SEEDS
Sustainability Environmental Economics
and Dynamics Studies

Working Paper Series

An Evolutionary approach to International Environmental Agreements

by

Tiziano Distefano, Simone D'Alessandro

05/2017

SEEDS Working Paper 05/2017
September 2017
by Tiziano Distefano, Simone D'Alessandro

An Evolutionary approach to International Environmental Agreements

Tiziano Distefano* Simone D'Alessandro†

September 13, 2017

Abstract

Our work contributes to explain the observation of two facts at odds: the number of signatories of international environmental agreements (IEA) has grown in time, meanwhile, the aggregate global level of greenhouse gas emissions is increasing at exponential rate. We introduce a novel multi-scale framework, composed by two tied games, to show under which conditions a country is able to fulfil the IEA: an Evolutionary Game which describes the economic structure through the interaction of households and firms' strategies; and a 2x2 one-shot Game, with asymmetric nations that negotiate on the maximum share of emissions. The distance between international environmental targets and country's emissions performances is explained in terms of heterogeneous economic structure, without the need to impose any free-riding behaviour. Consumer's environmental consciousness (micro level) together with global income (and technological) inequality (macro level), are found to be the key variables towards the green transition path. We provide analytical results paired with numerical simulations.

Keywords: International environmental agreements, asymmetry, evolutionary process, Multi-level perspective, climate change

JEL: C71, C72, C73, H41, F53, Q20

---

*Department of Environmental, Land and Infrastructure Engineering, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, (IT). Corresponding author's e-mail: tiziano.distefano@polito.it.

†University of Pisa, Department of Economics and Management, via C. Ridolfi, 10, 56124 Pisa (Italy). E-mail: simone.dalessandro@unipi.it

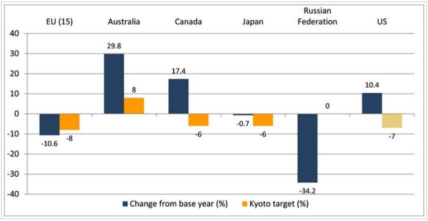
1 Introduction

Anthropogenic climate change is the biggest challenge that humans are facing, in order to avoid, or at least to restrain, the possible disasters that might occur in case of an increase of global temperature higher than 2 degrees, as described in the last Intergovernmental Panel on Climate Change report (see Field et al., 2014). The most important problem is related to transboundary pollution of greenhouse gas emissions. The formation and development of International Environmental Agreements (IEA) has been the subject of a fast growing branch of the economic literature over the past decade, in particular non-cooperative games go back to Hoel (1992), Carraro and Siniscalco (1993) and Barrett (1994). There are several important design issues that self-enforcing IEA have to address: despite the global benefits of reducing green-house gas discharges, no agent has any incentive to reduce her own burden, there is not any supranational force able to enforce any agreement, there is a temptation to free ride and a high level of asymmetry in historical responsibilities and in the (future and uncertain) benefits-costs distribution. At least this is the classical framework in which completely informed rational agents should operate. Yet the number of signatories of IEA is increasing and, at local level, many people are making efforts to reduce emissions and putting pressure on businesses and governments to do the same.

From COP1 in Berlin 1995 to COP21 in Paris 2015, the climate negotiations aimed at legally binding targets for greenhouse gas emission reduction. Contrary to what has been observed historically, it was predicted that a global agreement on emission reduction is not feasible (Carraro and Siniscalco, 1993), that a single coalition is ineffective, and that only a small number of coalitions are stable and that in general the number of signatories size is rather small (around three) (Barrett, 1994). Actually, the size of the IEA coalition seems a minor problem given that the number of signatories has grown substantially in time (see Table 1). Other authors tried to explain this dichotomy by including asymmetries (Pavlova and de Zeeuw, 2013; McGinty, 2005), transfers (Colmer, 2011; Carraro et al., 2006), moral concerns (Jeppesen and Andersen, 2002), uncertainty (Kolstad, 2007; Heal and Kristrom, 2002), or by framing a dynamic (de Zeeuw, 2008; Rubio and Ulph, 2007; Calvo and Rubio, 2012), or an evolutionary game (Courtois et al., 2004; McGinty, 2010; Vasconcelos et al., 2013). The consensus is that any case of failure of the compliance of the IEA is due to free-riders. Though often almost all parties agree that something should be done to protect the global environment, we observe a progressive increase in the yearly air pollution, at global level, measured by the concentration of CO_2. However, there is a great heterogeneity between countries in terms of the difference between international agreements and actual level of emissions, for instance some Kyoto participants are well above their target while others are well below (Figure 1).[1]

---

[1] In particular there are some successful examples of emission reductions: France, Italy, Germany and



Source: UNFCCC (1990-2010)

Figure 1: Comparison of Kyoto Protocol standards and actual CO2 emissions. Source: UNFCC (1990-2010)

Table 1:
Historical IEA and number of signatories.

IEA	Year	Signatories
Stockholm	1972	113
Rio de Janeiro	1992	153
Kyoto	1997	176
Montreal	2005	187
Paris	2015	195

There is a general consensus that ‘no one country’ can solve the global climate change problem Meserve (2008), neither waiting for a “single worldwide solution” appears less problematic. In addition to the problem of waiting too much, “global solutions” negotiated at a global level, if not backed up by a variety of efforts at national, regional, and local levels, however, are not guaranteed to work well (Ostrom, 2009). That is, the first step of each country is to pursue domestic climate policies consistent with domestic pressures (Bodansky et al., 2004), reinforced by an international agreement in line with the economic structure. The people most hurt by impacts may not have adequate representation at higher levels and may be unable to articulate clear solutions to reduce greenhouse gas emissions and help them adapt to the variety of threats they face (Agrawal, 2008). “Think Globally but Act Locally” hits right at a major dilemma facing all inhabitants of our globe.

Our paper aims to explain and simulate: *i*) under which economic conditions a country *fails* to respect the IEA or when it attains better results than expected, *ii*) the role played by consumers’ *environmental awareness*, an *iii*) how income (and technological) inequality might hamper the road toward a green transition. This paper follows the tradition of the literature that considers *uniform* emission reduction quotas. It differs from the previous literature in three respects. First, the analysis is not based on a stylized model where parties are modeled “as if” they were individual rational agents, but we ground their action on their economic structure. Second, we define the economic system as an Evolutionary Game where consumers and firms interact, determining the level of emissions, in equilibrium, for any given level of environmental standards fixed by the IEA. In designing the IEA game we decide to take into account only two countries for several reasons. First of all, what matters in any International Agreement is ‘who’ signs the treaty rather than ‘how many’ (which instead, so far, has been the focus of most of the current literature). Indeed, China and USA are responsible for almost the half of global emissions. Moreover, studying a 2x2 game is simpler and it allows a more tractable comparison when the evolutionary game is considered. Finally, we recall the recent

---

UK among others (see Oliver et al., 2014).

climate agreement (though not mandatory), just a year before the IEA of Paris (held in November 2015) in which China and USA ratify a reciprocal effort in curbing emissions, recognizing that Parties' mitigation efforts are crucial steps in a longer-range effort needed to transition to green and low-carbon economies.[2] Finally, the complexity of the model limits the possibility to analytically derive each result, therefore we complement our analysis with (parameterised) simulations, using a handy Maple algorithm, to determine the alternative evolutionary equilibria that each country reaches when IEA is enforced. The paper is structured as follow: Section 2 shows the results from the evolutionary interaction between household and firms and the different regimes, in terms of equilibria, that characterize each country. Section 3 describes the 2x2 one-shot IEA game and the conditions under which countries has convenience in coordinating their actions, while Section 4 presents the results from numerical simulations. Finally, Section 5 discusses the main implications of the model.

2 GAME 1 - Evolutionary (Micro-)Economic Structure

We study the evolutionary dynamics of production convection in a two-step procedure which integrates the results from two games (Γ_1 and Γ_2), the former at national-scale level and the latter at the global level (IEA). Γ_1 shows what we can consider the dynamic of isolated economies in which, due to interior conditions, it is established a certain percentage (in terms of investment or as a quota of GDP) of "green" production. In particular we assume that the *timing* of the whole model is as follow: countries start to care about the transboundary effect of pollution, for whatever reason,[3] then they bargain to setup an international environmental standard (θ) to be thought as the maximum share of CO_2 emissions allowable within each country (assumed to be equal to the share of polluting firms, as explained in Γ_2). Even if θ is not a 'common' target of IEA, its interpretation is straightforward and it captures the essence of each climate agreement: reducing greenhouse gas emissions. Note that θ can also be seen as an energy/production-mix criteria because it establishes the minimum quota of green firms and, therefore, the maximum share of fossil-fuel production allowable. Moreover, each agreement is composed by several targets that cannot be captured in a single model. Whereupon, in the second step, each signatory enforces θ within its own country. The level of emission of each country, in equilibrium, depends on the evolutionary strategic interaction between consumers and firms, as explained in details below.

---

[2] For a detailed description see https://www.whitehouse.gov/the-press-office/2015/09/25/us-china-joint-presidential-statement-climate-change.

[3] In Game 2 this fact is captured by the parameter $a > 0$.

Before going ahead it is worth to clarify the significance an the relevance of an Evolutionary model. Evolutionary game theory is a growing branch of research proved to be a worth methodology (Weibull, 1996; Young, 1998; Bowles, 2004) whenever players change behavior over time and interact strategically, in the sense that the outcome for each agent depends on others' behavior as well as her own. It is especially valuable when the relevance of static equilibria are unclear, e.g., when there are several Nash Equilibria. In our context applying an evolutionary analysis is particularly suitable because we assume that market interactions are frequently encountered and because we expect that people will devote effort to solve the environmental problems. We construct a dynamic model of the process by which the proportions of various strategies in a population change. This will typically be a stochastic process, but if the random events affecting individual payoffs are independent, and the population sufficiently large, a good approximation is obtained by examining the expected value of this process. Our model is focused on asymmetric pairwise interactions because the agents in a transaction have different (not interchangeable) identities, such as buyer and seller.
To analyse the evolutionary dynamics governing transitions between the two conventions (Green-Green, Carbon Economy), let us assume a two-person two-strategy game in a large population of individuals subdivided into two groups (consumers and firms), the members of which are randomly paired to interact in a non-cooperative game with members of the other group. Individuals' best-response play is based on a single-period memory: they maximize their expected payoffs based on the distribution of the population in the previous period (Bowles, 2004). Both populations are normalized to unit size, so we refer equivalently to the numbers of players and the fraction of the population. Note that Γ_1 does not deal with interactions that take place between more than two individuals at a time.

Let consider a normal-form (strategic) game with a player set composed by individuals that comprise $\Omega = \{\mathcal{H}, \mathcal{F}\}$ finite populations, namely households ($\mathcal{H}$) and firms ($\mathcal{F}$). Each population splits in clubs depending on the strategy $s = \{E, P\}$ agents play or the behavior that agents follow, that stand for *ecologic* (E) and *polluting* (P), respectively. The normal form representation of our described game is given by the payoff matrix (see Table 2).

Table 2:
Normal form game Γ_1.

