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Adoption Gaps of Environmental Adaptation Technologies with Public Effects

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Adoption Gaps of Environmental Adaptation Technologies with Public Effects

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Summary

The global nature of the climatic challenge requires a high level of cooperation among agents, especially since most of the related coping strategies produce some kind of externalities toward others. Whether they are positive or negative, the presence of externalities may lead the system towards Pareto-dominated states. In this work, we study under and over-adoption of environmental adaptation technologies which enhance environmental quality for the individual while transferring externalities to other agents. We distinguish adaptation technologies between maladaptation and mitigation ones, depending on the sign of the externalities. In particular, we show that over adoption may occur for maladaptive technologies, whereas under-adoption may occur in case of mitigation. We study a model with two regions at different stages of development, which allows us to draw considerations on well-being consequences of environmental dumping.

Keywords: Adaptation, Negative Externalities, Evolutionary Dynamics, Public Good Game, Environmental Dumping

JEL Classification: C70, D62, O13, O40, Q20

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1 Introduction

Environmental hazards are gaining relevance at an increasing pace, requiring humans to change their behaviour and decision making criteria. We had to forgo the comforting idea that "natural systems fluctuate within an unchanging envelope of variability"(Milly et al., 2008). As concerns environmental hazards, responses are typically characterised dichotomously: adaptation and/or mitigation (UNEP, 2019; IPCC, 2014), with the implementation of one not excluding the other's. On the one hand, humans may (and do) adapt to a changing climate, reducing their exposure to the ensuing harm. This includes responding to abnormal hot or cold temperatures, adopting new agricultural techniques to cope with the impoverishment of soil, creating artificial snow in ski resorts, and much more (for a broad review on many other forms of adaptation, see Tompkins et al., 2010). On the other hand, humans may (and do) try to take mitigation strategies, namely tackling the problem at its source and combating the causes of increased environmental risks. Efficient water management, restoration of soil, substitution of fossil fuels with agricultural by-products are some of the mitigation techniques currently under study for the agricultural sector (Smith et al., 2007). These strategies not only reduce the environmental hazards for the adopter, but for all agents, thus generating a positive externality to other agents. With respect to mitigation strategies, adaptation does not aim to reduce the problem, but rather to avoid at least part of its adverse affects. At times, this is done at the expense of other agents, i.e. adaptation strategies may generate negative externalities. For instance, a farmer suffering from reduced plot productivity due to soil degradation may decide to raze a forest area to expand her plot and compensate for her loss of income. However, in this way she is further contributing to the problem of soil erosion and to the general loss of regenerative capacity of the ecosystem. Another notorious instance of maladaptation is air conditioning: by improving domestic temperature for the user, it increases the risk of energy shortages and ultimately worsens the problem of climate change (Lundgren and Kjellstrom, 2013). When a strategy is such that it shifts environmental hazards to others, it postpones them for future generations to bear, or it disproportionally affects the most vulnerable, the literature defines it no more as adaptation, but rather as maladaptation (UNEP, 2019; Barnett and

O'Neill, 2010). However, the UNEP (2019)[1] stresses that every adaptation strategy that increases the opportunity cost of moving to a more sustainable alternative is maladaptation, as it has detrimental effects on long term sustainability. We here study the dynamics of mitigation and maladaptation, showing how global externalities lead to under-adoption of strategies of the former type and over-adoption of the latter.

Since mitigation strategies actually reduce environmental hazards instead of (temporarily) avoiding its effects, it is usually considered to be the most desirable strategy (IPCC, 2014). However, there are reasons why humans did not respond with enthusiasm to the emergence of mitigation solutions in the face of environmental hazards. Firstly, many mitigation strategies require long-term investments to pay off, with a time scale that may exceed the average life expectancy of a person before they become effective (Hallegatte, 2009). The incapacity of humans to make long-term investments and their preference for the present are additional threats to our capacity to make long-term commitments to stop environmental degradation (Warburton et al., 2018), leading to issues of intergenerational equity (Glotzbach and Baumgartner, 2012), which is a characterising feature of maladaptation (UNEP, 2019). We remark that the existence of mitigation solutions is not a sufficient condition for the abatement of environmental damage. The literature has uncovered several ways in which externalities of any type, either negative or positive (as is the case for mitigation strategies) may undermine the achievement of the social optimum. On the one hand, whenever an agent may transfer her cost to protect against environmental hazards onto others, in a way that is either anonymous or has no consequences on herself, she has little incentive to adopt a mitigation strategy. For instance, an agent might prefer to install a substantially cheaper air conditioning system instead of investing to enhance house insulation. On the other hand, if a strategy actually reduces environmental risks not only for the adopter, but also for other agents, i.e. it has a positive externality, then it may happen that all agents wait for the others to tackle environmental degradation for everyone, but none is willing to pay the cost for the benefit of others[2]. This is

[1] United Nations Environment Programme.

