premature technologies involves a severe risk of failure and the gain from investing in R&D is therefore highly uncertain. Countries are assumed to be risk neutral and welfare maximizing, and will only invest in R&D if it gives higher expected welfare.

If a country succeed in developing a new technology it gains reduced abatement costs, which will give more abatement in equilibrium, and possible market revenue from distributing the technology to other less successful countries. If a country is the only one succeeding it becomes the main provider of the new innovation and will behave like a monopolist. The monopolist licenses the developed technology to the rest of the world. The license fee is set equal to unsuccessful countries' willingness to pay. If more than one country succeed there will be several providers and the technology market becomes competitive and the license price falls to zero. The chance of becoming the single provider decreases as more countries invest in R&D. Unilateral incentives to invest will therefore depend on other countries actions. In our framework we study the special case where no country chooses to invest in the non-cooperative equilibrium. In cases where environmental externalities have not been fully internalized in market prices, it is likely that the investment level in relevant technologies are significantly below the socially desirable level.

In an R&D and climate club the investment decision and the abatement level becomes cooperative. The countries that sign a membership agree to share the license revenue in case of a success in the group of members, and all members access the technology for free. It is then no longer a single country's success that is important, but rather a success in the group of members, independent of which specific country that completed the innovation process. This illustrates the returns to scale in joining an R&D club: when pooling their resources the probability of inventing a successful technology increases. The cost however, is sharing the revenues with all members.

This model shows that in a world where no one performs R&D unilaterally, a club could find it beneficial to develop the technology. Establishing a club will give more abatement in equilibrium by all countries, both members and non-members. If the cost of abatement or the R&D start-up costs are sufficiently high an R&D and climate club can achieve full membership and reach the social optimal level of abatement.

The paper is organized as followed: Section 2 sums up the literature that focus on connecting IEAs and technology development. Then, section 3 introduces the model framework. The R&D and climate club is outlined in section 4. Section 6 ends the paper with a discussion of the results and possible extensions.

2 Literature

The challenge for international cooperation on global climate issues is to decrease or avoid the mechanisms that cause free-rider incentives. Free riding is especially problematic at the international level, where global regulatory institutions are not available. Free riding on international cooperation leads so insufficient participation (too few countries join IEAs) and insufficient compliance (the treaty is not stable and members opt out over time).[1]

To figure out how to improve future IEAs the literature has suggested issue linkage. For a long time this has been proposed in both the economic (Cesar and de Zeeuw, 1996; Carraro and Marchiori, 2004; Barrett, 2006) and the political science literature (Davis, 2004; Urpelainen, 2013; Hovi et al., 2017). Linkage connects environmental negotiations to other interrelated economic issues, typically a club-good whose benefits are exclusive to its members and thus cannot be reaped by free-riders. (See Maggi (2016) for a comprehensive literature review on linking issues in international cooperation).[2]

Common examples of linked issues are trade (access to inner markets) or research cooperation (access to an improved technology). An unstable IEA (public good) combined with a stable R&D agreement (club good) may increase the participation rate up to a certain threshold, (but not necessarily full participation which is the case in Carraro and Siniscalco (1997)). Issue linkage implies that countries signing a membership are required to hold simultaneous membership in both treaties. In the real world we do observe that countries cooperate in several policy dimensions at the same time when entering agreements and coalitions such as NATO, UN, WTO/GATT, EU and ASEAN. Another example is the Montreal Protocol which regulated the members' production of CFC gases in addition to prohibiting trade in CFCs with non-members. It has been suggested that this connection of policy issues was key to the protocol's success and the restoration of the Ozon layer.

Considering climate change and mitigation the link between abatement policy and abatement-cost technology has been seen as intrinsic since innovation is crucial for combating climate change (as in Hoffert et al. (2002)). Both issues are somewhat connected

[1]This two-parted separation of the free rider incentives was introduced by Finus (2008) in order to categorize the two main approaches in the literature of IEAs: Reduces stage games study insufficient participation and infinitely repeated games investigates compliance.

[2]Maggi (2016) distinguishes between three types of linkage, and the categories relate to three different analytical methods: Enforcement linkage typically focus on repeated games; negotiation linkage typically focus on bargaining games; and participation linkage typically focus on simple coalition-formation games (in contrast to the division by Finus and Caparrós (2015) which discusses issue linkage concerning Membership models and Compliance models, but not Negotiation models). Our R&D and climate club belongs to the third category considering coalition-formation games.

already and many existing policies target both issues. The literature connecting IEAs to innovation is widespread and several approaches has been explored. Barrett (2006) concludes that in general the focus on technology development cannot improve the performance of IEAs unless technology adoption involves increasing returns due to knowledge spillovers or network externalities. On the other hand, Hoel and de Zeeuw (2010) show that if the adoption costs of a breakthrough technology vary with the level of R&D, it can result in a large stable coalition.

Buchholz and Konrad (1994) considered a possible "hold-up problem" that might arise if technology choice precedes agreements on abatement. Then countries have an incentive to commit to low-quality technologies before they enter the negotiation of the agreement. In this way research effort might decrease prior to negotiations. However, Harstad (2012) shows that in a dynamic context where both size and length of the agreement is negotiated, the hold up problem may actually be beneficial. If agreements can be renegotiated it enables countries to design an agreement that achieve social optimal level of R&D investments and emissions. In our static approach there is no discussions of the hold-up problem.

As we construct a simple framework without differentiating between sectors, other scholars have studied a similar approach in a more specific manner. As an example, Strand (2007) considers technology treaties aimed at alternative energy sources, replacing fossil fuels. This framework investigate how such treaties affect the incentives of fossil fuel producers, and how it might motivate them to extract more and at a faster rate, which again raise aggregate emissions. We do not specify sectors and are therefore not modeling their response to the club.

de Coninck et al. (2008) discuss international technology-oriented agreements (TOAs) as part of constructing international climate-change policy. They outline four categories for organizing R&D pooling: (i) Knowledge sharing and coordination, which include meetings, planning, informational exchange and coordinating the research agenda. (ii) R&D agreements, which include jointly research, funding commitments and mutual agreements to expand domestic research investments. (iii) Technology transfers (financing research projects across borders) and (iv) Technology deployment mandates such as renewable portfolio standards. In our model the R&D and climate club belongs to the second category of TOAs where research effort is pooled in order to achieve a shared success.