Players	$\mathcal{F}_E$	$\mathcal{F}_p$
$\mathcal{H}_E$	h_E , f_E	0 , 0
$\mathcal{H}_P$	0 , 0	h_P , f_P

Note that the payoffs out of the diagonal are always zeros because we assume that when people with different strategies are matched they do not sign any contract. To wit, the green consumers do not want to buy polluting goods and viceversa.[4] The dynamic evolution of the fraction of each club i.e., given the complementarity of the two strategies {E, P}, is simply derivable from the evolution of the proportion of ecological households and firms, namely of α and β, according to the following replicators dynamics (Santos and Pacheco, 2011):

$$\dot{\alpha} = \alpha \cdot (1 - \alpha) \cdot [H_E - H_P] \tag{1}$$

and

$$\dot{\beta} = \beta \cdot (1 - \beta) \cdot [F_E - F_P] \tag{2}$$

where H_s and F_s are the expected fitness of choosing the $\mathcal{H}_s$ and $\mathcal{F}_s$ strategies respectively. In the framework of evolutionary game theory, the evolution or social learning dynamics in a large population is commonly described by the the replicator dynamics equation (Hofbauer and Sigmund, 1998; Santos et al., 2012; Sigmund, 2010) which characterizes the behavioral dynamics of the population. According to the replicator equation the percentage of green players increases if the fit given by the green strategy is higher than what expected when the polluting strategy is played. The payoffs depend on the actions of the co-players and hence on the frequencies of the strategies within the population (Sigmund, 2010). Here, the individual game payoff is typically associated with fitness or social success of an individual. The more successful (fitter) individuals will be imitated by others, so that the number of individuals adopting a given behaviour will evolve in time. Let introduce the payoff structure for both players and strategies, the expected values and the evolutionary dynamics which characterize Γ_1.

2.1 Households

The utility of a household h depends on his material payoff (h_s). We assume, for simplicity, that the consumption of each kind of good gives the same level of utility (u),[5] yet the relationship between the environmental standards (θ) and the share of firms operating under green production (β) shape the total payoff. In particular, the payoff of the green household is a piece-wise function defined as:

$$h_E = \begin{cases} u - c(\theta - \beta), & \text{if } \beta < \theta. \\ u, & \text{otherwise.} \end{cases} \tag{3}$$

---

[4] Following Weibull (1996, p. 34) we might consider that the zeros out of diagonal are the results of payoff's normalization. In other words, even if we assume that agents get some constant positive payoff when they play different strategy, it would not be affect the structure of Γ_1. For simplicity we get rid of this possibility and we study only the model with zeros out of diagonal.

[5] In other words, green and polluted goods are perfect substitutes because both goods are able, through their material characteristics, to satisfy in the same manner the needs of consumers.

where $u > 0$ is the constant level of utility from consumption, independent from market conditions – not modelled here – because it simply comes from the material characteristic of the good. For instance, a consumer should be indifferent from an ecological home cleaning product and a chemical one, if they are both equally suitable for housecleaning. What matters here is the role of the extra cost a green product carries (c) compared to the social pressure against carbon intensive goods (δ). Households who decide to play the green strategy carry a monetary cost ($c > 0$) proportional to the difference between the environmental standard ($1 \geq \theta \geq 0$) and the share of green firms ($1 \geq \beta \geq 0$). This additional cost represents the willingness to finance the ecological friendly production. We assume that in case of no environmental concerns – i.e. $\beta > \theta$ – the green household simply receives utility from consumption because we assume no environmental concerns. There is a double interpretation of c: the first stands on the assumption that green consumers pay more because the good carries an extra-cost, imposed by the Government, in order to finance the green start-up, yet our model do not take into account the process of formation of prices nor the mechanism of redistribution of this extra payment. Secondly, from a broader perspective, we report, among the several real-case initiatives, that many green startups got off the ground using *crowd-funding* sites, such as 'FoodCycle', which recycles food waste into nutritious meals for those in need. However the potential gains from this kind of investments are not modelled. On the other hand, the polluter household plays the polluting strategy h_P and obtains the following payoff:

$$h_P = \begin{cases} u - \delta(\theta - \beta), & \text{if } \beta < \theta. \\ u, & \text{otherwise.} \end{cases} \tag{4}$$

where δ represents how much the consumer (and public opinion) perceives the possible damages from a polluting consumption, thus representing a (kind of) moral cost. Here $0 < \delta \leq 1$ is a parameter used as a proxy of the level of *environmental consciousness* spread in the society. Given δ, the utility of h_P decreases inasmuch the environmental standards are not respected, i.e. when $\theta - \beta$ is high. Since that the utility from consumption is the same in both cases, households simply compare the monetary cost of being environmental friendly (c) with the moral cost (δ) of consuming polluting goods. Note that if $c = \delta$ than the consumer is indifferent between the two strategies. However the share of green households, in equilibrium, depends on the stringency of θ, and therefore on the proportion of green firms (β). This is a remarkable results of any evolutionary game: what in a simple 2x2 game reflects a mixed strategy, in an evolutionary game, when the whole population is considered, it translates in different shares of agents playing either one or the other strategy. The same holds true even when $c \neq \delta$ because there is no a linear relationship between the payoff and the proportion of green and polluting consumers in equilibrium. This point is made clear in the subsection 2.3.

It is simple to recover the fit of each strategy, assessing whether households prefer the green or the polluting strategy. The expected payoff of choosing the green and the polluting strategy are $H_E = E(\mathcal{H}_E) = \beta h_E$ and $H_P = E(\mathcal{H}_P) = (1-\beta)h_P$ respectively. Households choose the green (polluting) strategy if and only if $H_E > H_P$ ($H_E < H_P$). Note that if $\beta = 0$ then $H_E > H_P$ if and only if $\theta > \theta_0 \equiv \frac{u}{\delta}$; while if $\beta = 1$, it always holds $H_E > H_P$. Therefore, in case $0 < \theta \leq \theta_0$ there is only one intersection between H_E and H_P, that we define $\beta^*_{0,1}$, given either by:

$$\beta^*_0 \equiv \frac{1}{2}, \text{ if } 0 < \theta < \min\{\theta_0, \frac{1}{2}\} \tag{5}$$

or by

$$\beta^*_1 \equiv \frac{\theta(c+\delta) + \delta + \sqrt{\Delta_\beta}}{2(c+\delta)} \text{ if } \frac{1}{2} < \theta < \theta_0, \tag{6}$$

where $\Delta_\beta = [\theta(c+\delta) + \delta - 2u]^2 - 4(c+\delta)(\delta\theta - u)$.[6] Note that when $\beta = 0$ so does H_E, therefore, the only way to disincentive polluting consumption is to fix θ high enough to make H_P (temporarily) negative.[7] Moreover, if the environmental awareness is 'sufficiently low' (i.e. $\delta < u$), there is a single intersection between H_E and H_P for any value of $\theta \in [0,1]$. In case $\beta < \beta^*_{0,1}$, the expected payoff of the polluting strategy is greater than that of the green one, while if $\beta > \beta^*_{0,1}$ the reverse holds (see Figure 1(a)). When $\theta > \theta_0$, the two curves – H_E and H_P – can be either secant ($\Delta_\beta > 0$), tangent ($\Delta_\beta = 0$) or without any point in common ($\Delta_\beta < 0$) when the expected payoff of the green strategy is always greater than the polluting one. It holds that if $\delta \leq \frac{c^2+4u^2}{4u}$ the determinant is always positive, otherwise

$$\Delta_\beta \geq 0 \Longleftrightarrow \theta \leq \theta_1 \equiv \frac{\delta + 2u - 2\sqrt{(\delta - c)u}}{c+\delta}.$$

When $\theta_0 < \theta \leq \theta_1$, H_E and H_P have two intersections: the first one is $\beta^*_{0,1}$, while the second is given by:[8]

$$\beta^*_2 = \frac{\theta(c+\delta) + \delta - \sqrt{\Delta_\beta}}{2(c+\delta)}. \tag{7}$$

In this case, for $0 \leq \beta < \beta^*_2$ and for $\beta^*_{0,1} < \beta \leq 1$ the expected payoff of the green strategy is greater than that of the polluting one, while for $\beta^*_2 < \beta < \beta^*_{0,1}$ the reverse holds (see Figure 1(b)). Figure 1(c) shows a case in which there is no intersection between the two expected payoff, i.e. $\theta > \theta_1$. In this case the green strategy is always preferred for any

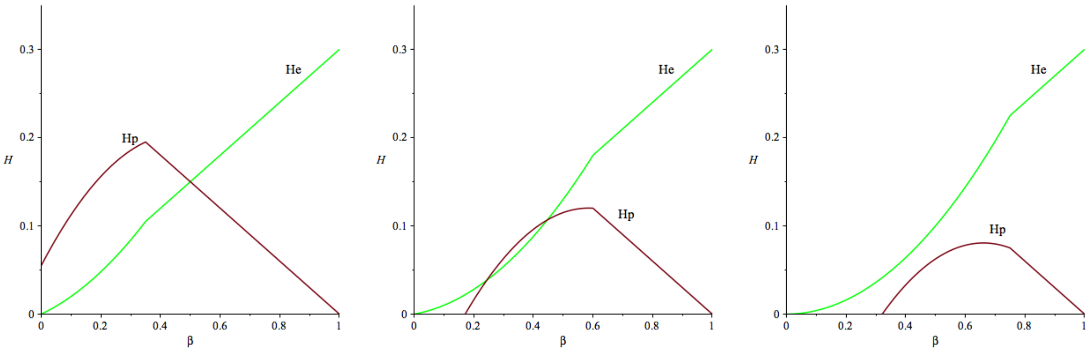
---

[6] From the last term of Δ_β, it is straightforward that $\theta < \theta_0$ is a sufficient condition for $\Delta_\beta > 0$.

[7] As noted above, we might avoid negative utilities simply by assuming any scale factor – out of the diagonal – big enough to compensate the gap. However, this issue does not alter the nature of the game.

[8] More precisely, if $\theta_0 < \theta < \min\{1/2, \theta_1\}$, the solutions are β^*_2 and β^*_0, while if $\max\{\theta_0, 1/2\} < \theta < \min\{1, \theta_1\}$, the solutions are β^*_2 and $\beta{*}_1$. This difference does not affect the dynamics.

value of β.



(a) (b) (c)

Figure 1: Examples of households equilibrium. Values of parameters: $\delta = 0.7$, $c = 0.4$, $u = 0.3$. (a) A single intersection ($\theta = 0.35$), (b) Two intersections ($\theta = 0.6$), (c) No intersection ($\theta = 0.75$).