[2] In an experimental setting, Hasson et al. (2010) show that agents rarely contribute to the mitigation solution and that their contributions to a common mitigation policy are not sensitive

but an instance of the well known free rider problem, which emerges from the non-excludability of agents from the benefits of a public good (Heller and Starrett, 1976). Scholars studying these shiftable externalities highlighted that policy tools hindering maladaptive strategies and promoting mitigation ones are desirable, e.g. a tax on negative externalities or a subsidy on positive ones (Bird, 1987; Shaw and Shaw, 1991; Shogren and Crocker, 1991; Geaun, 1993).

In this work, we focus on the dichotomy between maladaptation and mitigation, studying the adoption dynamics of the related strategies. We assume that individuals from a more developed region and a less developed one have the possibility to adopt a technology which enhances environmental quality for the adopters, but also generates externalities on other agents. In particular, each region has a local environmental indicator which is affected by the adoption dynamics of both regions, so that the externalities have a global effect. These externalities may be either negative, in case of a maladaptation technology, or positive, in case of a mitigation technology. We highlight what is the underlying mechanism which leads to over-adoption of maladaptation strategies and under-adoption of mitigation ones. In addition, we show what are the effects on the less developed region if the maladaptation technology is such that it disproportionally burdens its population with respect to the agents from the more developed region. The adoption dynamics is modelled by a two population evolutionary game which employs replicator equations, so that all agents may imitate their peers in the region, if the well-being of the latter is greater. Our analysis leads to three major conclusions: 1) when only a maladaptive technology is available, either all agents adopt it or none, depending on the initial distribution of strategies; 2) when only a mitigation technology is available, the system *typically* reaches a state in which a part of the population adopts the technology while the rest does not; no path dependency arises 3) if the more developed region dumps negative externalities onto the less developed one, it might happen the the well-being of all agents decreases. In section 2 we illustrate our model. We then employ it to analyse the adoption dynamics of a maladaptive technology (section 3) and of a mitigation one (section 4). Finally, in section 5 we

to the likelihood of extremely adverse events. In a somewhat similar experiment, Milinski et al. (2006) show that reputation effects may nudge agents to contribute to a public good in an environmental framing.

elaborate on the results, draw some policy implications and sketch future research directions.

2 The model

Let us consider two regions $j = N, S$. Agents from both regions can either adopt a strategy $\boldsymbol{A}$ enhancing personal environmental quality at a cost C^j or choose not to do so (strategy $\boldsymbol{NA}$). When all agents adopt strategy $\boldsymbol{NA}$, the environmental quality for all agents is equal to $\overline{E}^j$. When agents adopt strategy $\boldsymbol{A}$, their action has both a public effect (P^j) on the environmental quality of all agents and a private effect (p^j) effect on themselves. As a consequence, the overall environmental quality for agents i is described as follows:

$$E_t^j = \begin{cases} \overline{E}^j + P_t^j & \text{if } i \text{ chooses strategy } \boldsymbol{NA} \\ \overline{E}^j + P_t^j + p^j & \text{if } i \text{ chooses strategy } \boldsymbol{A} \end{cases}$$

where P^j can take either sign. The well-being of an agent i from region j depends on E^j and on whether she incurs in the adoption cost:

$$\Pi_i^j := \begin{cases} \ln(\overline{E}^j + P_t^j) & \text{if } i \text{ chooses strategy } \boldsymbol{NA} \\ \ln(\overline{E}^j + P_t^j + p^j) - C^D & \text{if } i \text{ chooses strategy } \boldsymbol{A} \end{cases} \tag{1}$$

where the adoption cost C^j is strictly positive. We now define the public effect P_t^j, which depends on the shares of agents $x_t, z_t \in [0, 1]$ adopting strategy $\boldsymbol{A}$ at time t in regions N and S, respectively. More in detail, we differentiate between domestic and foreign effects of the adaptation technology. The former describes the impact on a local environmental indicator of same-region adopters, whereas the latter describes the impact of cross-region adopters. For the sake of simplicity, we assume that the public effects are determined by linear functions:

$$P_t^N := -d^N \cdot x_t - f^N \cdot z_t \tag{2a}$$

$$P_t^S := -f^S \cdot x_t - d^S \cdot z_t \tag{2b}$$

where parameters d^j and f^j measure the domestic and the foreign public effects, respectively, for country $j = N, S$. They represent the public impact of adoption of all agents on the local environmental indicator of region j, distinguished according to the source of such impact. Domestic effects d^j are caused by agents in region j and worsen the quality of their own local environmental indicator, whereas foreign effects f^j affect the local environmental indicator of region j but are caused by agents in the other region. We do not apply any sign restriction on the public effects, so that externalities of adoption of the environmental adaptation technology may take either sign. When a public effect P^j is positive, adoption of strategy $\boldsymbol{A}$ by an agent carries part of its benefits over to other agents. This case qualifies as a mitigation case, in which an agent is working for the cooperative improvement of environmental quality, or equivalently towards the abatement of pollution. By contrast, when the public effect is negative, an agent adopting strategy $\boldsymbol{A}$ is actually benefiting herself by worsening environmental quality for others. From the concavity of (1), we may add that a negative public effect affects relatively more (reduces well-being by a higher amount) the agents who are not adopting the environment enhancing strategy $\boldsymbol{A}$. By the definition provided by Barnett and O'Neill (2010), this is a case of maladaptation.