One might ask whether there actually are underinvestments in abatement technologies compared to other types of R&D. Although it is hard to find data on global aggregate R&D spending on dirty and clean technologies, several sources indicate that the former greatly outperforms the latter. Aghion et al. (2016) find that the number of new patents is higher within dirty transportation technologies. Jaffe et al. (2003) argue that there are several economic rationales for why R&D in climate relevant technologies are especially vulnerable for underinvestment. When the abatement exernality is not taken into account, countries do not see the need for an improved technology that reduces costs when abating more. The market for R&D in abatement technologies relies heavily on the stability of domestic and international policy, and in case of an insufficient IEA R&D-investments will be too low.

Another possible reason for under-investment is knowledge spillovers, non-excludability and public benefits. Then the developer is unable to capture the full revenue of its investments, which reduces the incentives to perform R&D. However, this will depend on the type of technology considered, and to what degree one is able to fully exclude free riders. We will assume that international intellectual property rights are fully enforced, and that countries manage to protect their research from leaking to other countries. Our purpose is not to investigate the spillover externality[3], but the returns to scale that emerge when countries manage to share the gains from their joint research. This is the reason for why we name our type of linkage a club and not a technology treaty.

In a seminal paper, Buchanan (1965) outline the theory of clubs, by considering collective ownership-consumption arrangements where agents choose to organize themselves in cooperative groups. He considered clubs as a private alternative to the optimal provision of a special class of public goods, later known as club goods. In this framework club members coordinated their actions in order to maximize the welfare of the group. In this way one member's cooperative action becomes Pareto optimal for all members.

Clubs can be defined as organizations whose members collectively produce/consume a good that no single member find it beneficial to provide or finance alone. In order to sustain the club it must be possible to exclude outsiders from taking part of the good the club provides. The good must therefore be characterized with some degree of excludability, and clubs will accordingly never provide pure public goods. A club good is a subtype of public goods which is non-rival in consumption but possible to exclude others from using. It can be discussed whether innovations and technology actually can be excludable at all, as this would depend on the enforcement of intellectual property rights and patents.

[3]This has been studied by El-Sayed and Rubio (2014), which builds on the framework of Kamien et al. (1992), where countries cooperate on R&D investments to fully internalize spillover effects but act non-cooperatively in their abatement decision. This agreement promotes cooperation, but the effects on participation is modest. Kamien et al. (1992) analyze different ways of coordinating research in order to internalize knowledge spillovers, where R&D spillovers are internalized when firms pool their research effort.

3 The model

3.1 Preliminaries

Standard self-enforcing IEA models consider a two-stage game of coalition formation; Membership stage and abatement stage. In the first stage, referred to as the membership stage, countries decide whether to sign the agreement and join a climate coalition. In the second stage, the abatement stage, countries choose their contributions to the public good. We introduce an intermediate stage in which countries can choose to invest in their R&D sector. If someone successfully develops the technology, it will be distributed to everyone. Whether adopting countries access the technology for free depends on the level of competition in the technology market. Countries that adopt the technology experience reduced abatement costs, such that abatement levels will depend on technology access. It is therefore logical that the abatement stage is after the investment stage and the revealed result from the research process, se the timeline below. In order to investigate whether

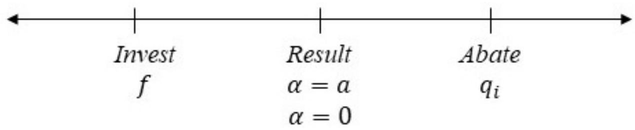

Figure 1: The intermediate stage

extending cooperation into the R&D field is worth following, we need to look at the non-cooperative outcome with the possibility of doing individual R&D.

3.2 Optimal abatement without a club

Consider a world of $N > 2$ countries. We assume countries are symmetric, denoted by $i \in I$, where $I = \{1, ..., N\}$. Each country emits a pollutant that disturbs a shared environmental good, such as the atmosphere. A contribution to the public good is interpreted as one unit of abatement (pollution reduction), where q_i is the national abatement level. We choose to rule out strategic abatement decisions across countries by assuming linear benefits of abatement. The benefit of abatement to each country is then given by:

$$B(q_i; Q) = \beta Q + \sigma q_i \tag{1}$$

where $\beta > 0$ is a positive constant equal for all countries, $\sigma \geq 0$ is local co-benefits of national abatement and $Q = \sum_{i=1}^{N} q_i$ is the global aggregate abatement level.

The abatement cost is increasing and convex and its curvature depends on whether a technological breakthrough has happened.[4] Thus, each country has abatement costs

[4] As mentioned the technological breakthrough can be usable fusion energy, cheap carbon capture and

(absent of any patent licensing costs):

$$C_i(q_i;\alpha) = c\frac{(q_i)^2}{2} - \alpha q_i \quad \text{where} \quad \alpha = \{0, a\} \tag{2}$$

where $c > 0$ and $\alpha = \{0, a\}$ is the cost reducing abatement technology and $a > 0$ denotes "the size" of the technological breakthrough, i.e., a higher α implies a better technology and a larger shift in the marginal cost curve. If $\alpha = 0$ the research process failed or the country has not adopted the technology on the market. Country i abatement decision (net of investment or licensing costs) follows from (1) and (2), which is maximized with respect to the national abatement level q_i. We will refer to this term as net benefit of abatement:

$$U_i = \beta\sum_{i=1}^{N} q_i + (\sigma + \alpha)q_i - c\frac{(q_i)^2}{2} \quad \text{where} \quad \alpha = \{0, a\} \tag{3}$$

In the case where no climate club is formed, each country sets individual abatement levels, taking as given the abatement levels by the other countries. This yields the following non-cooperative abatement levels, where $q^{NC}(a)$ and $q^{NC}(0)$ denotes with and without the technology respectively, (we simplify notation by skipping the individual country notation i as countries are symmetric):

$$q^{NC}(\alpha) = \frac{\beta + \sigma + \alpha}{c} \quad \text{where} \quad \alpha = \{0, a\} \tag{4}$$

Note that the optimal abatement level is increasing in the size of a. Adopting the technology increase abatement levels. A technological breakthrough may happen as a consequence of other countries' R&D investments, or it may follow from the R&D investment of the country itself. Given that all countries choose the same abatement level, we denote the non-cooperative (NC) net benefit of abatement by $U^{NC}(\alpha)$, which depends on success in the R&D sector:

$$U^{NC}(\alpha) = \frac{(\beta(2N-1) + \sigma + \alpha)(\beta + \sigma + \alpha)}{2c} \quad \text{where} \quad \alpha = \{0, a\} \tag{5}$$

Note that net benefit of abatement is always strictly higher when everyone access the technology, which implies that the technology is a global welfare improvement, hence $U^{NC}(a) - U^{NC}(0) = \frac{a(2N\beta + 2\sigma + a)}{2c} > 0$.