2.2 Firms

From the firm's side we assume that the green firms are characterized by the following payoff:

$$f_E = \begin{cases} \pi_E + \frac{c(\theta-\beta)\alpha}{\beta}, & \text{if } \beta < \theta, \\ \pi_E, & \text{otherwise.} \end{cases} \tag{8}$$

where $\pi_E > 0$ is the profit from the green selling. Analogously to u, π_E is constant because our model does not assess any market effect, but it focuses to which (evolutionary) equilibrium the economy reaches when the green firms are relatively less efficient (and productive, then profitable) compared to fossil fuel ones and how citizens and Governments should act to ensure a green transition, under these conditions. Each green firm receives a subsidy which is equal to the total amount of extra-cost paid by each green household multiplied by the share of green consumers (α). This amount decreases as the share of green firms β approaches the environmental standards (θ). We assume that, in any period, the total amount paid by green consumers is equally shared among green firms. This is justified by the fact that the green technology is not yet developed to be as efficient as the polluting one and its impact is still marginal. An instructive example is provided by the last OECD report (2014) that confirms the tiny share (1%), by 2011, of renewable resources in the production of primary energy, while oil, gas and coal together cover more than four-fifths of the total amount (30.7%, 29.2% and 21.5%, respectively). Therefore, the public subsidy should help to boost the investment in new green startups to stimulate investments in green sectors. On the other side, the polluting firms are characterized by the following payoff:

$$f_P = \begin{cases} \pi_P - \frac{\gamma(\theta-\beta)}{1-\beta}, & \text{if } \beta < \theta, \\ \pi_P, & \text{otherwise.} \end{cases} \tag{9}$$

where $\pi_P > 0$ is the net profit that, in line with what stated above, is assumed to be greater than that of the non-polluting firms ($\pi_P > \pi_E$). They can be interpreted as an average profit proportional to the market share of the belonging sector. Moreover, $\frac{\gamma(\theta-\beta)}{1-\beta}$ is a *tax* function which depends on the relation between the actual level of green production (β), the ecological standards fixed by the government (θ) and a multiplicative factor (γ) which measures the monetary cost of the difference $\theta - \beta$. The total cost afforded by the F_P depends on the stringency of environmental policies and on the number of polluting firms. Since the polluting firms must jointly cover the cost of environmental damages, the total amount is determined by the percentage of polluting firms. We assume that the tax paid by polluting firms is used by Governments either to restore their environmental damages or to face future adverse catastrophes due to (anthropogenic) climate change. Given the share of households which choose the green or the polluting strategy, firms find it convenient to choose the green (polluting) production if and only if the expected payoff of $\mathcal{F}_E$ is greater (lower) than the expected payoff of choosing $\mathcal{F}_P$. As before, let us define $F_E = E(\mathcal{F}_E) = \alpha f_E$ and $F_P = E(\mathcal{F}_P) = (1-\alpha) f_P$ the expected payoff of the green and the polluting production respectively. The expected payoffs of firms depend on both α and β. Note that F_E is an increasing function of α, such that $F_E = 0$ when $\alpha = 0$ and $F_E > 0$ when $\alpha = 1$.[9] On the other hand, the expected payoff of the polluting strategy is linear in α, and it is decreasing in α if $\beta > \theta$. Instead, when $\beta < \theta$ the slope of the function F_P depends on the sign of $\pi_P - \frac{\gamma(\theta-\beta)}{1-\beta}$ which expresses the difference between the whole profits of polluting industries and the (monetary evaluation) of the environmental damages. Obviously when this last expression is negative, that is when $\beta < \bar{\beta} \equiv \frac{\gamma\theta-\pi_P}{\gamma-\pi_P}$, F_E is greater than F_P for any value of α.

Figure 2 shows the resulting interceptions between F_E and F_P in the plane $\{\theta, \beta\}$. When $\beta > \theta$ there is an internal value of α (α_0^*), such that firms are indifferent between the two strategies, which does not depend on β. When instead $\bar{\beta} < \beta < \theta$, there is an internal value of α (α_1^*), such that $F_E = F_P$, but this value is an increasing function of β. Note that $\theta > \frac{\pi_P}{\gamma}$ is a necessary condition to induce at least one firm to deviate from the polluting convention – i.e. when $\alpha = 0$ and $\beta = 0$. More precisely the two alternative

---

[9] The value of F_E at $\alpha = 1$ depends on the relation between θ and β. If $\beta < \theta$ then $F_E = \pi_E + \frac{c(\theta-\beta)}{\beta}$, otherwise $F_E = \pi_E$.

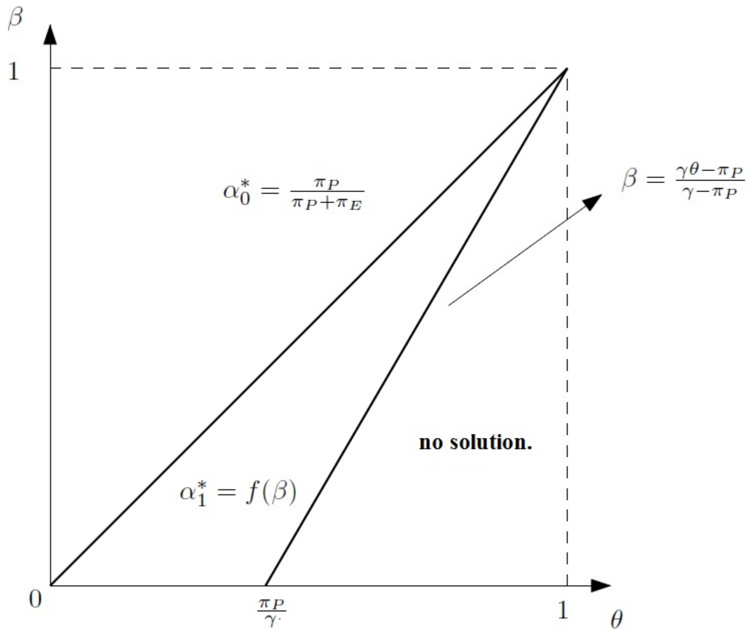


Figure 2: The intersection between the expected payoff of green and polluting strategies in the plane $\{\theta, \beta\}$.

solutions are:

$$\alpha_0^* = \frac{\pi_P}{\pi_P + \pi_E}, \tag{10}$$

$$\alpha_1^* = \frac{\beta[\gamma(\theta-\beta) - (\pi_P+\pi_E)(1-\beta)] + \sqrt{\Delta_\alpha}}{2c[(\theta-\beta)(1-\beta)]}. \tag{11}$$

where Δ_α is always positive.[10] These results, combined with those of the previous subsection, determine analytically the equilibria of the evolutionary game. In what follows we establish under which conditions (*Regimes*) the dynamic system converges to an interior equilibrium and when it is (locally) stable.

2.3 Regimes

Households and firms change their behavior according to the replicator dynamics described by equations (1) and (2). Given the results above, depending on the value of θ we get five *Regimes* (R_i) that qualitatively change the dynamic properties of the system.[11] For the sake of clearness, we assume that the economy is, as a starting point, in the polluting convention where $\beta = \alpha = 0$ and that the government establishes a certain level of environmental standard ($\theta > 0$).

---

[10] Note that the other solution in α of $F_E = F_P$ is always negative. Moreover $\Delta_\alpha = \beta^2\{(1-\beta)[2\gamma(\pi_P+\pi_E)((\beta-\theta)+(\pi_P+\pi_E)(1-\beta)] + 4c(\pi_P-\gamma)(2\theta+\beta^2)+\gamma^2(\theta-\beta)^2\} + 4c\{\beta\pi_P(\beta^2(2+\theta)-(\theta+\beta)) + \gamma(\beta^2\theta^2-\beta-2\theta)-\theta^2\}$

[11] Figure 3 shows the phase diagram for each Regime. Note that the black circles indicate the (locally) stable equilibria and the dotted line the level of stringency of the environmental law (θ).

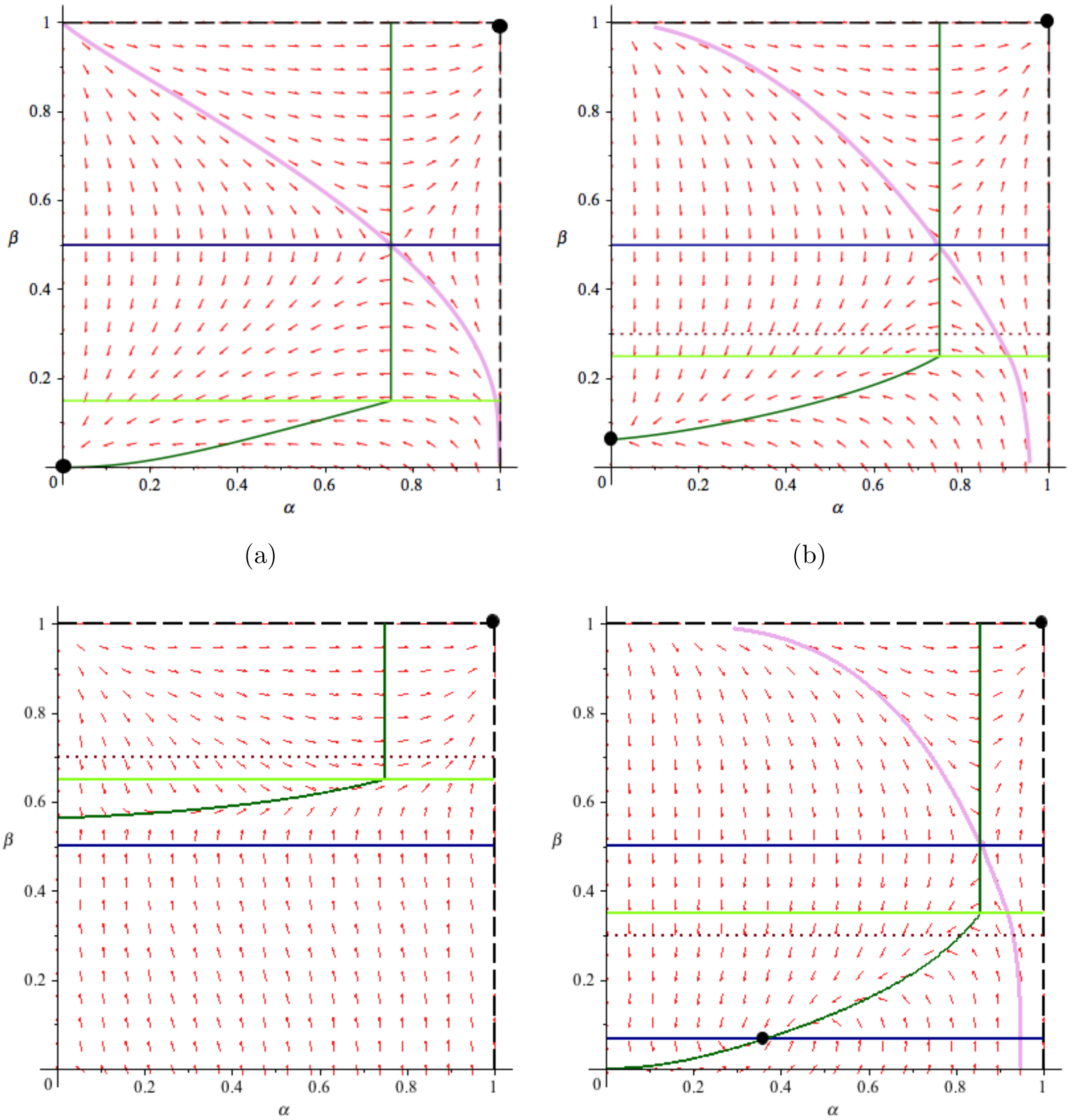
R_1: When $0 \leq \theta < \min\{\frac{u}{\delta}, \frac{\pi_P}{\gamma}\}$, the isoclines and the phase diagram of the system are shown in Figure 3(a). In this case there is no interior (locally) stable equilibrium. The introduction of an environmental law ($\theta > 0$) is not sufficient to induce the system to detach from the polluting productive convention. The possible explanations of the failure of the policy (θ) could be: that consumers are not enough aware of the potential environmental damages they may suffer from contaminant goods and they thus weigh more the utility from consumption, or that the gain from dirty production are so high to more than compensate the covering of the environmental costs. Note that given θ an increase in δ or γ may induce the system to depart from R_1 and to follow one of the other regimes.