In order to study the dynamics of this system, we now describe the way in which the share of agents adopting strategy $\boldsymbol{A}$ in either country varies. We assume that if the difference in well-being $\Delta\Pi^j = \Pi^j_A - \Pi^j_{NA}$ between strategy $\boldsymbol{A}$ and strategy $\boldsymbol{NA}$ is positive for region j, then the share of agents adopting the technology (either a maladaptive or a mitigation one) in that region will increase, since it provides higher payoffs. The opposite holds if the payoff difference is negative. Finally, if the payoff difference equals zero, economic agents are indifferent between adopting or not adopting the technology, so that the population shares of agents adopting the technology keeps constant over time. Therefore, we have that:

$$\Delta\Pi^N(x_t, z_t) \gtreqless 0 \Rightarrow \dot{x} \gtreqless 0 \quad \Delta\Pi^S(x_t, z_t) \gtreqless 0 \Rightarrow \dot{z} \gtreqless 0 \tag{3}$$

where $\dot{x}$ and $\dot{z}$ are the time derivatives of x_t and z_t, respectively. Hence, in each region the payoff difference $\Delta\Pi^j(x_t, z_t)$ in N and $\Delta\Pi^S(x_t, z_t)$ in S has the same sign as the time derivative of the population share that adopts the environmental adaptation technology in that region. Referring to the well-being definition (1), we may explicit the payoff difference $\Delta\Pi^j$:

$$\Delta\Pi^j(x_t,z_t) = \Pi^j_A(x_t,z_t) - \Pi^j_{NA}(x_t,z_t) = \ln\frac{\overline{E}^j + p^j + P^j_t}{\overline{E}^j + P^j_t} - C^j \tag{4}$$

For the sake of simplicity, we assume that the dynamics of x_t and z_t is given by the so-called "replicator dynamics"(see e.g. Weibull, 1995):

$$\begin{cases} \dot{x} = x(1-x)\Delta\Pi^N(x,z) \\ \dot{z} = z(1-z)\Delta\Pi^S(x,z) \end{cases} \tag{5}$$

where we omitted the temporal subscript t to improve readability. Dynamics (5) describes an adaptive process based on an imitation mechanism: every period t, a (very) small fraction of the population changes its strategy adopting the more remunerative one. Differently from the "classical" contexts where replicator dynamics are introduced (in which economic agents are pairwise randomly matched), here the well-being of each agent depends on the technological choice by *all* agents, in both regions, and at the same instant; that is, we analyse a *population game*. Replicator dynamics may be generated by several learning mechanisms in a random matching context (see e.g. Börgers and Sarin, 1997; Schlag, 1998); however, rationales for such dynamics can be found also in our context (see e.g. Sacco, 1994). Sethi and Somanathan (1996) propose an application of replicator equations in a context similar to ours.

1.1 Basic mathematical results

As the shares of agents adopting strategy $\boldsymbol{A}$ are defined in the interval $[0,1]$, the dynamic system (5) is defined in the square $\boldsymbol{Q}$:

$$Q = \{(x,z) : 0 \le x \le 1, \quad 0 \le z \le 1\}.$$

We will henceforth denote with $Q_{x=0}$ the side of $\boldsymbol{Q}$ along which $x=0$, and with $Q_{x=1}$ the side along which $x=1$. Similar interpretations apply to $Q_{z=0}$ and $Q_{z=1}$. All sides of this square are invariant; in other terms, if the pair (x,z) initially lies on one of the sides, then the whole correspondent trajectory also lies on that side.

Note that the states $\{(x, z) = (0,0), (0,1), (1,0), (1,1)\}$ are always stationary states of the dynamic system (5). In such states, only one strategy (either $\boldsymbol{A}$ or $\boldsymbol{NA}$) is played in each region. Other stationary states are the points of intersection between the interior of the sides $Q_{x=0}$, $Q_{x=1}$ (where $\dot{x} = 0$) and the locus $\Delta\Pi^S(x, z) = 0$ (where $\dot{z} = 0$) and the points of intersection between the interior of sides $Q_{z=0}$, $Q_{z=1}$ (where $\dot{z} = 0$) and the locus $\Delta\Pi^N(x, z) = 0$ (where $\dot{x} = 0$). In such stationary states, there is a region in which both available strategies are played by a positive share of agents, while in the other region all agents choose the same strategy. In addition, the point in the interior of $\boldsymbol{Q}$ where the loci $\Delta\Pi^N(x, z) = 0$ and $\Delta\Pi^S(x, z) = 0$ meet are other possible stationary states. In such points, both strategies are adopted by a positive share of agents in both regions. Finally, we find that the loci $\dot{x} = 0$ and $\dot{z} = 0$ are respectively represented by the lines:

$$z = \frac{\overline{E}^N}{f^N} - \frac{p^N}{f^N\left(e^{C^N} - 1\right)} - \frac{d^N}{f^N}x \tag{6a}$$

$$z = \frac{\overline{E}^S}{d^S} - \frac{p^S}{d^S\left(e^{C^S} - 1\right)} - \frac{f^S}{d^S}x \tag{6b}$$

where we recall that $e^{C^j} - 1 > 0$. This is obtained by substituting the public effects (2) into the well-being differential (4). Note that the slope of (6a) is negative if the domestic effect d^N and the foreign effect f^N in N have the same sign, whereas the slope of (6b) is negative if the domestic effect d^S and the foreign effect f^S in S have the same sign. Furthermore, the slope of (6a) is greater than the slope of (6b) if $\frac{d^N}{f^N} < \frac{f^S}{d^S}$. Finally, we note that $\Delta\Pi^N(x, z)$ is positive (i.e. $\dot{x} > 0$) above (6a) if $f^N > 0$ (vice versa if $f^N < 0$) and that $\Delta\Pi^S(x, z)$ is positive (i.e. $\dot{z} > 0$) above (6b) if $d^S > 0$ (vice versa if $d^S < 0$). Since both (6a) and (6b) are straight lines, there generally[3] exists at most one stationary state in the interior of each side of $\boldsymbol{Q}$ and at most one in the interior of $\boldsymbol{Q}$. Consequently, by recalling that

[3]In the unlikely circumstance that lines (6a) and (6b) have the same slope and the same intercept, the two lines completely overlap and all their points in the interior of $\boldsymbol{Q}$ are stationary states.

all vertices are stationary states, as well, the highest number of stationary states that can be generally observed is nine (four vertices, four points on the sides, and an internal point).

2 Technologies with negative public effects

Let us now outline the possible scenarios the system may reach when the adaptation technology is characterised by: 1) negative public effects towards all agents (maladaptation); 2) positive public effects towards all agents (mitigation). Other relevant cases could be investigated, yet we restrain the analysis to these two cases for the sake of parsimony. In this section we study the first case, in which the adaptation technology is maladaptive, i.e. it is such that it lowers the environmental quality for all. Formally, this maladaptation technology has both a domestic and a foreign negative public effect. One common example of such technology in the literature is air conditioning: it provides the person with an improvement of her environmental quality at the cost of a small deterioration of the environmental quality (and energy security) for all other people (Deschênes and Greenstone, 2011; Lundgren and Kjellstrom, 2013). From an analytical perspective, this translates into all public effect parameters being strictly positive: d^N, d^S, f^S, $f^N > 0$.

2.1 Dynamic regimes

First of all, we note that if d^N, d^S, f^S, $f^N > 0$, then both lines (6a) and (6b), along which $\dot{x} = 0$ and $\dot{z} = 0$, respectively, have negative slope. Above these lines, we have that the share of agents adopting strategy $\boldsymbol{A}$ increases. In particular, $\dot{x} > 0$ above line (6a) and $\dot{z} > 0$ above line (6b), whereas the reverse occurs below these lines. This is very informative with respect to the behaviour of agents: for a higher value of x, z must be lower in order for agents in either region to be indifferent to the maladaptation technology, or else they would all adopt strategy $\boldsymbol{A}$. From another perspective, for a given point (x, z) which lies on either line (6a) or (6b), a translation to the right would destabilise the system towards full adoption by agents in region N or S (or both), respectively. The adoption process of the maladaptation technology is thus self-reinforcing: the higher is the proportion of agents adopting it in either group, the higher is the incentive for others to do the same. Moreover, we note that lines (6a) and (6b) move downwards if the autonomous environmental quality for region N or S is lower. For sufficiently low values of $\overline{E}^N$ and $\overline{E}^S$, we have that $\dot{x} > 0$ and $\dot{z} > 0$, respectively, for all points in $\boldsymbol{Q}$. The reverse applies when $\overline{E}^N$ and $\overline{E}^S$ are sufficiently high.

The following proposition characterises the dynamics of the system when d^N, d^S, f^S, $f^N > 0$.

Proposition 1 *Under the assumption that* d^N*,* d^S*,* f^S*,* $f^N > 0$*, the system* (5) *has the following features:*

(a) Every trajectory of the system approaches a stationary state.

(b) Only the vertices of $\boldsymbol{Q}$*, i.e. the stationary states* $(0,0), (0,1), (1,0), (1,1)$*, can be attractive.*

2.2 Stability properties of the vertices

In order to assess the stability properties of the vertices of $\boldsymbol{Q}$, we derive the Jacobian matrix of the system (5 evaluated at the stationary state $(x, z) = (i, k)$, $i = 0, 1$ and $k = 0, 1$:

$$\begin{pmatrix} (1-2i)\Delta\Pi^N(i,k) & 0 \\ 0 & (1-2k)\Delta\Pi^S(i,k) \end{pmatrix} \tag{7}$$

which has the eigenvalues: $(1-2i)\Delta\Pi^N(i,k)$ and $(1-2k)\Delta\Pi^S(i,k)$.