3.3 Innovation without a club

At the outset, each country has an innovating technology sector which performs negligible research on abatement technologies. A country can boost this research activity with

storage or re-chargeable batteries able to compete with gasoline energy storage per $ and and volume.

substantial investments in order to increase its chances in developing a breakthrough technology. All countries that support its innovation sector competes in becoming the global leader in clean technology. The global leader will obtain a patent on the technology and as the single supplier it is able to extract income from licensing the patent to other non-successful/non-investing countries.

In the case of a global leader/monopoly supplier of the technology, everyone else needs to decide whether its beneficial to pay the license and adopt the technology ($U_i^A - \ell$) compared to not adopting (U_i^{NA}). This decision is strategic. Since each country's abatement level is increasing in the technology, every country's decision to adopt benefit everyone else. Suppose that $x \in [0, N-1]$ countries has already adopted the innovation, then country i will become the $x+1$ country that adopt if the following condition holds:

$$U_i^A(x+1) - \ell \geq U_i^{NA}(x)$$

$$\Leftrightarrow$$

$$\begin{aligned}\beta(N-x-1)q^{NC}(0) + [\beta(x+1)+\sigma+a]q^{NC}(a) - \frac{c(q^{NC}(a))^2}{2} - \ell \\ \geq \beta x q^{NC}(a) + [\beta(N-x)+\sigma]q^{NC}(0) - \frac{c(q^{NC}(0))^2}{2}\end{aligned}$$

that is, if the individual country's net benefit of abatement is higher by adopting the new technology $\alpha = a$ and paying the license, than by staying with the old, "generic" technology $\alpha = 0$. Inserting for (4) and solving for the license fee:

$$\ell \leq \frac{\alpha}{2c}(2\beta + 2\sigma + a) \equiv \ell^* \tag{6}$$

Since x, the number of other adopting countries, does not appear in the expression of ℓ^*, we can conclude that if the single supplier sets $\ell = \ell^*$, all non-innovating/non-successful countries will adopt the innovation. Moreover, for any license above ℓ^*, no country will adopt the innovation, and thus ℓ^* is optimal. The license income to the single supplier is equal to the license times the number of countries adopting the innovation, which is everyone else: $(N-1)\ell^*$. The monopolist's license rent is then $(N-1)\frac{a}{2c}(2\beta + 2\sigma + a)$.

In order to participate in the R&D race a country needs to decide whether to invest. Supporting the national R&D sector requires a fixed cost f. The investment decision is binary, either a country invest $f > 0$ or it chooses not invest and $f = 0$. Furthermore, every country that applies this investment effort has a probability p of discovering a breakthrough technology. We assume that the research process is independent (there are no network effects, no spillovers and no increasing returns) which gives a fixed probability for every R&D process in each symmetric country. In addition we assume the research has a binary outcome, either the development is successful ($\alpha = a$) or it fails ($\alpha = 0$). The final important factor is the fixed number of countries that invest, which gives us a fixed number of trials in the global economy. These three characteristics correspond to the Binomial probability distribution, where the number of success is Binomially distributed.[5]

We assume countries are unable to organize without the club and that if two or more countries succeed the license income will be competed away. Thus, when a country decides to invest f, there are four possible outcomes; (i) the country becomes the sole owner of the patent and earns the license income, (ii) some other country becomes the sole owner of the patent and the country has to pay the license, (iii) two or more countries come up with the patent and the license is competed away or lastly (iv) the innovation does not occur. Consider a Nash equilibrium in which $y \in [0, N-1]$ countries invest. In such an equilibrium, an additional country that invests may earn the following expected welfare:[6]

$$\mathbb{E}_i[W_I^{NC}] = (1-p)^{y+1}U^{NC}(0) + (1-(1-p)^{y+1})U^{NC}(a) + (N-1-y)p(1-p)^y\ell^* - f$$

We see that expected license income is zero if $y = (N-1)$, i.e., if every other country except i is investing. In case country i does not invest, the country earns the following expected welfare:

$$\mathbb{E}_i[W_{NI}^{NC}] = (1-p)^y U^{NC}(0) + (1-(1-p)^y)U^{NC}(a) - yp(1-p)^y\ell^*$$

Thus, the investment criterion for the $y+1$ country is:

$$\mathbb{E}[W_{NI}^{NC}] < \mathbb{E}[W_I^{NC}]$$

$$\Leftrightarrow$$

$$f < p(1-p)^y\left[U^{NC}(a) - U^{NC}(0) + (N-1)\ell\right] \tag{7}$$

As stated we are interested in a severe under-investment problem in green R&D, in line with what we experience in the abatement sector today. Neglectable investment levels will most likely not cause the needed technological breakthrough that is necessary. We therefore assume that this breakthrough technology require a investment effort larger than any unilateral country is willing to accept. We assume that (7) does not hold for $y = 0$:

[5]The probability mass function of a binomial random variable S is $P(S = s) = \binom{k}{s}p^s(1-p)^{k-s}$, where s is the number of successes from k trials. Then the probability that "at least two" succeed is given by $\left[1 - P(S = 1) - P(S = 0)\right]$ where $P(S = 0) = (1-p)^k$ and $P(S = 1) = kp(1-p)^{k-1}$.

[6]This expression is outlined in Appendix A

Assumption 1.

$$f \geq p\big[U^{NC}(a) - U^{NC}(0) + (N-1)\ell\big] \tag{8}$$

Observe that since $p(1-p)^y < p < 1$, condition (7) cannot hold for any y due to the assumption in (8). The condition determines the minimum level of f for which the model is valid:

$$f^{min} = p\big[U^{NC}(a) - U^{NC}(0) + (N-1)\ell\big]$$

inserted for (5) and (6), condition (8) yields $f^{min} = p\frac{a}{2c}\big[2(2N-1)\beta + 2N\sigma + Na\big]$. Thus, given that (8) holds, the only Nash equilibrium is that no country invests unilaterally. Hence, no clean technology breakthrough will happen in the non-cooperative equilibrium. The question is then whether a green R&D club can facilitate a clean technological breakthrough and improve the equilibrium outcome.