R_2: When $\frac{\pi_P}{\gamma} < \theta < \frac{u}{\delta}$, the polluting convention becomes unstable because the environmental law is 'sufficiently high' to induce the start-up of new green firms, or the shift towards clean processes, as long as $\beta < \bar{\beta}$, that is the condition for which $F_E > F_P$. If $\bar{\beta} < \beta^*_{0,1}$, then all the trajectories departing from the polluting convention converge to the point with coordinate ($\alpha^* = 0$, $\beta^* = \bar{\beta}$). This is a corner solution (Figure 3(b)), where, in order to avoid the cost of polluting strategy, some firms find it convenient to choose the green technology even without any consumer. This result is odd, but it signals the imbalance between the high cost for polluting firms and the low awareness of households to environmental concerns. Given that $\beta^*_{0,1} \leq 1/2$, when $\gamma < \pi_P$ this case disappears because $\bar{\beta} > 1/2$. On the other hand if $\bar{\beta} > \beta^*_{0,1}$, as long as β increases, households find it convenient to choose the green production. This process ends up when $\alpha = \beta = 1$. Thus the only globally stable equilibrium is the green convention (see Figure 3(c)).

R_3: When $\frac{u}{\delta} < \theta < \frac{\pi_P}{\gamma}$, households find it convenient to choose the green strategy so that they induce the firms to supply more green goods and services. The dynamical system is characterized by two locally stable equilibria, an interior point ($\alpha^* > 0$, $\beta^* > 0$) and the clean convention ($\alpha^* = 1$, $\beta^* = 1$). In this case all the trajectories departing from the polluting convention join the interior equilibrium where $\beta^* \leq \theta$ (see Figure 3(d)), therefore the policy has only a partial effect and it is not wholly efficacious because θ is not strict enough to induce the expected share of firms to shift their production from the polluting convention. Its impact is indirect and simply stands on the stimulus from the demand side.

R_4: When $\max\{\frac{u}{\delta}, \frac{\pi_P}{\gamma}\} \leq \theta < \min\{\theta_1, 1\}$, households and firms find it convenient to choose the green strategy. The dynamical system is characterized by two locally stable equilibria, the interior and the green convention. In this regime all the trajectories departing from the polluting convention end up to the interior equilibrium where $\beta^* \leq \theta$ (see Figure 3(e)), accordingly the same considerations of the previous regime holds true here.

R_5: When $\theta_1 < \theta < 1$ the only globally stable equilibrium is the green convention (see Figure 3(f)) because the environmental law is sufficiently high to induce any agent to prefer the ecological strategy. Note that in this case the environmental standards have not to be necessarily strict to obtain the green transition, rather its success is strictly tied with the economic structure of the country. As it will be clear with the numerical simulation (Section 4) the role of firms and consumers is crucial. When the environmental consciousness is highly spread in the society and the industrial profits are close to those coming from clean production, then it is sufficient a (relatively) little stimulus from the Government. This result shows that the country should not simply impose an environmental law, rather it should put an effort to stimulate the citizens' responsibility because it might be a channel to save resource otherwise spent to recover the environmental damages.

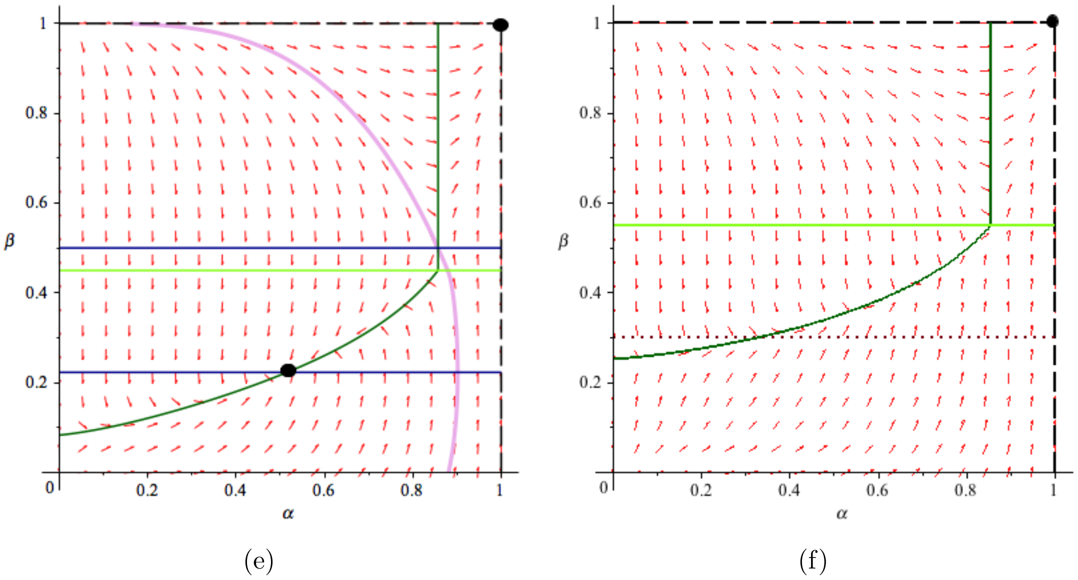


(a)

(b)

(c)

(d)



(e)

(f)

Figure 3: Phase diagram of the dynamical system. The red arrows show the directions of the trajectory. The isocline of the share of green firms (β) is given by the dark green curve. The isocline of the share of green households (α) is given by the horizontal dark blue line(s). The value of θ is the light green horizontal line. The dot horizontal line is the value of u/δ. The magenta curve shows the basin of attraction of the two convention if applicable. Value of parameters: (a) $\delta = 0.7$, $c = 0.3$, $u = 0.35$, $\gamma = 1.1$, $\pi_E = 0.1$, $\pi_P = 0.3$, $\theta = 0.15$; (b) $\delta = 0.5$, $c = 0.5$, $u = 0.35$, $\gamma = 1.5$, $\pi_E = 0.1$, $\pi_P = 0.3$, $\theta = 0.6$; (c) $\delta = 0.5$, $c = 0.1$, $u = 0.15$, $\gamma = 1.5$, $\pi_E = 0.1$, $\pi_P = 0.3$, $\theta = 0.25$; d) $\delta = 0.5$, $c = 0.1$, $u = 0.15$, $\gamma = 1.5$, $\pi_E = 0.1$, $\pi_P = 0.6$, $\theta = 0.35$; (e) $\delta = 0.5$, $c = 0.1$, $u = 0.15$, $\gamma = 1.5$, $\pi_E = 0.1$, $\pi_P = 0.6$, $\theta = 0.45$; (f) $\delta = 0.5$, $c = 0.1$, $u = 0.15$, $\gamma = 1.5$, $\pi_E = 0.1$, $\pi_P = 0.6$, $\theta = 0.55$.

3 *GAME 2 - Bi–lateral IEA*

We based our model on Endres and Finus (1998) with the needed extensions given the results of Γ_1. Assume two countries $i = \{N, S\}$ with a welfare objective function $W_i(\theta_i)$, dependent on national θ_i, defined as the difference between the industrial profits $(\pi_{E,i} + \pi_{P,i})$, proxy for the benefits $\Pi_i(\theta_i)$, and the costs or damages due to the global pollution $D_i(\theta_i, \theta_{-i})$. The asymmetric nature of IEA implies that N and S must be two different groups, where N stands for Northern and richer countries, whilst S means Southern and poorer countries. For simplicity we model only the case with two countries, each one the leader or the representative of its group in order to define a bilateral treaty, as for instance the last agreement between USA and China held in November 2014. We assume, as Pavlova and de Zeeuw (2013), a one-to-one relationship between production and emission given by $\pi_{P,i}$ and quadratic profit and damage functions. Notice that in our model, given the evolutionary foundation of country's economic structure, we do not interpret the country as if it were an individual (given that it is not an homogeneous entity), in fact it may even fail to engage the treaty due to the economic structure rather than a deliberatively choice to free-ride. For these reasons each country, when involved in an IEA, bargains in order to define an uniform θ^*_{global}. Let us assume:

- 2 countries which decide *simultaneously*;
- *Single agreement* on θ^*_{global} based on the smallest common denominator (SCD)-rule which ensures *external stability*;[12]
- *"Good-faith"* commitment which ensures *internal stability.*

Each party agrees and decides simultaneously over a uniform international environmental standard (θ^*_{global}). Among the different bargaining process, we restrict our attention to uniform solutions, by assuming that governments already recognize the externality before negotiations start. Though often almost all parties agree that something should be done to protect the global environment, they disagree about the degree of emission reduction therefore negotiators claim for different clean production standards. Frequently, since international agreements are voluntary and governments do not have the same interests, a compromise is sought which only reflects the *Smallest Common Denominator* (SCD).[13] The SCD-decision rule implies that if $\theta_i < \theta_j$, then $\theta^*_{global} = \theta_i$. In an international bargaining context, one would expect that proposals are strategically motivated, however, as demonstrated in (Endres and Finus, 1998, p. 539-540), the SCD-decision rule is immune to strategic offers, it is a best-reply and a Nash Equilibrium. Furthermore, we assume that each country behaves 'as if' it believes that it is actually able to respect the international treaty (*good-faith commitment*). This ensures the internal stability and, in our context, it is fundamental because our aim is to show a different source of IEA failure rather than free-riding. When states do not comply with an agreement, the reason is often that states do not have the means to comply rather than that they do not have the desire to comply (Chayes and Chayes, 1991, p. 311).

Once that the international environmental treaty is embodied in Γ_1, each country reaches an evolutionary equilibrium (α^*, β^*) dependent on both parameters' value and initial conditions, that are assumed unknown to the governments. This implies that it would be no more necessary to assume free-riding in order to have different performances ($\beta^* \neq \theta^*_{global}$) than what ratified during the IEA. Each country *i*={*N,S*} is characterized by the following welfare function:[14]

$$W_i = \Pi_i - a_i \cdot D \tag{12}$$

---

[12] See Endres and Finus (1998) for the mathematical proof.

[13] See Hoel (1992), Endres (1995), Endres and Finus (1998) and Finus (2001) for a theoretical explanation and empirical assessments.