The analysis of the sign of the eigenvalues allows us to illustrate the stability properties of the stationary states $(0,0)$, $(0,1)$, $(1,0)$, $(1,1)$.

Stability of the stationary state $(0,0)$ In this scenario no agent adopts the technology. In order for this non-adoption scenario to be attractive, it must be individually convenient to adopt strategy $\boldsymbol{NA}$ in both regions. In order for this to hold, both the eigenvalues in the direction of $Q_{z=0}$ and $Q_{x=0}$ must be negative. This is verified when it holds that:

$$\overline{E}^j > \frac{p^j}{e^{C^j} - 1} \qquad \textit{with } j = N, S \tag{8}$$

whereas the eigenvalues are strictly positive iff the opposite of (8) holds. To the right hand side of this inequality we have the ratio of the positive private effect of the technology over its cost of adoption, which we may interpret as its efficiency in region j. We note that the denominator is strictly positive since $C^j > 0$. To the left hand side we have the autonomous environmental quality in j, which also coincides with the overall environmental quality since no agent is adopting strategy $\boldsymbol{A}$ ($x = 0, z = 0$). Condition (8) thus requires that in both regions the efficiency of the technology is lower than the environmental quality.

Stability of the stationary state $(0, 1)$ In this case, only agents in S adopt the technology, while no agent does so in N. We now have that the eigenvalue in direction of $Q_{z=1}$ of the Jacobian matrix (7), evaluated at $(0, 1)$, is strictly negative iff:

$$\overline{E}^N - f^N > \frac{p^N}{e^{C^N} - 1} \tag{9}$$

whereas it is strictly positive iff the opposite of (9) holds. We note that this condition is similar to condition (8), but we now have that the autonomous environmental quality is adjusted by the public effect of the agents in S adopting strategy $\boldsymbol{A}$ (since $z = 1$). In other terms, in order for the agents in N to be more convenient not to adopt the technology, its efficiency needs to be lower than the overall environmental quality, which includes the public effects of agents in S. We remark that environmental quality in this case can be either lower or higher than in the non-adoption scenario, since the public effect can be either positive or negative; condition (9) can thus be either less or more restrictive than (8), respectively. As concerns the eigenvalue in direction of $Q_{x=0}$, it is strictly negative iff:

$$\overline{E}^S - d^S < \frac{p^S}{e^{C^S} - 1} \tag{10}$$

whereas it is strictly positive iff the opposite of (10) holds. In order for agents in

S to adopt the technology, its efficiency needs to be greater than the environmental quality, which includes the domestic public effect d^S.

Stability of the stationary state $(1, 0)$ This case is specular to the previous one, with all agents in N adopting the technology and no agent adopting it in S. We find that the eigenvalue in direction of $Q_{z=0}$ of the Jacobian matrix (7), evaluated at $(1, 0)$, is strictly negative iff:

$$\overline{E}^N - d^N < \frac{p^N}{e^{C^N} - 1} \tag{11}$$

whereas it is strictly positive iff the opposite of (11) holds. This condition states that all agents in N adopt strategy $\boldsymbol{A}$ only if its efficiency is greater than the environmental quality adjusted by the domestic public effect d^N. The eigenvalue in direction of $Q_{x=1}$ is strictly negative iff:

$$\overline{E}^S - f^S > \frac{p^S}{e^{C^S} - 1} \tag{12}$$

whereas it is strictly positive iff the opposite of (12) holds. Agents in S do not adopt strategy $\boldsymbol{A}$ only if its efficiency is lower than their environmental quality, adjusted by the foreign public effect f^S.

Stability of the stationary state $(1, 1)$ Finally, this case represents a full adoption scenario, in which all agents from both regions adopt the technology. We have that the eigenvalues in direction of $Q_{z=1}$ and $Q_{x=1}$ of the Jacobian matrix (7), evaluated at $(1, 1)$, are strictly negative iff:

$$\overline{E}^j - (d^j + f^j) < \frac{p^j}{e^{C^j} - 1} \qquad \text{with } j = N, S \tag{13}$$

whereas they are strictly positive iff the opposite of (13) holds. On the left hand side of condition (13) we see that now the environmental quality is affected by both domestic and foreign public effects, since all agents are adopting $\boldsymbol{A}$. The condition requires the efficiency of the technology for both regions to be greater than the environmental quality.