4 The green R&D club

In a green R&D club members cooperate in two dimensions: First they act as one unity in the market for technology, secondly they choose their abatement levels cooperatively. Their interest is to achieve at least one success in the group of member countries, and are therefore more likely to end up as the monopoly supplier. In the case of success members share the revenue from the license fee. The shared revenue from licensing the technology to $(N-m)$ non-members is given by $(N-m)\ell^*/m$, where $m \geq 2$ denotes the number of members in the club. Since the license fee is independent of club members, the licensing revenue is decreasing in the number of members.

Members access the technology at a zero price, $\ell_m = 0$, while the club charges a positive license fee on non-members, $\ell_n = \ell^*$. The agreement enters into force if at least $\tilde{m}$ countries join the R&D and climate club. Each member must invest the fixed cost f when the number of members meet the ratification threshold.

The game sequence of the R&D and climate club is as follows:

1. Membership stage: Each country decides whether to join the R&D and climate club
2. Investment stage:

   ($2a_1$) Non-members do not invest[7] $f = 0$

   ($2a_2$) Club members invest $f > 0$

[7]Follows from the assumption in (8)

(2b) If the research was successful ($\alpha = a$): The club sets the license $\ell_n = \ell^*$ such that all non-members buy the technology

3. Abatement stage:

(3a) If the research was successful ($\alpha = a$): Members decide their abatement level, q^m, cooperatively

(3b) Non-members $(N - m)$ behave non-cooperatively and set $q^{NC}(a)$:

We solve the game by backward induction.

4.1 Optimal abatement with a club

Club members set abatement levels cooperatively by taking into account the positive external effect of abatement on other members. We assume that if no innovation occurs $\alpha = 0$, the club will dissolve itself, and the members will choose the non cooperative abatement level as given by (4). A single club member's net benefit of abatement, given a success in green R&D:

$$U^m = (N - m)\beta q^{NC}(a) + (m\beta + \sigma + a)q^m - c\frac{(q^m)^2}{2} \tag{9}$$

Maximizing (9) yields the following abatement levels:

$$q^m = \frac{(m\beta + \sigma + a)}{c} \tag{10}$$

Inserted for (4) and (10) in (9) yields $U^m = \frac{(m\beta+\sigma+a)^2+(N-m)2\beta(\beta+\sigma+a)}{2c}$, such that club members' net benefits of abatement is increasing in the number of members: $dU^m/dm > 0$ and $d^2U^m/dm^2 > 0$ $\forall m \geq 2$. Given that a research success occurs, a country that choose not to sign a club membership will free ride on the abatement and research effort of members, as well as licensing the technology from the club. Net benefit levels for non-members/free riders of the club yields:

$$U^{FR} - \ell^* = m\beta q^m + \big((N - m)\beta + \sigma + a\big)q^{NC}(a) - c\frac{(q^{NC}(a))^2}{2} - \ell^* \tag{11}$$

where the first term is the external benefit from all club members that abate cooperatively, the second term is the external and local benefit when $(N - m)$ countries choose to free ride on abatement levels but adopting the technology. Inserted for (4), (6) and (10) yields $U^{FR} - \ell^* = \frac{[(2N-1)+2m(m-1)]\beta^2+(2N\beta+\sigma)\sigma+2(N-1)a\beta}{2c}$. However, if no breakthrough occurs, $\alpha = 0$, the club implode and net benefit of abatement for members and non-members is given by $U^{NC}(0)$.

4.2 Innovation with a club

As already stated in Assumption 1, a single country has no incentive to invest unilaterally, independent of how many other countries that choose to invest. This implies that non-member countries still are discouraged from investing even if the club invests. Even though the cost of research investments is unchanged, the probability of success increases in the number of members. For the club to become the technology provider it only needs a single success in the group of member countries. The probability that at least one member is successful is given by $P(S \geq 1) = 1 - P(S = 0)$ which can be written as:

$$P(m) = 1 - (1 - p)^m \tag{12}$$

where m is the number of trails. The probability is increasing at a diminishing rate in the number of members $m \in [2, N]$, such that $P'(m) > 0$ and $P''(m) < 0$. If the a club member choose to invests, the single member have the following expected welfare:

$$\mathbb{E}[W^m] = P(m)\Big[U^m + \frac{N-m}{m}\ell^* - f\Big] + \big(1 - P(m)\big)\big[U^{NC}(0) - f\big] \tag{13}$$

where the term $P(m) = 1-(1-p)^m$ is the probability that at least one member develops the breakthrough technology. With probability $(1 - P(m))$ the club's R&D process fails, and each country obtains $U^{NC}(0)$ i.e., the Nash equilibrium from the no club scenario, as above. A country will join the club if it improves or is equal to its outside option ($U^{NC}(0)$). Thus, the investment criterion for a single member of the club is $U^{NC}(0) \leq \mathbb{E}[W^m]$. Inserting for (13) yields the following condition:

$$0 \leq P(m)\Big[U^m - U^{NC}(0) + \frac{N-m}{m}\ell^*\Big] - f \tag{14}$$

We see that this collapses to (8) if $m = 1$, and will by assumption never hold. Hence, condition (14) only applies for $m > 1$.

We assume that membership is voluntary, but that the club restrict the minimum number of members to a "ratification threshold", such that club members do not invest before this threshold is met. The ratification threshold, m^*, is given by the number of members that equalize condition (14), i.e., $\mathbb{E}[W^m(m^*)] = U^{NC}(0)$ which yields:

$$0 = P(m^*)\Big[U^m(m^*) - U^{NC}(0) + \frac{N-m^*}{m^*}\ell\Big] - f^*$$

As the club dissolves at $m^* - 1$, a member will never leave the club if the threshold is met, i.e., if the country is the pivotal member which ensures the club meets the ratification threshold and enters into force. One less member would implode the club before the technology is developed and give everyone the non-cooperative equilibrium net benefit

$U^{NC}(0)$ – which is a severe threat: Not only does everyone abate non-cooperatively, the welfare improving technology will not be developed nor distributed. As long as the free rider incentive dominates the club welfare at $m^* + 1$, no more than m^* countries will join the club and everyone else $(N - m^*)$ will choose to free ride. Moreover, If the threshold is met and there exist a club, no excess country benefit from joining the club since the welfare from free riding always dominates:

$$U^{FR}(m^* + 1) - \ell^* \geq \mathbb{E}\left[W^m(m^*)\right] = U^{NC}(0)$$

$$\Leftrightarrow$$

$$[2(m^* + 1)m^* + 1]\beta + 2(N - 1)a \geq 0$$

This implies that the threshold m^* is internally and externally stable.[8] The threshold exist as long as the right hand side of (14) increases as long as the marginal increase in club net utility $dU^m/dm > 0$ dominates the marginal decrease in license revenue $-N\ell^*/m^2$ for all $m \in [2, N]$. Moreover, the expression on the right hand side may increase in m for low probability levels, which implies that a club member finds it worthwhile to invest if m is sufficiently high. This gives us the following proposition[9]:

Proposition 1. *There exist two stable equilibriums: $m = 0$ and $m = m^*$*

Proof. A sufficient, but not necessary condition is that:

$$0 < \frac{dU^m}{dm} - \frac{N}{m^2}\ell^* \quad \forall m \in [2, N]$$

$$0 < 2m^2(m - 1)\beta^2 - Na(2\beta + 2\sigma + a) \quad \forall m \in [2, N]$$

□

The stable equilibrium threshold $m^* \geq 2$ determines the size of the club, but the equilibrium is not unique. In equilibrium m^* countries abate q^m and invest f and $(N - m^*)$ countries license the technology but abate non-cooperatively. But we cannot say which

[8] The concept of internal and external stability is based on D'Aspremont et al. (1983) and first applied to IEAs by Barrett (1994). This has become the regular stability criteria for all frameworks with reduced stage games. Let I^m denote the set of members and I^{FR} denote the set of non-members, such that $I^m \cup I^{FR} = I$, then the definition of stability is given by:

Definition 1. A coalition is Internally Stable (IS) if there is no incentive for a member to leave the coalition, and a coalition is Externally Stable (ES) if there is no incentive for a non-member to join.

[9] An numerical illustration of the proposition can be found in appendix B

countries, and it therefore exist multiple equilibriums with all possible set of countries as members.

Figure 2 is a general illustration of the game and the club threshold's stability (the details of the figure depends on parameter values and for simplicity we draw the welfare payoffs as continuous). The figure is from a single country's point of view, such that the horizontal axis measures the number of *other countries* that has joined the R&D club. Whether it is best for a country to become a member depends on the other countries' choices. And since all countries are identical, this figure is precisely the same for each country. We see that if $m^* - 1$ countries has agreed to join the club (but its not ratified), country i would always choose to join as well in order to ratify the club and receive the higher expected welfare. It is important to notice that as m^* is the minimum level of participation, it also determines the max - since no countries has the incentive to join a club with $m^* + 1$ members. We see from the figure that the free rider incentive always dominates the club's expected welfare above m^*. When the two payoff functions cross, as

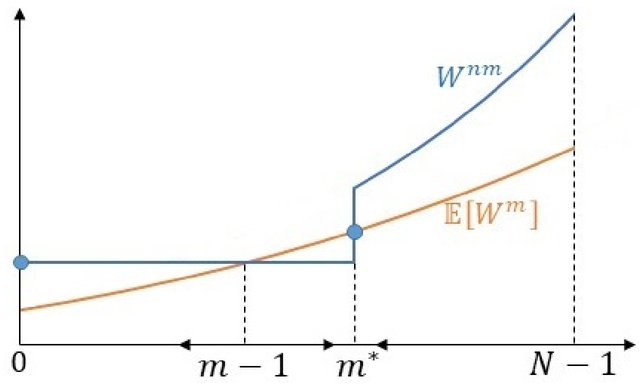

Figure 2: The R&D club

in Figure 2, there is multiple of pure strategy equilibria for each combination of countries that choose to join/free ride. We cannot say which *other* $m^* - 1$ countries that joined the club. All these equilibriums are inefficient when $m^* < N$, but the new equilibrium is an improvement relative to the non-cooperative.

5 Extensions

5.1 Variable investment and size of the breakthrough

In this section we look at the case in which each country can influence the "quality of the innovation" through its clean R&D investment f_i. The investment effort $f_i \in R^+$ is now connected to the size of the breakthrough $\alpha = a_i$, in the following way:

$$a_i \equiv \zeta f_i - \gamma \tag{15}$$

where $\zeta > 0$ and $\gamma \geq 0$. As before each country that redirects its innovation activity has a probability p of success from any investment effort f_i. In order to start the R&D process the investment needs to be sufficient such that $a_i > 0$, i.e., $f_i > \gamma/\zeta \equiv \bar{f}$. Where $\bar{f}$ is the minimum level required to start up a clean technology program. (For simplicity, we do not allow the probability p to be dependent of f_i). The license fee will be the same as before, replacing (15) in (6):

$$\ell_f = \frac{\zeta f_i - \gamma}{2c}(2\beta + 2\sigma + \zeta f_i - \gamma) \tag{16}$$

We denote non-cooperative net benefit, given that everyone choose the same abatement levels, by $U^{NC}(0)$ and $U^{NC}(a_i)$ for the scenarios without and with a technological breakthrough, respectively.

5.1.1 No club

As before, when a country decides to invest f_i, there are four possible outcomes in the *no club* case: (i) the country becomes the sole owner of the patent and earn the license income, (ii) another country becomes the sole owner of the patent and the country has to pay the license, (iii) two or more countries come up with the patent and the license is competed away or lastly, (iv) the innovation does not occur since everyone's R&D fails. Consider a Nash equilibrium in which $x \in [0, N-1]$ countries invest. In such an equilibrium, an additional country that invests may earn the following expected welfare:

$$\mathbb{E}_i[V_I^{NC}] = P(x+1)U^{NC}(a_i) + [1 - P(x+1)]U^{NC}(0) + (N-1-x)p(1-p)^x \ell_v - \phi f_i$$

where $P(x+1) = (1-(1-p)^{x+1})$ and $\phi > 0$ is the social cost of clean R&D investment. Inserting for (5), (6) and (15) we can take the derivative with respect to f_i. We can solve for the optimal investment level for a single country as a function of x:

$$f_i^*(x) = \frac{c\phi - \zeta P(x+1)(\sigma + N\beta - \gamma) - \zeta(N-1-x)p(1-p)^x(\beta + \sigma - \gamma)}{(P(x+1) + (N-1-x)p(1-p)^x)\zeta^2} \qquad \forall x \in [0, N-1]$$

Since all countries are symmetric, they will all invest the same amount. If no one else is investing, $x = 0$ then the optimal investment level for country i becomes:

$$f_i^*(x=0) = \frac{c\phi - p\zeta[(2N-1)\beta + N(\sigma - \gamma)]}{Np\zeta^2} \tag{17}$$