[14] Note that, in line with the current literature, W does not include consumers' utility for two reasons: i) we want to compare our results within a classical framework to understand the contribution of Γ_1 and ii) consumers' utility does not affect the welfare in equilibrium (i.e when $\beta^* = \theta$). From a mathematical point of view its exclusion simplifies the calculations without any significant loss in the meaning of the results. Indeed, their contribution does not depend on θ but it simply represents a scale factor that cancels out when it is computed the first derivative and, therefore, it does not affect the structure of the game.

and, in particular, the profit and damage function are defined as:

$$\Pi_i = b_i[d_i(\theta_i \cdot \pi_{E,i} + (1-\theta_i)\cdot \pi_{P,i}) - \frac{((1-\theta_i)\cdot \pi_{P,i})^2}{2}] \tag{13}$$

$$D = (\sum_{k=\{i,j\}} (1-\theta_k)\cdot \pi_k)^2 \tag{14}$$

where a, b, $d \,\epsilon\, (0,1)\ \forall i, j \epsilon \{N, S\}$, with $i \neq j$, and $D(\theta_i, \theta_{-i})$ is a quadratic function of the global emissions, representing a proxy of the potential damages caused by extreme climate events. Π_i is composed by two components: the first one is the benefit deriving from production, which is reflected by an higher level of profit, and a second member which stands for the *local* environmental deterioration and health problems due to industrial discharges of polluting firms. In case a_i is null, each nation chooses the business-as-usual (BAU) solution given by θ_i^{BAU} that maximizes Π_i. Pavlova and de Zeeuw (2013) interpret $0 \leq \mathrm{a}_i \leq 1$ as the vulnerability to environmental damages, to wit the probability to incur in negative climate events with the consequent economic losses. In our model it is exogenous and might be interpreted as the result coming from a social debate in which are taken into account the opinion of the scientific community, the environmental consciousness of citizens (δ) and the pressure of public opinion.[15] At this point it is straightforward to list the many connections between Γ_1 and Γ_2: i) the level of industrial efficiency (and profits) determine the gross benefit of a country, ii) the share of green firms might reduce the negative, local and global, environmental damages, iii) the citizens' environmental consciousness, together with other factors, allows the emergence of global ecological concerning ($a > 0$), and iv) the nature of interactions at micro level, between firms and consumers, determine the gap between the expected result of the international policy (θ) and the real one (β^*).

We show that the success of the environmental policy depends on the preferences of consumers, the efficiency of green technology and on the level of environmental awareness spread in the society. The optimum share of emissions under the business-as-usual hypothesis is:

$$\theta_i^{BAU} = 1 - d_i \frac{(\pi_{P,i} - \pi_{E,i})}{\pi_{P,i}^2} \tag{15}$$

Notice that θ^{BAU} is always ϵ (0,1)[16] and that, given d and $\pi_{E,i}$, it increases with the respect of π_P because the government must fix more stringent environmental standards in order to compensate the local ecological damages. On the other hand, a rich country with $\pi_{P,i}$ high might still find convenient to fix stringent environmental standards if it has an advanced green technology, and then when $\pi_{E,i}$ is high as well. In fact in this case it

---

[15] This interpretation recalls the concept of extended-peer-community introduced by Futowicz and Ravetz in their core paper on Post-Normal Science. The interested reader is referred to Futowicz and Ravetz (1994).

[16] Obviously in case of negative values, the country opts for no environmental laws.

would be an advantage to speed up the green transition because it can yield high profits without hurting the environment, avoiding public expenditure to recover any possible environmental damage.

In contrast, if the global externality is recognized by each state ($a_i > 0$), then each country is affected by emissions emanating from its own and the foreign industry and there is the necessity to bargain in order to reach an agreement. The *uncoordinated* equilibrium is given by the max of equation 13 with the respect to θ_i (for each country), while the social optimum (SO) is computed over the sum of all the Welfare functions involved. Thus there is a difference between the non-cooperative (uncoordinated) equilibrium and the cooperative (coordinated) equilibrium.

We are interested in an *endogenous* determination of abatement under different economic conditions, showing the importance of local actions and environmental consciousness. The chances that local actions and environmental organisations will have a major role in future IEAs seem to have improved recently. For instance several international environmental organizations, such as GreenPeace and WWF, have put pressure to governments in order to actively protect and preserve the ecological systems, and they also help public opinion to become more sensitive to the care of nature. Even a recent report of the World Bank (2015) explicitly recognizes the role played by local communities in the management of natural resources. The numerical simulations of Section 4 explain the role of local environmental consciousness for the success of IEA policies. If the global externality is recognized by both governments, each country maximise W_i, and it will propose:

$$\begin{aligned} \theta_i^{NC} = K_i^{NC}\{&\pi_{P,j}(b_j b_i + a_j b_i)[\pi_{P,i}^2 - d_i(\pi_{P,i} - \pi_{E,i})] + \\ &+ \pi_{P,i} a_i b_j [\pi_{P,i}\pi_{P,j} + d_j(\pi_{P,j} - \pi_{E,j})]\} \end{aligned} \tag{16}$$

where

$$K_i^{NC} = [\pi_{P,i}^2 \pi_{P,j} \cdot (b_j b_i + a_j b_i + a_i b_j)]^{-1} \tag{17}$$

with $(j,i) = \{\text{N,S}\}$ and $j \neq i$. Given the high non linearity of the functions involved, it is not possible to establish a simple relationship between the optimal level of environmental standards and the parameters and variables involved. Section 4 shows the results from different numerical simulations which give fruitful insights, here we limit the exposition to two extreme cases which make the equation more tractable. We derive the conditions under which a country behaves as the bottleneck of the international agreement, to wit the country that defines the smallest common denominator. We compare the results under the hypothesis that countries differ only either in the marginal industrial benefits ($b_i \neq b_j$) or in the risk to suffer economic losses from climate change and global pollution ($a_i \neq a_j$). Let assume that both green and polluted profits of the former country follow the same proportion with respect to those of the second country, that is $\pi_{_{P,N}} = m\pi_{_{P,S}}$ and $\pi_{_{E,N}} = m\pi_{_{E,S}}$, with $m > 1$, and that the green profits are $\pi_{_E} = n\pi_{_P}$, with $n \in$

(0,1), in both country. Obviously N is richer than S because $m > 1$, which is a measure of income and technological inequality. Furthermore, let us assume that both countries have the same marginal benefits, $b_{_N} = b_{_S} = b$ and $d_{_N} = d_{_S} = d$, but *different climatic risks*: $a_{_N} = \tilde{z} \cdot a_{_S}$, with $\tilde{z} > 0$. Differences in a might be due to either different weights put to the environment, which can be related to the economic development of a region, or to the geographical location (e.g. Italy may suffer more from sea level rise than Russia). Country i will be the bottleneck (i.e. if $i = S$ and $\theta_N > \theta_S$, then it results that $\theta^*_{global} = \theta_S$) of the IEA game inasmuch as:

$$\tilde{z} > \bar{z}^{NC} \equiv 1 + \frac{b}{a_{_S}} \frac{(1-m)}{(1+m)} \tag{18}$$

$$\lim_{m \to +\infty} \bar{z}^{NC} = 1 - \lambda_{_S} \tag{19}$$

where $\frac{b}{a_{_S}} = \lambda_{_S} > 0$ is the *benefit-risk ratio* of country S given by the benefit of local production and potential losses from global emissions. The threshold $\bar{z}^{NC}$ depends on both the income (and historical) inequality (m) and $\lambda_{_S}$. Given that N is richer than S then, independently from $\lambda_{_S}$, if country N is more risky ($\tilde{z} > 1$) it prefers an higher joint emission reduction, however the convention will be dictated by country S (i.e. $\theta^*_{global} = \theta_S$). The same result holds even when $\tilde{z} < 1$ under the assumption that $\lambda_{_S} > 1$ and that the level of inequality is sufficiently high ($m >> 1$). A typical example is given by China that is likely to suffer from extreme climate events (e.g. desertification) but is finding more convenient to develop further the industrial production and it is thus less concerned about emission reductions.

Let us now consider the opposite case of equal climate damage, $a_{_N} = a_{_S} = a$ but *different opportunity costs* of abatement: $b_{_N} = \hat{z} b_{_S}$. In this case country S will determine the stringency of the IEA game inasmuch as:

$$\hat{z} < \bar{\bar{z}}^{NC} \equiv \frac{a \cdot (1+m)}{a(1+m) + b_S \cdot (1-m)} \tag{20}$$

$$\lim_{m \to +\infty} \bar{\bar{z}}^{NC} = \frac{1}{1 - \lambda_S} \tag{21}$$

where in this case $\lambda_{_S} = \frac{b_S}{a}$. A richer country proposes an higher environmental convention inasmuch as it faces lower opportunity costs and the poorer country expects low benefit-risk ratio. Assume that N has low opportunity costs ($\hat{z} < 1$) and that $\lambda_{_S} < 1$, then $\theta_N > \theta_S$ always because the threshold is greater than 1. In case $\lambda_{_S} > 1$, and m 'sufficiently high', we have that $\bar{\bar{z}}^{NC} < 0$ and thus country N dictates the IEA because S, though poorer, faces a greater opportunity cost with respect to the same climate risk. Note that our results confirm that there is an inverse relation between damage and opportunity costs, furthermore we show that the level of inequality can lead to counterintuitive results

where, for instance, a riskier country prefers a lower level of emission abatement.
To the other side the *coordinated* equilibrium based on the extended welfare function the social optimum and we denote it by the superscript C, that is obtained by maximising the sum of the welfare functions of the two countries:

$$\begin{aligned}\theta_i^C = K_i^C \cdot [\pi_{P,j}[(b_j b_i + a_j b_i + a_i b_i) \cdot (\pi_{P,i}^2 - d_i(\pi_{P,i} - \pi_{E,i})]+ \\ + \pi_{P,i}[(a_i b_j + a_j b_j)(\pi_{P,i}\pi_{P,j} + d_j(\pi_{P,j} - \pi_{E,j})]]\end{aligned} \tag{22}$$

where

$$K_i^C = [\pi_{P,i} \cdot \pi_{P,j}(b_j b_i + a_j b_i + a_i b_j + a_i b_i + a_j b_j)]^{-1} \tag{23}$$

which follows the same structure of the uncoordinated equilibrium, but it includes the interaction effect of cost opportunity and climate risk within each country. Given the non-linearity of this solution, we apply the same comparative analysis, explained above, in order to establish under which conditions $\theta_N^C > \theta_S^C$ and when $\theta_i^C > \theta_i^{NC}$ for all $i = \{N, S\}$. Let assume again that both countries have the same marginal benefits, $b_{_N} = b_{_S} = b$ and $d_{_N} = d_{_S} = d$, but *different climatic risks*: $a_{_N} = \tilde{z}a_{_S}$, with $\tilde{z} > 0$. In this case country S will always be the bottleneck of the IEA game because $m > 1$. It means that, independently from the level of climate risk, the poorest country always dictates the IEA. A possible explanation is that, in a context of coordinated maximization, S knows that, even when it is more risky ($\tilde{z} < 1$), the same percentage of emission reduction after the IEA has the same opportunity cost in both countries, however in absolute values N will reduce more, since that the amount of its polluted production is greater.
More interesting is the comparison between uncoordinated and coordinated values, which returns two thresholds ($0 < \zeta_i^C < 1 < \zeta_j^C$) which define the space where coordinated environmental standards are higher in both countries, that is:

$$\theta_i^C > \theta_i^{NC} \qquad if \qquad \tilde{z} > \zeta_i^C \tag{24}$$

$$\theta_j^C > \theta_j^{NC} \qquad if \qquad \tilde{z} < \zeta_j^C \tag{25}$$

$$\zeta_i^C \equiv \frac{1}{2}\frac{\sqrt{b^2 + 4a_i^2} - b}{a_i} \qquad < 1 \qquad always \tag{26}$$

$$\zeta_j^C \equiv \frac{\sqrt{a_i^2 + a_i b}}{a_i} \qquad > 1 \qquad always \tag{27}$$