Finally, we remark that the vertices of $\boldsymbol{Q}$ can be simultaneously attractive, which occurs when the following condition holds:

$$\frac{p^j}{e^{C^j}-1} + f^j < \overline{E}^j < \frac{p^j}{e^{C^j}-1} + d^j \qquad \text{with } j = N, S \tag{14}$$

We note that in order for condition (14) to hold, it is necessary that $f^j < d^j$ for $j = N, S$. By checking their definitions in (2), we can see that this implies that foreign public effects must be lower than domestic public effects, in both N and S. If foreign public effects were stronger than domestic ones in at least one region, then the stationary states $(0, 1)$ and $(1, 0)$ could not be simultaneously attractive. Indeed, it would not be otherwise convenient for an agent not to adopt strategy $\boldsymbol{A}$ when all agents in the other region are doing so unless foreign public effects were neglectable with respect to domestic ones.

Some examples of multistability are shown in Figures 1–5, where attractive stationary states are represented by full dots $\bullet$, repulsive ones by open dots $\circ$, and saddles by squares $\square$. In all cases graphically represented, agents in each region coordinate on one of the two strategies. The most interesting dynamics of this kind is the one represented in Figure 1, where condition (14) is satisfied. In this case all vertices of $\boldsymbol{Q}$ are attractive, whereas all other stationary states along the sides of $\boldsymbol{Q}$ are saddle points and the stationary state inside $\boldsymbol{Q}$ is a source. As Figure 1 shows, almost every trajectory[4] will lead to a vertex of $\boldsymbol{Q}$, where each region ends up choosing a single strategy (either adopting the environmental maladaptation technology or not). The basins of attraction of the vertices are delimited by the stable manifolds of the saddle point in the interior of the sides of $\boldsymbol{Q}$.

[4]The stable branches of the saddles are exceptions, as they lead the system toward the saddle point, which is stationary.

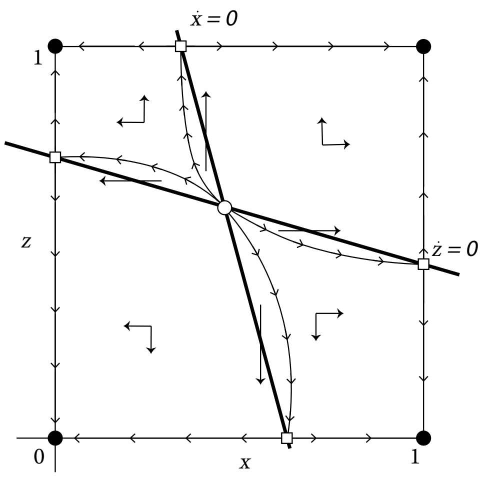

Figure 1: All nine stationary states exist: the vertices are attractors, the ones on the sides are saddles and the internal one is a repulsor.

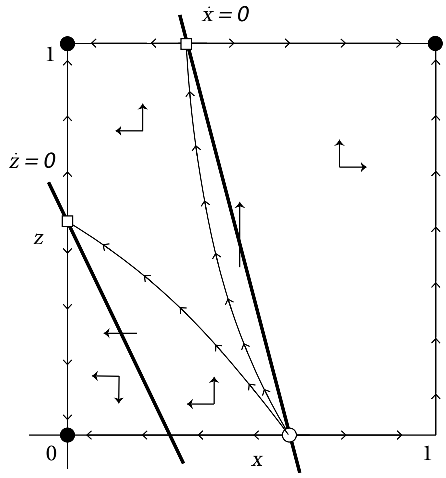

Figure 2: In this case, there are three attractors: $(0,0)$, $(0,1)$, $(1,1)$, whereas the other stationary states are either repulsors or saddles.

2.3 Well-being analysis

We will now examine the average level of well-being in the two regions when all public effects are negative, i.e. the coefficients are positive: d^N, d^S, f^S, $f^N > 0$. The average level of well-being in N and in S is equal to the weighted average of the well-being of agents adopting strategy $\boldsymbol{A}$ and the well-being of agents adopting $\boldsymbol{NA}$, where the weights are given by share of adopters in the region. Formally, we have that:

$$\widetilde{\Pi}^N(x,z) \coloneqq x \cdot \Pi^N_A(x,z) + (1-x) \cdot \Pi^N_{NA}(x,z) \tag{15}$$

$$\widetilde{\Pi}^S(x,z) \coloneqq z \cdot \Pi^S_A(x,z) + (1-z) \cdot \Pi^S_{NA}(x,z) \tag{16}$$

so that $\widetilde{\Pi}^N(0,z) = \Pi^N_{NA}(0,z)$ represents the average well-being in N when no agent is adopting $\boldsymbol{A}$ in this region, whereas $\widetilde{\Pi}^N(1,z) = \Pi^N_A(1,z)$ represents the opposite case. The interpretation is analogous for region S. The following proposition applies:

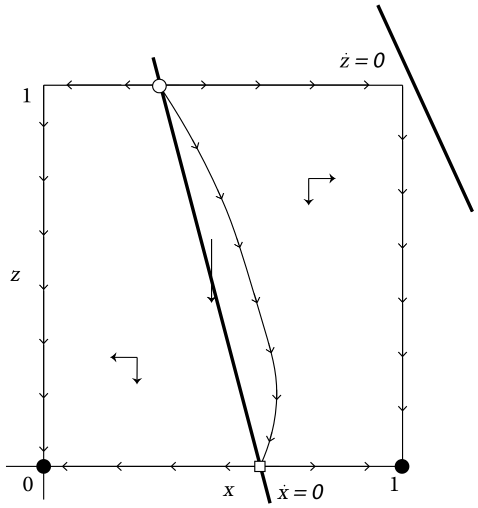

Figure 3: In this case only the stationary states $(0, 0)$ and $(1, 0)$ are attractors. The stationary state in the interior of the top side of $\boldsymbol{Q}$ is a repulsor whereas the one lying in the interior of the botom side is a repulsor.