If everyone else invest, $x = N - 1$ then the optimal investment level for country i becomes:

$$f_i^*(x = N-1) = \frac{c\phi - P(N)\zeta(N\beta + \sigma - \gamma)}{P(N)\zeta^2}$$

The technology must be larger than zero: $a_i = \zeta f_i - \gamma > 0$:

$$f_i^* > \gamma/\zeta$$

$$\Leftrightarrow \quad c\phi/\zeta - P(x+1)(\sigma + N\beta) - (N-1-x)p(1-p)^x(\beta + \sigma) > 0$$

The optimal investment level is decreasing in the number of investors, $f_i'(x) < 0$:

$$\frac{df_i^*(x)}{dx} = \frac{(1-p)^x}{\big[P(x+1) + (N-1-x)p(1-p)^x\big]^2\zeta}$$
$$\Bigg(\Big(p(N-1-x)((N+1)\beta + 2\sigma - 2\gamma) - [(N-x)p - 1]c\phi/\zeta\Big)\ln(1-p)$$
$$+ p\Big[xc\phi/\zeta + P(x+1)((1-xN)\beta + \sigma(1-x) - \gamma(1-x)) + (1-x)(N-1-x)p(1-p)^x(\beta + \sigma - \gamma)\Big]$$

Consider the case where country i does not invest and earns the following expected welfare:

$$\mathbb{E}_i[V_{NI}^{NC}] = P(x)U^{NC}(a_i) + [1 - P(x)]U^{NC}(0) - xp(1-p)^x\ell_v$$

Thus, the investment criterion for the $x+1$ country is:

$$\mathbb{E}_i[V_{NI}^{NC}] < \mathbb{E}_i[V_I^{NC}] \quad \Leftrightarrow \quad \phi f_i^*(x) < p(1-p)^x\big[U^{NC}(a_i) - U^{NC}(0) + (N-1)\ell_v\big] \tag{18}$$

Inserting (5), (16) and (17), it follows that country i always prefer to invest, when no one else is investing $x = 0$, if the following holds:

$$\phi f_i^*(x=0) < p\big[U^{NC}(a_i) - U^{NC}(0) + (N-1)\ell_v\big]$$
$$\Leftrightarrow \quad 0 < N\gamma 2c\phi - \Big(c\phi - p\zeta[(2N-1)\beta + N\sigma]\Big)^2$$

5.1.2 Club when no one invest in unilateral equilibrium

Assume for simplicity that the optimal investment level in the non-cooperative framework are less than required $f_i^* < \zeta/\gamma$ or there is no incentives to invest, $\mathbb{E}_i[V_{NI}^{NC}] \geq \mathbb{E}_i[V_I^{NC}]$, such that all countries are discouraged from investing in the non-cooperative Nash equilibrium. In case of a club, the members pool their R&D resources such that they exploit possible spillovers:

$$a_m \equiv \zeta f_m - \gamma \tag{19}$$

where f_m is the club's total investment effort $\sum_{i=1}^m f_i = f_m$.

Consider the case where no non-members invest in the technology. If the club obtains the patent, it shares the income between its members and net benefit of abatement is given by

$$U_{f_m}^m = (N-m)\beta q^{NC}(a_m) + (m\beta + \sigma + \zeta f_m - \gamma)q^m(a_m) - c\frac{(q^m(a_m))^2}{2}$$

where $q_m(a_m) = \frac{m\beta+\sigma+\zeta f_m-\gamma}{c}$ is the club's abatement level. The club then maximizes its expected collective welfare from investing the aggregate amount f_m:

$$\max_{f_m} \quad \mathbb{E}[V^m] = P(m)\Big[m\Big(U_{f_m}^m + \frac{N-m}{m}\ell_{f_m}\Big)\Big] + \big(1-P(m)\big)mU^{NC}(0) - \phi f_m$$

where $P(m) = \big(1-(1-p)^m\big)$ is the club probability of an success and the license charged is given by $\ell_{f_m} = \frac{\zeta f_m-\gamma}{2c}\big(2\beta+2\sigma+\zeta f_m-\gamma\big)$. Inserting for (5), (9), and (16) and maximizing with respect to f_m gives the optimal investment level for the club as a whole:

$$f_m^*(m) = \frac{c\phi/\zeta - P(m)\Big[(m+1)(N-m)\beta + m^2\beta + N(\sigma-\gamma)\Big]}{P(m)N\zeta} \tag{20}$$

Each member of the club commits to invest f_m/m and abate $q_{f_m}^m = (m\beta+\sigma+\zeta f_m-\gamma)/c$ if an innovation happens. A single member choose to join a club if the expected welfare of becoming a member is greater or equal to the non-cooperative Nash equilibrium:

$$\mathbb{E}[V^m(m)]/m \geq U_0^{NC} \tag{21}$$

The optimal number of members m^* is given by:

$$\mathbb{E}[V^m(m^*)]/m^* = U_0^{NC}$$

Proposition 2. *For a single county, being a club member is a dominant strategy for any number of members less than the threshold, $m < m^*$, which implies that the club threshold* *is a stable (but not unique) equilibrium and no initial push is needed.*

Proof.

$$
\begin{aligned}
U^{NC}(0) &\leq \mathbb{E}[V^m]/m \\
c\phi f_m &\leq P(m)\Big[\big[m(N-1)\beta + N(\beta+\sigma)\big](\zeta f_m - \gamma) + \frac{m(m-1)^2\beta^2}{2} + \frac{N}{2}(\zeta f_m - \gamma)^2\Big]
\end{aligned}
$$

□

The Free rider incentive is always dominating if:

$$U^{FR}(m^*) - \ell_{f_m}(m^*) > \mathbb{E}[V^m(m^*)]/m^* = U_0^{NC}$$

where $U^{FR} - \ell_{f_m}(m^*) = \frac{[(2N-1)+2m^*(m^*-1)]\beta^2+(2N\beta+\sigma)\sigma+2(N-1)\beta(\zeta f_m-\gamma)}{2c}$.