Hence for $\tilde{z} \, \epsilon \, (\zeta_i^C, \zeta_j^C)$ both N and S find optimal to fix more stringent emission reductions under a coordination regime. Differently from the great bulk of literature, here coordinated actions are not necessary more environmental friendly, but their success depends on the level of inequality, in terms of potential economic losses due to climate change. Notice that the space for which coordination leads to curb more emissions increases with respect to λ_i, in fact $\frac{\partial \zeta_i^C}{\partial a_i} > 0$ and $\frac{\partial \zeta_i^C}{\partial b} < 0$, furthermore $\frac{\partial \zeta_j^C}{\partial a_i} < 0$ and $\frac{\partial \zeta_j^C}{\partial b} > 0$. On the other hand, in case of *different opportunity costs* of abatement ($\mathrm{b}_N = \hat{z} \cdot b_S$) country S will be the bottleneck if:

$$\hat{z} < \frac{2a(1+m)}{2a(1+m) + b_i(1-m)} = \bar{\bar{z}}^C \tag{28}$$

$$\lim_{m \to +\infty} \bar{\bar{z}}_C = \frac{2}{2 - \lambda_S} \tag{29}$$

thus the same reasoning for uncoordinated equilibrium holds here, where the only exception is represented by the fact that now the benefit-risk ratio is halved since that we are considering the aggregate welfare function. Moreover, in this case, the coordinated equilibrium is always higher than the uncoordinated, in both countries, for each $\hat{z} > 0$.

In summary, we have shown that when the economic framework, to wit consumers and firms's choices, is taken into account the structure of IEA becomes less trivial than what exposed in the great bulk of literature. Indeed, the relation between BAU, non-cooperative and coordinated action is determined by the degree of international (income and technological) inequality, by the level of polluting profits and by the benefit-risk ratio. Their combination could lead to (apparently) counterintuitive results, that actually are able to grasp several real case phenomena. First of all, we establish the conditions for which a poor and risky country is less concerned about environmental issues (e.g. China) because it focuses more on economic growth. Secondly, higher benefit-risk ratio, in both countries, increases the possibility of greater emission reductions under coordinated actions. Third,the coordination of action does not automatically imply more stringent international environmental standards, rather when the inequality is large ($m >> 1$)and the expected loss from climate change is not too high in the bottleneck country, the bargaining process could lead to ratify a smaller θ_{global}. This is a possible explanation of the fact that, in the case of the Kyoto Protocol, for many developing countries (non-Annex I Parties) the compliance of the treaty was not mandatory.

4 Numerical Simulations with 2 asymmetric countries

For sake of simplicity we identify four different kind of countries structured along two axes, representing two key dimensions: environmental consciousness (δ) and economic performance (π), which can be either high or low. Their combination reflects the North-South dichotomy between rich and poor countries but it adds the possibility to be green also in low-income regions (see Figure 4). In particular, we compare three different regimes of environmental consciousness depending on the level of δ (high, medium or low). Section 3 gives some insights in very simplified worlds where only one parameter was allowed to change, i.e. under a ceteris paribus framework we have shown the impact from climate change and the opportunity costs ought to the green transition. Numerical simulations allow to elaborate several alternatives, with many parameters that vary at the same time, giving a range of possibilities which clarifies the relation between the stringency of IEA standards (θ^*) and the actual result (β^*) that each country should attain given its own economic structure.[17] In what follows, we assume that $\gamma = 1$ always, that the Rich country N has $\pi_{P,N} = 0.60$ and $\pi_{E,N} = 0.20$ and that the level of inequality is $m = 2$ such that industries of country S generate the half of the profits: $\pi_{P,S} = 0.30$ and $\pi_{E,S} = 0.10$. Moreover, we keep constant the cost that each green household faces, that is $c = 0.50$ (medium level) and the utility from consumption at $u = 0.10$. In this way we simply set the level of δ to high (0.90), medium (0.50) or low (0.3) to study the relative impact of the environmental consciousness. The other parameters, $\{a, b, d\}_i$ for each country i, vary in order to define four alternative scenarios:

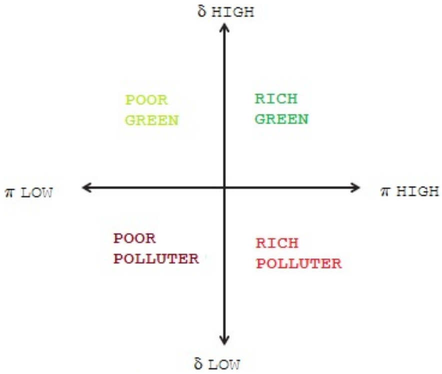


Figure 4: The four categories of countries in this study.

1. *High Benefit-Risk in Southern country*: $a_S > a_N$, $b_S > b_N$ and $d_S = d_N$ so that $\{0.40, 0.80, 0.45\}_S$ and $\{0.20, 0.40, 0.45\}_N$;
2. *High Benefit-Risk in Northern country*: $a_S < a_N$, $b_S < b_N$ and $d_S = d_N$ so that $\{0.20, 0.60, 0.45\}_S$ and $\{0.45, 0.90, 0.45\}_N$;
3. *Asymmetric Benefit-Risk distribution*: $a_S > a_N$, $b_S < b_N$ and $d_S < d_N$ so that $\{0.60, 0.20, 0.45\}_S$ and $\{0.20, 0.60, 0.75\}_N$;
4. *Extreme Asymmetry*: $a_S >> a_N$, $b_S << b_N$ and $d_S < d_N$ so that $\{0.90, 0.10, 0.45\}_S$ and $\{0.10, 0.90, 0.75\}_N$.

Each scenario returns the level of expected welfare $W_i^*(\theta^*_{global})$, under the 'good-faith' commitment assumption (as if each country is able to attain the IEA standards θ^*_{global})

---

[17] Numerical simulations were performed using a Maple algorithm that is available upon request.

and following the SCD-rule in which, in case of different proposals, countries agree to ratify the less stringent environmental standard. Whereupon, we compute the actual welfare $\hat{W}_i(\beta_i^*)$[18] which depends on the actual quota of green firms (β_i^*), the expected ($G_i^* = (1 - \theta_{global}^*)\cdot\pi_P$) and actual level (determined by the fraction of polluting firms, i.e. $\hat{G}_i = (1 - \beta^*)\cdot\pi_P$) of greenhouse gas emissions and the interior equilibrium in each country (α_i^*, β_i^*). Finally, we show the result from an hypothetical 2x2 static game (Tables 3- 6) in which both countries have dichotomic strategies: polluting ($\theta = 0$) or being environmental friendly ($\theta = 1$). There are four different outcomes: $W_i^{00} = b_i(d_i\pi_{P,i} - \frac{\pi_{P,i}^2}{2}) - \frac{a_i(\pi_{P,i}+\pi_{P,j})^2}{2}$ in case both countries neglect environmental issues, $W_i^{11} = b_i d_i \pi_{E,i}$ when they decide to get rid of any polluting production process, $W_i^{10} = b_i d_i \pi_{E,i} - \frac{a_i\pi_{P,j}^2}{2}$ when country j pollutes and i acts unilaterally to green up the production while the reverse holds for $W_i^{01} = b_i(d_i\pi_{P,i} - \frac{\pi_{P,i}^2}{2}) - \frac{a_i(\pi_{P,i})^2}{2}$. The results from the following normal form game give further insights on which country has more convenience in being the bottleneck of the IEA.

Table 3:
High Benefit-Risk in Southern country.

Players	S_E	S_P
N_E	(0.036, 0.036)	**(0.027, 0.054)**
N_P	(0.00, -0.036)	(-0.045, -0.09)

Table 4:
High Benefit-Risk in Northern country.

Players	S_E	S_P
N_E	(0.081, 0.027)	**(0.06, 0.045)**
N_P	(0.00, -0.009)	(-0.101, -0.27)

Table 5:
Asymmetric Benefit-Risk distribution.

Players	S_E	S_P
N_E	(0.09, 0.009)	(0.081, -0.009)
N_P	**(0.126, -0.099)**	(0.081, -0.225)

Table 6:
Extreme Asymmetry.

Players	S_E	S_P
N_E	(0.135, 0.005)	(0.13, -0.031)
N_P	**(0.225, -0.157)**	(0.202, -0.355)

Note: The subscript E stands for ecological strategy ($\theta = 1$),
while P stands for polluting actions ($\theta = 0$).

Case 1 and 2 have only one Nash Equilibrium (bolded) in pure strategy in which S finds convenient to pollute while N acts *unilaterally* to abolish fossil fuels and any other polluting source. Case 3 and 4 present the different equilibria in case N opts for dirty productions while S is environmental friendly. In any case, who finds optimal to choose the strategy $\theta = 1$ receives the greatest payoff. These simple games are worthwhile because, depending on the Nash equilibrium, they predict who will be the bottleneck of the IEA game when θ is allowed to get any value in the continuum $\Re$ within the interval

---

[18] In order to compute the actual welfare we assume that even when country i does not attain the IEA ($\beta_i^* \neq \theta_{global}^*$), the other one does.

[0,1], in fact the polluter in any of the above Nash Equilibria is who dictates the IEA. However, when the decision is not discrete both countries find convenient, in the examples below, to set up green environmental standards such that θ^*_{global} >0.

4.1 Case 1

In the first scenario S faces a medium risk, higher than that of N, to incur in damages due to global pollution and even higher opportunity costs. Under the BAU hypothesis, given this structure, S finds convenient to not impose any environmental restrictions while N would have an incentive to halved its polluting production. When environmental externality is recognized, both countries are involved in international agreement and, differently from what expected, they agree for more stringent policies under the NC framework. Given the SCD-rule the bottleneck (bolded) is the poor country that, notwithstanding the peril of environmental damages, does not want to curb excessively its economic growth. Indeed, in the poorest region the absolute difference between polluting and green profit, and the extreme low level of the latter, overwhelm the weight put to local damages (d) making the ecological strategy less convenient. Under coordinated actions S is again the bottleneck, thought it fixes a slightly lower percentage of green production ($\theta^{*NC}_S > \theta^{*C}_S$). Note that here, and in the subsequent examples, the expected payoff is always greater under the most stringent environmental standard. This is obvious because θ maximizes the welfare function, so that the more β is close to that value the higher is the welfare. When θ^*_{global} is embodied in Γ_1 it becomes evident the crucial role played by the level of *environmental consciousness* (δ): only when it is *high*, keeping constant the other parameters, both countries are able to precisely respect the treaty under the non-cooperative framework, while if they had coordinated their action they would attain a quota of green firms slightly below what ratified.