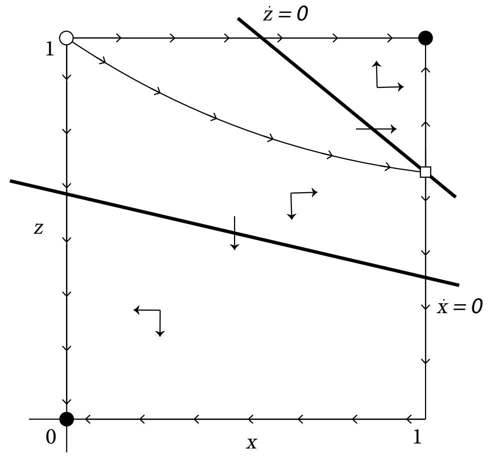

Figure 4: There are two attractors, corresponding to the full adoption $(1, 1)$ and the non-adoption $(0, 0)$ scenarios. There are also a saddle point on the right hand side and a repulsor in the asymmetric state $(0, 1)$.

Proposition 2 *If d^N, d^S, f^S, $f^N > 0$, then:*

(a) for agents in N, the non-adoption stationary state $(0, 0)$ Pareto-dominates all other stationary states in $\boldsymbol{Q}$, when they exist, with $0 \leq x < 1$ and $0 \leq z \leq 1$. Equivalently, $\widetilde{\Pi}^N(0, 0) > \widetilde{\Pi}^N(x, z)$ for every $(x, z) \neq (0, 0)$ with x and z such that $0 \leq x < 1$ and $0 \leq z \leq 1$.

(b) for agents in S, the non-adoption stationary state $(0, 0)$ Pareto-dominates all other stationary states in $\boldsymbol{Q}$, when they exist, with $0 \leq x \leq 1$ and $0 \leq z < 1$. Equivalently, $\widetilde{\Pi}^S(0, 0) > \widetilde{\Pi}^S(x, z)$ for every $(x, z) \neq (0, 0)$ with x and z such that $0 \leq x \leq 1$ and $0 \leq z < 1$.

(c) for agents in both regions N and S, the non-adaptation stationary state $(0, 0)$ Pareto-dominates also the full adoption stationary state $(1, 1)$ when the efficiency of strategy $\boldsymbol{A}$, net of domestic public effects, is lower than local autonomous environmental quality. Equivalently, $\widetilde{\Pi}^j(0, 0) > \widetilde{\Pi}^j(x, z)$ for every $(x, z) \neq (0, 0)$ when $\overline{E}^j > \frac{p^j - d^j}{e^{C^j} - 1}$, with $j = N, S$.

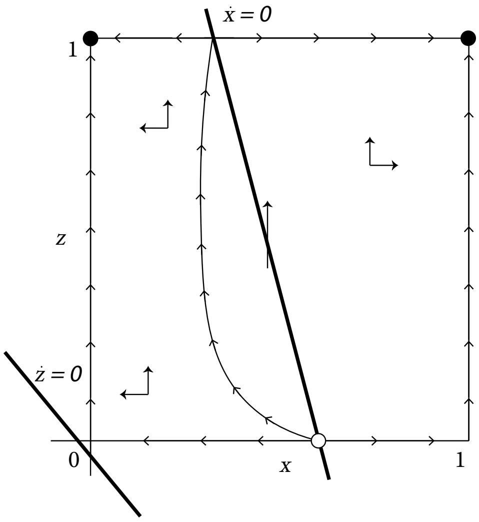

Figure 5: In this case, the vertices $(0, 1)$ and $(1, 1)$ are attractors, whereas a repulsor lies on the interior of the bottom side of $\boldsymbol{Q}$.

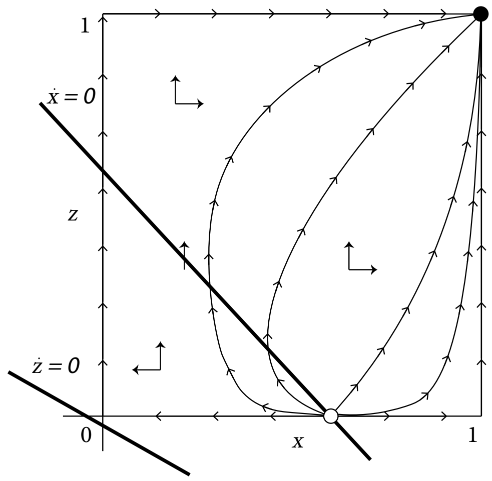

Figure 6: There exist a global attractor, corresponding to the full adoption scenario $(1, 1)$. There is alsoa repulsor in the interior of the bottom side of $\boldsymbol{Q}$.