$$2m^*(m^*-1)\beta^2 + 2(N-1)\beta(\zeta f_m^*(m^*) - \gamma) > 0$$

5.2 Time consistency

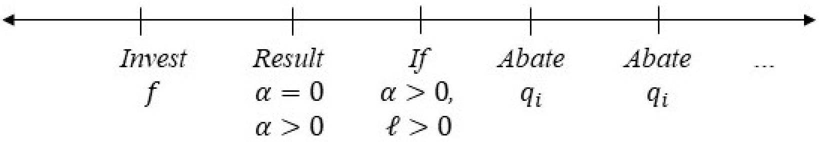

Figure 3: The model in a longer time-perspective

We could consider a dynamic version of the model, to see whether the club is stable over time. Suppose that after the technology has been successfully developed members do not need to invest $f > 0$. Countries will re-optimize to find out whether its beneficial to opt out of the club and instead free ride. As a non-member they abate less, but the technology would no longer be free. Members abate more, but receive the revenue from licensing the technology. A country would prefer to stay member as long as:

$$
\begin{aligned}
(\hat{m}-1)\beta q^m(\hat{m}-1) + (\beta(N-(\hat{m}-1)) + \sigma + \alpha)q_\alpha^{NC} - c\frac{(q_\alpha^{NC})^2}{2} - \ell \leq \\
(N-\hat{m})\beta q_\alpha^{NC} + (\hat{m}\beta + \sigma + \alpha)q^m(\hat{m}) - c\frac{(q^m(\hat{m}))^2}{2} + \frac{N-\hat{m}}{\hat{m}}\ell
\end{aligned}
$$

This condition would depend on how many countries that are free riders, hence, the number of members. Some terms cancels out and we can rewrite the condition into:

$$(\hat{m}\beta + \sigma + \alpha)q^m(\hat{m}) - c\frac{(q^m(\hat{m}))^2}{2} + \frac{N}{\hat{m}}\ell \geq (\hat{m}-1)\beta q^m(\hat{m}-1) + (\beta+\sigma+\alpha)q_\alpha^{NC} - c\frac{(q_\alpha^{NC})^2}{2}$$

$$\frac{(\hat{m}\beta+\sigma+\alpha)^2}{2c}+\frac{N}{\hat{m}}\ell \geq (\hat{m}-1)\beta q^m(\hat{m}-1)+\frac{(\beta+\sigma+\alpha)^2}{2c}$$

$$N\frac{\alpha(2\beta+2\sigma+\alpha)}{\beta^2} \geq \hat{m}(\hat{m}-1)(\hat{m}-3) \qquad (C_{Time})$$

We see that this condition always holds for $\hat{m} \leq 3$, which implies that once the club has been established it will always exist. The minimum number of members staying in the club depends crucially on parameter values such as the total number of countries and the size of the breakthrough.

Result 1. *The club will always exist once established, with a minimum of 2 members*

In the extended version of the model, where investments are variable and effect the quality of the technology:

$$N\Big(\frac{N(\beta+\sigma)+m(N-1)\beta}{2c\phi/P(m)-N}\Big)^2\frac{2(\beta+\sigma)+}{\beta^2}+\frac{1}{\beta^2}\frac{N(\beta+\sigma)+m(N-1)\beta}{2c\phi/P(m)-N} \geq \hat{m}(\hat{m}-1)(\hat{m}-3) \qquad (C_{Time})$$

6 Discussion

This model has investigated a new approach to issue linkage in global cooperation in order to increase abatement levels. In particular, we have considered the case where no country invests unilaterally as the Nash Equilibrium of the business as usual scenario and with a standard IEA. This club, which demands countries to join their R&D effort and share the revenue from a successful innovation, will achieve more abatement and ensure that the breakthrough technology is developed. If the fixed investment is sufficiently high all countries will join the club, achieving the goal of a large stable club that abate cooperatively. Further extensions of the model will introduce an endogenous link between the investment effort and the quality of the investment.

Appendix A

The non-cooperative investment level

Country i's expected welfare from deciding to investing, when $y \in [0, N-1]$ other countries are investing too:

$$\begin{aligned}
\mathbb{E}_i[W_I^{NC}] &= \underbrace{p(1-p)^y\Big(U_\alpha^{NC} + (N-1)\ell - f\Big)}_{\text{only } i \text{ succeed}} + \underbrace{yp(1-p)^y\Big(U_\alpha^{NC} - \ell - f\Big)}_{\text{one other expect } i \text{ succeed}} \\
&+ \underbrace{\Big[1-(1-p)^{y+1} - (y+1)p(1-p)^y\Big]\Big(U_\alpha^{NC} - f\Big)}_{\text{at least two succeed}} + \underbrace{(1-p)^{y+1}\Big(U_0^{NC} - f\Big)}_{\text{Everyone fails}} \\
&= (1-p)^{y+1}U^{NC}(0) + (1-(1-p)^{y+1})U_\alpha^{NC} + (N-1-y)p(1-p)^y\ell - f
\end{aligned}$$

In case the country does not invest, the country earns the following expected welfare:

$$\begin{aligned}
\mathbb{E}_i[W_{NI}^{NC}] &= \underbrace{yp(1-p)^{y-1}\Big(U_\alpha^{NC} - \ell\Big)}_{\text{only one other succeed}} + \underbrace{\Big[1-(1-p)^y - yp(1-p)^{y-1}\Big]U_\alpha^{NC}}_{\text{at least two others succeed}} + \underbrace{(1-p)^y U_0^{NC}}_{\text{Everyone fails}} \\
&= (1-p)^y U^{NC}(0) + (1-(1-p)^y)U_\alpha^{NC} - yp(1-p)^y\ell
\end{aligned}$$

The condition below states whether a single country find it beneficial to invest, depending on how many other countries $y \in [0, N-1]$ that are investing:

$$\mathbb{E}_i[W_{NI}^{NC}] < \mathbb{E}_i[W_I^{NC}]$$

Taking the derivatives: Both expected utilities are increasing in number of countries investing, since the probability of a successful invention increases.

$$\begin{aligned}
\frac{d\,\mathbb{E}_i[W_I^{NC}]}{dy} &= -(1-p)^{y+1}\Big[U_\alpha^{NC} - U^{NC}(0)\Big]\ln(1-p) - p(1-p)^y\ell\big[y\ln(1-p)+1\big] \\
\frac{d\,\mathbb{E}_i[W_{NI}^{NC}]}{dy} &= -(1-p)^y\Big[U_\alpha^{NC} - U^{NC}(0)\Big]\ln(1-p) - p(1-p)^y\ell\big[y\ln(1-p)+1\big]
\end{aligned}$$

The expected utility of investing increases more gradual, since:

$$\frac{d\,\mathbb{E}_i[W_I^{NC}]}{dy} < \frac{d\,\mathbb{E}_i[W_{NI}^{NC}]}{dy} \quad \text{since} \quad 0 < p\Big[U_\alpha^{NC} - U^{NC}(0)\Big]$$