Here, as in the other three cases, we always obtain that $\beta^*_N = \beta^*_S$ and that $\alpha^*_N \geq \alpha^*_S$. The reason is rather simple: the fraction of green firms is the same because in each (sub-)scenario, dependent on δ, the value of the parameters (c, u, δ, θ), which determine β^*, are the same in both country. On the other hand, the fraction of green consumers, that makes the firms indifferent, is bigger in the richer country because, even thought the ratio (n) between polluting and green profits is the same in both countries, the absolute difference $\pi_P - \pi_E$ is greater in this region. It is thus required more green consumers to make the polluted firms, in the rich region, indifferent.

4.2 Case 2

$\forall i$={N,S}, the parameters d_i, $\pi_{_{P,i}}$ and $\pi_{_{E,i}}$ are the same as in Case 1 then, based on equation 15, under the BAU hypothesis the results of Case 1 hold here, where S is again the bottleneck in the NC framework. Case 2 is in line with the great bulk of

Table 7:
High Benefit-Risk in Southern country.

		BAU ($a = 0$)		NON-COOP (NC)		COORD (C)	
Scenario	*Outcome*	N	S	N	S	N	S
'Good-Faith'	θ^*	*0.50*	*0.00*	*0.75*	**0.50**	*0.96*	**0.46**
	W*	0.054	0.072	0.034	0.023	0.030	0.017
	G*	0.30	0.30	0.30	0.15	0.320	0.161
δ HIGH	α^*	0.75	0.00	0.75	0.75	0.67	0.59
	β^*	**0.50**	*0.00*	**0.50**	**0.50**	*0.404*	*0.404*
	$\hat{W}$	*0.054*	0.072	0.034	0.023	0.026	0.016
	$\hat{G}$	0.30	0.30	0.30	0.15	0.36	0.18
δ MEDIUM	α^*	0.47	0.00	0.47	0.10	0.47	0.15
	β^*	*0.30*	*0.00*	*0.30*	*0.30*	*0.26*	*0.26*
	$\hat{W}$	0.051	0.072	0.019	0.017	0.013	0.015
	$\hat{G}$	0.42	0.30	0.42	0.21	0.44	0.22
δ LOW	α^*	0.23	0.00	0.23	0.00	0.24	0.00
	β^*	*0.125*	*0.00*	*0.125*	*0.125*	*0.098*	*0.098*
	$\hat{W}$	0.044	0.072	0.001	0.008	-0.007	0.001
	$\hat{G}$	0.52	0.30	0.52	0.26	0.54	0.27

literature since that the Social Optimum requires more stringent environmental standards ($\theta_N^{*C} > \theta_S^{*NC}$), that yield lower emissions and higher welfare. Note that the value of $\theta_C^* = 0.75$ is not as ambitious or not realistic, indeed Field et al. (2014) suggests that, in order to avoid a temperature increasing greater 2 Celsius degree, is feasible only lowering global greenhouse gas emissions by 40 to 70 percent compared with 2010 by mid -century, and to near -zero by the end of this century. Ambitious mitigation might even require removing carbon dioxide from the atmosphere. If both countries have ratified θ_N^{*C} they would attain a complete green transition with only green firms and consumers, to wit they obtain environmental performances better than what ratified independently from the level of environmental consciousness.

The latter does not play any role because in this case $\theta_N^{*C} > \theta_1$ which is the threshold upon which the system converges to the (1,1) equilibrium (see Regime 3(f)). Note that in column 5-6 the welfare associated with $\alpha_i^* = \beta_i^* = 1$ is lower than that of Table 8 because each country assumes that the other fits the IEA standard (that is lower than 1). δ plays a crucial role only under the NC framework, in fact when it is *low* both countries reaches an interior equilibrium close to (0,0) where the emissions are maximum. Inasmuch as inequality increases the level of emissions increases as well showing that a more equal distribution of environmental risks and industrial profits would lead to better environmental status.

Table 8:
High Benefit-Risk in Northern country.

		BAU ($a = 0$)		NON-COOP (NC)		COORD (C)	
Scenario	*Outcome*	N	S	N	S	N	S
	θ^*	*0.50*	*0.00*	*0.77*	**0.36**	**0.75**	*0.77*
'Good-Faith'	W*	0.121	0.072	0.044	0.017	0.10	0.033
	G*	0.30	0.30	0.382	0.19	0.146	0.072
	α^*	0.75	0.00	0.62	0.50	1.00	1.00
δ HIGH	β^*	**0.50**	*0.00*	*0.275*	*0.275*	**1.00**	**1.00**
	$\hat{W}$	0.121	0.054	0.025	0.016	0.079	0.024
	$\hat{G}$	0.30	0.30	0.38	0.19	0.00	0.00
	α^*	0.47	0.00	0.43	0.21	1.00	1.00
δ MEDIUM	β^*	*0.30*	*0.00*	*0.163*	*0.163*	**1.00**	**1.00**
	$\hat{W}$	0.115	0.054	-0.005	0.013	0.079	0.024
	$\hat{G}$	0.42	0.30	0.50	0.25	0.00	0.00
	α^*	0.23	0.00	0.01	0.00	1.00	1.00
δ LOW	β^*	*0.125*	*0.00*	*0.023*	*0.023*	**1.00**	**1.00**
	$\hat{W}$	0.099	0.054	0.05	0.008	0.079	0.024
	$\hat{G}$	0.52	0.30	0.59	0.295	0.00	0.00

4.3 Case 3 and Case 4

Case 3 defines a more realistic scenario where richer country is less risky but faces higher opportunity cost since it has to convert advanced, and profitable, polluting production process through high technological and infrastructural investments. Case 4 proposes an extreme version of Case 3 to underline the impact of unequal distribution of risks and profits between countries. Obviously, in both cases, N dictates the IEA because has less convenience in reducing the emissions since it faces high cost-risk ratios ($\lambda_N^{(3)} = 3$ and $\lambda_N^{(4)} = 9$).

Under the BAU hypothesis both countries have low incentive in promoting environmental laws, therefore the quota of green firm is (almost) null independently from δ which plays a marginal role when it is not supported by governmental policies. The SO requires more stringent standards and returns higher level of welfare. Under a NC regime they converge to low green production convention when the environmental consciousness is not 'sufficiently' high. These are remarkable results because they underline the negative (environmental) effect of global inequality, the possible ineffective role of citizens when they are hampered by insufficient environmental laws and the need to integrate the bottom-up level with the top-down one in order to achieve successful climate targets.

In summary, a cross comparison between different scenarios allows to clarify the impor-

Table 9:
Asymmetric Benefit-Risk distribution.

		BAU ($a = 0$)		NON-COOP (NC)		COORD (C)	
Scenario	*Outcome*	*N*	*S*	*N*	*S*	*N*	*S*
'Good-Faith'	θ^*	*0.17*	*0.00*	**0.27**	*1.00*	**0.45**	*1.00*
	W^*	0.165	0.018	0.120	-0.112	0.132	-0.058
	G^*	0.50	0.30	0.438	0.219	0.332	0.166
δ HIGH	α^*	0.47	0.00	0.57	0.44	0.66	0.57
	β^*	*0.07*	*0.00*	*0.17*	*0.17*	*0.38*	*0.38*
	$\hat{W}$	0.163	0.018	0.113	-0.012	0.131	-0.06
	$\hat{G}$	0.558	0.30	0.50	0.25	0.372	0.186
δ MEDIUM	α^*	0.00	0.00	0.353	0.187	0.463	0.17
	β^*	*0.00*	*0.00*	*0.07*	*0.07*	*0.247*	*0.247*
	$\hat{W}$	0.162	0.018	0.107	-0.136	0.126	-0.07
	$\hat{G}$	0.60	0.30	0.558	0.28	0.452	0.226
δ LOW	α^*	0.00	0.00	0.00	0.00	0.233	0.00
	β^*	*0.00*	*0.00*	**0.00**	**0.00**	*0.08*	*0.08*
	W^*	0.162	0.018	0.09	-0.145	0.113	-0.11
	G^*	0.60	0.30	0.60	0.30	0.552	0.276

Table 10:
Extreme Asymmetry.

		BAU ($a = 0$)		NON-COOP (NC)		COORD (C)	
Scenario	*Outcome*	*N*	*S*	*N*	*S*	*N*	*S*
'Good-Faith'	θ^*	*0.17*	*0.00*	**0.17**	*1.00*	**0.29**	*1.00*
	W^*	0.247	0.009	0.22	-0.23	0.224	-0.17
	G^*	0.50	0.30	0.50	0.25	0.427	0.213
δ HIGH	α^*	0.47	0.00	0.47	0.34	0.58	0.45
	β^*	*0.07*	*0.00*	*0.07*	*0.07*	*0.192*	*0.192*
	$\hat{W}$	0.246	0.009	0.21	-0.257	0.223	-0.19
	$\hat{G}$	0.558	0.30	0.558	0.279	0.484	0.242
δ MEDIUM	α^*	0.00	0.00	0.00	0.00	0.38	0.199
	β^*	*0.00*	*0.00*	**0.00**	**0.00**	*0.09*	*0.09*
	$\hat{W}$	0.243	0.009	0.20	-0.273	0.217	-0.214
	$\hat{G}$	0.60	0.30	0.60	0.30	0.546	0.273
δ LOW	α^*	0.00	0.00	0.00	0.00	0.00	0.00
	β^*	*0.00*	*0.00*	**0.00**	**0.00**	**0.00**	**0.00**
	$\hat{W}$	0.243	0.009	0.20	-0.273	0.209	-0.22
	$\hat{G}$	0.60	0.30	0.60	0.30	0.60	0.60

tance of local environmental consciousness in attaining higher level of clean production. Note that in Case 1 with $\theta^{*NC} = 0.50$ both countries converge to $\beta^* = 0.125$ when δ

is *low*, while in Case 3 with $\theta^{*NC} = 0.26$ both countries converge to $\beta^* = 0.17$ if δ is *high*. This clearly shows that local participation can have the positive impact to fasten the process of cleaning production and to save resources for alternative use, because they allow governments to fix less stringent standards and to avoid additional expenditures to recover environmental damages.

5 Discussion and concluding remarks

This paper has considered two countries with different economic structures negotiating emission reductions and it compared the outcomes for several combinations of abatement costs, environmental consciousness and consumers' preferences both analytically and with numerical simulations. Negotiators were assumed to agree on the smallest common denominator, defining an unique global environmental standard. Our mathematical framework confirms that 'global solutions' negotiated at international level, if not backed up by a variety of efforts at national, regional, and local levels to prompt environmental consciousness, are not guaranteed to work well. To best of our knowledge this study is the first combining two different games in a consistent framework, which is a methodological novelty. We showed that the different evolutionary paths at micro level, determined by the interactions between firms and consumers, are essentials to explain different environmental performances and the heterogenous capacity of each country to precisely attain, to fail or to overcome the international environmental standards.

From the *micro* point of view, our model is able to identify five different Regimes under which each economy reaches different equilibria. Each of them defines the range of 'success' of global standards bargained between countries. We have shown that IEA alone are 'weak' policies if not backed up by local initiatives and a sufficient level of ecological awareness. In fact, from our numerical simulations, it seems clear that the very same international standards may lead to very different results. If public opinion is particularly 'biased' toward environmental preservation then the government may impose lower standards and thus saving resources for other public investments.

From the *macro* point of view we have defined both analytically and with numerical simulations the impact of inequality, asymmetric risks and opportunity costs distribution. Firstly, our results confirm that there is an inverse relation between damage and opportunity costs. Given a certain level of inequality, a country establishes environmental friendly standards inasmuch the benefit–cost ratio is high. Secondly, historical inequality, in terms of different level of profits generated by the industries and different technological development of both green and polluting firms, and heterogenous risks play a key role. Case 4 shows that, in case of extreme inequality, the environmental standards are low, which determines higher level of emissions and a lower welfare for the poorest country. This might explain why the Kyoto protocols were not mandatory for the developing countries. Even though we considered only two countries, our paper provides a possible insight for the emergence of multiple coalitions composed by (almost) homogeneous countries, indeed Case 4 shows that, when the asymmetries are too high, the IEA results in poor environmental standards. We think that the inclusion of many parties will be an interesting extension of the current model.

The main contribution, with the respect to the current literature on IEA, stands on the modelisation of the economic structure which gives further insights to explain the gap between the promises of the agreements and the actual results. The notion of free-riding might be misleading when dealing with collective entities, like countries, which do not behave as (rational) individual. Rather, what we observed, in terms of national performances, is the outcome of a complex system where agents interact to fulfil their needs and desires. Our model captures many features that characterized the last IEA held in Paris (November, 2015). Genuine concern about the climate ($a > 0$), public opinion (δ) and international pressure produced the pledges that were made for Paris. These, and similar, bottom-up processes, together with international (top-down) efforts, are the necessary steps to drive up the level of action in decades to come. In this respect our paper highlights the role of environmental consciousness and citizen's responsibility thought as a key feature for the possible transition towards a fossil-free economy. Another remarkable extension of the current study is to explicitly model the formation of δ, its influence on both government decisions and international agreements. As seen above, many ONGs, local communities or simply groups of people have put pressure towards a definitions of serious and ambitious environmental standards. Furthermore, this variable stands behind the consumer's choices and its contribution is crucial to boost a kind of 'innovation' from the demand-side aimed at change the consumption bundle and to force markets to shift towards the supply of sustainable goods and services.

One of the caveats, which must be mentioned when interpreting our model, is that it uses rather specific functions and parameter values to derive the bargaining outcomes and the evolutionary paths. We assumed quadratic profit and damage function in line with the great bulk of literature because we aimed to show a different source, from free-riding, of the heterogenous environmental performances. A promising extension of our model could be to assess the outcomes when more realistic damage and profit functions are involved. This would open the door towards an empirical assessment of the factors that hamper or facilitate the green transition. Secondly, climate change is strictly tied with other factors, not included in our model, such as population and economic growth, technological progress and spillover, heterogeneous impact of different pollutants, stock of emitted GHGs remaining in the atmosphere, creation of new green jobs, trade and international transfers and the time and cost of conversion from a fossil-based economy towards a new one fed by renewable energies. Obviously, taking into account all these features in an unique, simple and tractable mathematical model is unattainable. From a theoretical point of view we offer an innovative perspective where grounding a multi-scale analysis. However, Game 2 is based on one-shot game, while in reality parties do have a chance of switching strategies, players can make multiple moves and counter-moves during the course of the bargaining process and there is a time lag between proposals and the final ratification of the IEA. In accordance with the observation of Kolstad (2011), we have shown the importance of income inequality which is often neglected in classical IEA games.

Finally, from the numerical simulations and from subsection 2.3 and Section 3, it emerges that the results are quite robust and have clear economic explanations. We thus can claim to have found a reasonable compromise between the complexity of the problem at hands and the elaboration of a theoretical model able to grasp the most important relations, with a tractable system of equations (most results are derived analytically). Another promising extension of our model could be to define a more general framework in which combine the micro and macro levels in line with a multi-scale perspective. This seems to be suggestive because it opens the debate around the coordination between international agreements and the active role of citizenship. Combining all these elements in a consistent and integrated theoretical model presents a substantial challenge but this study wants to pave the way towards more comprehensive game where real and relevant factors are seriously taken into account in a reasonably simple and tractable model.

Acknowledgments

Tiziano Distefano gratefully acknowledges IMT for the financial support of his PhD scholarship. Authors also thank the Department of Economics, of the University of Pisa, Prof. Douglas Crawford-Brown (University of Cambridge) and Dr. Valeria Andreoni (Liverpool Hope University) for the feedbacks and the comments received.

References

Agrawal, A. (2008, March 5-6). The role of local institutions in adaptation to climate change. Technical report, Social Dimensions of Climate Change, Social Development Department, The World Bank, Washington DC.

Barrett, S. (1994). Self-enforcing international environmental agreements. *Oxford Economic Papers 46*, 878–894.

Bodansky, D., E. Diringer, J. Pershing, and X. Wang (2004). Strawman elements: Possible approaches to advancing international climate change efforts. Technical report, Washington: Pew Center on Global Climate Change.

Bowles, S. (2004). *Microeconomics: Behavior, Institutions, and Evolution: Behavior, Institutions, and Evolution.* Oxford - Princeton University press.

Calvo, E. and S. J. Rubio (2012). Dynamic models of international environmental agreements: A differential game approach. In *International Review of Environmental and Resource Economics.*

Carraro, C., J. Eyckmans, and M. Finus (2006). Optimal transfers and participation decisions in international environmental agreements. *Review of International Organizations 1*(4), 379–396.

Carraro, C. and D. Siniscalco (1993). Strategies for the international protection of the environment. *Journal of Public Economics* (52), 309–328.

Chayes, A. and A. H. Chayes (1991, July). Compliance without enforcement: State behavior under regulatory treaties. *Negotiation Journal 7*, 311–330. doi: 10.1111/j.1571-9979.1991.tb00625.x.

Colmer, J. (2011). Asymmetry, optimal transfers and international environmental agreements. *GRI Working Papers 66, Grantham Research Institute on Climate Change and the Environment.*

Courtois, P., J. Péreau, and T.Tazdaït (2004). An evolutionary approach to the climate change negotiation game. *Louvain Economics Review 70*(1), 31–51.

de Zeeuw, A. (2008). Dynamic effects on the stability of international environmental agreements. *Journal of Environmental Economics and Management 55*(2), 163–174.

Endres, A. (1995). Zeitschrift für umweltpolitik. *Zur Ökonomie Internationaler Umweltschutzvereinbarungen 8*, 143–178.

Endres, A. and M. Finus (1998, September). International environmental agreements: How the policy instrument affects equilibrium emissions and welfare. *Journal of Institutional and Theoretical Economics (JITE) / Zeitschrift für die gesamte Staatswissenschaft 155*(3), 527–550.

Field, C., V. Barros, D. Dokken, K. Mach, M. Mastrandrea, T. Bilir, M. Chatterjee, K. Ebi, Y. Estrada, R. Genova, B. Girma, E. Kissel, A. Levy, S. MacCracken, P. Mastrandrea, and L. White (2014). Summary for policymakers. in: Climate change 2014: Impacts, adaptation, and vulnerability. part a: Global and sectoral aspects. Technical report, IPCC, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Finus, M. (2001). *Game Theory and International Environmental Cooperation.* Edward Elgar Publishing Limited.

Futowicz, S. and J. Ravetz (1994). The worth of a songbird: Ecological economics as a post-normal science. *Ecological Economics 10*(3), 197–207.

Heal, G. and B. Kristrom (2002). Uncertainty and climate change. *Environmental and Resource Economics 22*, 3–39.

Hoel, M. (1992). International environment conventions: The case of uniform reductions of emissions. *Environmental and Resource Economics 2*, 141–159.

Hofbauer, J. and K. Sigmund (1998). *Evolutionary Games and Population Dynamics.* Cambridge Univ. Press.

Jeppesen, T. and P. A. Andersen (2002). Commitment and fairness in environmental games. In N. Hanley and H. Folmer (Eds.), *Game Theory and the Environment*, Chapter 4, pp. 65–83. Cheltenham, UK: Edward Elgar.

Kolstad, C. D. (2007, January). Systematic uncertainty in self-enforcing international environmental agreements. *Journal of Environmental Economics and Management 53*(1), 68–79.

Kolstad, C. D. (2011). Bridging reality and the theory of international environmental agreements. In R. W. Hahn (Ed.), *Climate Change and Common Sense: Essays in Honour of Tom Schelling.* Oxford University Press. http://dx.doi.org/10.1093/acprof:oso/9780199692873.003.0005.

McGinty, M. (2005). International environmental agreements among asymmetric nations. *Oxford Economic Papers New Series 59*(1), 45–62.

McGinty, M. (2010). International environmental agreements as evolutionary games. *Environmental and Resource Economics 45*(2), 251–269.

Meserve, R. A. (2008). An introduction to energy and climate change. *Bulletin of the American Academy (Winter)*, 29–32.

Oliver, J., G. Janssens-Maenhout, M. Muntean, and J. Peters (2014). Trends in global co2 emissions. Technical report, PBL Netherlands Environmental Assessment Agency and EU Joint Research Centre, Ispra.

Ostrom, E. (2009). A polycentric approach for coping with climate change. *The World Bank Development Economics, Washington, DC*.

Pavlova, Y. and A. de Zeeuw (2013). Asymmetries in international environmental agreements. *Environment and Development Economics 18*(1), 51–68.

Rubio, S. J. and A. Ulph (2007). An infinite-horizon model of dynamic membership of international environmental agreements. *Journal of Environmental Economics and Management 54*(3), 296–310.

Santos, F. C. and J. M. Pacheco (2011). Risk of collective failure provides an escape from the tragedy of the commons. *PNAS 108*(26), 10421–10425.

Santos, F. C., V. V. Vasconcelos, M. D. Santos, P. N. B. Neves, and J. M. Pacheco (2012). Evolutionary dynamics of climate change under collective-risk dilemmas. *Mathematical Models and Methods in Applied Sciences 22*(1140004). DOI: : 10.1142/S0218202511400045.

Sigmund, K. (2010). *The Calculus of Selfishness.* Princeton University Press.

Vasconcelos, V. V., F. C. Santos, J. M. Pacheco, and S. A. Levinf (2013). Climate policies under wealth inequality. *PNAS 111*(6), 2212–2216.

Weibull, J. W. (1996). *Evolutionary Game Theory.* (1 ed.), Volume 1. MIT Press Book.

Young, H. P. (1998). *Individual Strategy and Social Structure: An Evolutionary Theory of Institutions.* Princeton University Press.