Appendix B

Numerical illustration

In order to numerically illustrate proposition 1 we can consider the following example:

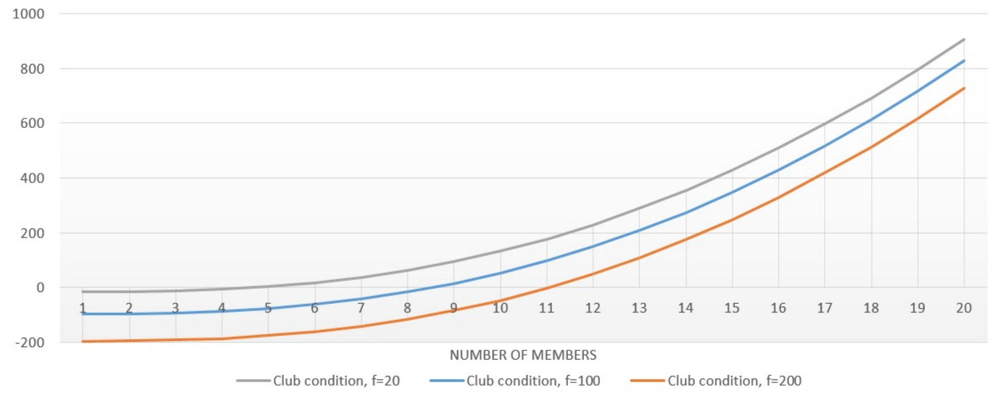

Figure 4: The investment condition for a single club member

α	β	σ	c	p	N
0,5	5	2,5	4	0,08	20

Figure **??** illustrates condition (14) for three different investment levels, $f = 20$, $f = 100$ and $f = 200$, which is satisfied at 7, 9 and 11 members respectively. The parameter values used in this example is displayed in the table above. In this numerical example any $f \geq 4$ creates a club where $m^* > 1$, and full membership, $m^* = N$ is achieved at $f \geq 818$.

Figure 5 is a numerical example of the club equilibrium, which is equal to $m^* = 8$ members when the fixed investment cost is $f = 100$ and the same parameter values apply:

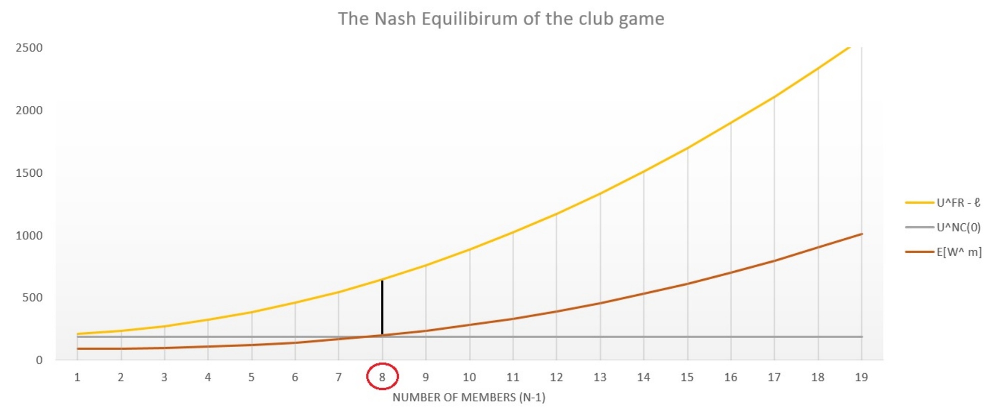

Figure 5: The investment condition for a single club member

Appendix C

Corner solutions of condition (14)

If $\tilde{m} = 1 \quad \rightleftarrows \quad 0 \geq p\alpha\big[2(2N-1)\beta + 2N\sigma + N\alpha\big] - 2cf$

If $\tilde{m} = N \quad \rightleftarrows \quad 0 \leq P(N)\Big[(N-1)^2\beta^2 + (2N\beta + 2\sigma + \alpha)\alpha\Big] - 2cf$

Appendix D

Comparative statics of the club's investment condition

Insert for (5), (6) and (9) and the investment condition yields

$$P(m)\Big[U^m - U^{NC}(0) + \frac{N-m}{m}\ell\Big] \geq f \quad \Rightarrow \quad \underbrace{P(m)\Big[\frac{(m-1)^2\beta^2 + 2(N-1)\beta\alpha + \frac{N}{m}\alpha(2\beta+2\sigma+\alpha)}{2c}\Big]}_{=LHS} \geq f$$

Applying the following approximation:[10] $P(m) \approx pm/(1+p(m-1))$, we see that the derivative with respect to m is clearly positive if p is small:

$$\frac{\partial LHS}{\partial m} \geq 0 \quad \text{if}$$

$$P'(m)\Big[(m-1)^2\beta^2 + 2(N-1)\beta\alpha + \frac{N}{m}\alpha(2\beta+2\sigma+\alpha)\Big] + P(m)\Big[2(m-1)\beta^2 - \frac{N}{m^2}\alpha(2\beta+2\sigma+\alpha)\Big] \geq 0$$

Applying the approximation:

$$\frac{(1-p)}{1+p(m-1)}\Big[(m-1)^2\beta^2 + 2(N-1)\beta\alpha + \frac{N}{m}\alpha(2\beta+2\sigma+\alpha)\Big] + 2m(m-1)\beta^2 - \frac{N}{m}\alpha(2\beta+2\sigma+\alpha) \geq 0$$

$$\Big[[(1-p) + 2pm](m-1) + 2m\Big](m-1)\beta^2 + \alpha\Big[2(N-1)(1-p)\beta - Np(2\beta+2\sigma+\alpha)\Big] \geq 0$$

[10] This approximation is thoroughly outlined in the working paper by Gersbach and Riekhof (2017).

The comparative statics of the condition (14) where $P(\tilde{m})\left[U_{\alpha}^{\tilde{m}} - U^{NC}(0) + \frac{N-\tilde{m}}{\tilde{m}}\ell\right] = f$:

$$\frac{d\tilde{m}}{dp} < 0$$
$$\frac{d\tilde{m}}{d\sigma} < 0$$
$$\frac{d\tilde{m}}{d\beta} < 0$$
$$\frac{d\tilde{m}}{d\alpha} < 0$$
$$\frac{d\tilde{m}}{dc} > 0$$
$$\frac{d\tilde{m}}{df} > 0$$

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