By the above proposition, and by virtue of section 2.2, it is easy to check that when the stationary state $(0, 0)$ is locally attractive, then it Pareto-dominates all others. Furthermore, the non-adoption stationary state $(0, 0)$ may Pareto-dominate the stationary state $(1, 1)$ (in both regions) even if $(1, 1)$ is the only attractive stationary state (see Figure 6), provided that $\overline{E}^N$ and $\overline{E}^S$ are sufficiently high. In such case, the adoption of maladaptation technologies in both regions reduces the well-being of agents as system moves from the repulsive non-adoption state $(0, 0)$ to the attractive full adoption state $(1, 1)$. One could also check that if $(0, 0)$ does not Pareto-dominate all other stationary states (in both N and S), then the dynamics (5) is trivial, i.e. $\dot{x}$ and $\dot{z}$ are always positive in $\boldsymbol{Q}$. In such case, the stationary state $(1, 1)$ is globally attractive and Pareto-dominates any other possible state (x, z) in N and S.

Remark *From the well-being analysis above, in the context represented in Figure 1, every agent, from each region, achieves its highest level of well-being in* $(0, 0)$*. Therefore, only one of the four attractive vertices yields the maximum level of well-being. Furthermore, the lowest level of well-being is achieved in* $(1, 1)$*,* *whereas intermediate levels are reached in* $(0, 1)$ *and* $(1, 0)$.

2.4 Environmental dumping

At the centre of debates of both environmental and development economists, environmental dumping is the phenomenon for which an economic activity in an industrialised country results in the disproportionate degradation of the environment of a developing country. Some scholars even argued that policies targeted to improve environmental quality in industrialised countries lead to increased pollution in developing ones. For instance, scholars investigating the Pollution Haven Effect[5] maintain that carbon taxes and stricter environmental regulation are a push factor for firms, which offshore to developing countries with laxer environmental institutions. Opponents of this theory argue that international trade and offshoring incentivise developing countries to raise their environmental standards and thus help tackling the problem of environmental degradation. The analysis of the North American Free Trade Agreement performed by Gallagher (2000) seems to partly support both claims: Mexican firms reduced their emission intensity following the agreement, yet overall emissions increased due to the relatively lower Mexican standards with respect to the US ones. Since CO_2 emissions are a public bad (their negative effects affect the whole world), this increased pollution might have damaged industrialised countries, as well.

We here investigate this hypothesis, for which shifting environmental burden from one country to the other might worsen the well-being of all agents. More precisely, our model allows to study the adoption dynamics of an environmental maladaptation technology with negative public effects and which asymmetrically degrades the environmental quality indicator of one of the two regions. We here discuss what happens when an exogenous factor (e.g. a new policy) raises the foreign effect f^S in S, whereas it decreases domestic effect d^N in N. This is the case of a green tax or policy in the industrialised region which decreases the domestic effect on the local resource but increases the foreign effect on the resource of the other region, further degrading it. By means of a simple comparative dynamics

[5] See Copeland and Taylor (2004) for a definition of the concept and its differences with the slightly similar Pollution Haven Hypothesis.

analysis, we note that a smaller value of d^N improves the environmental quality in N and decreases the well-being differential of adopters of the maladaptation technology. Since the foreign effect f^S on the local environmental indicator of S is greater, the environmental degradation of agents in S is greater, and the well-being differential of the adopters increases and leads more agents to adopt the maladaptation technology. The overall well-being effects for agents in N cannot be assessed a priori. If the reduction in the domestic effect d^N is sufficiently large, it might counterbalance the additional degradation deriving from more adopters in the S region, who emit the foreign effect f^N affecting the environmental quality in region N. Vice versa, if the domestic effect is weaker with respect to the increased adoption induced in the foreign region, then the well-being of N decreases as a consequence of the exogenous change.

A graphical illustration is provided by Figures 1 and 5. In the former figure, we recall that the non adoption state $(0,0)$ is Pareto-dominant. However, a change in the value of f^S may cause the stationary states $(0,0)$ and $(1,0)$ to become unstable (see section 2.2), giving rise to the dynamic regime represented in Figure 5. In this case, the Pareto-dominant state $(0,0)$ would no more be an attractor, and the system would lose its social optimum. By contrast, the Pareto-dominated state $(1,1)$ would still be attractive. This analysis highlighted that environmental policies in an industrialised region may have either a positive or a negative effect for its agents, depending on the feedback effects of agents in the developing region.

3 Technologies with positive public effects

We now study the case in which all public effects of the environmental adaptation technology are positive, that is: d^N, d^S, f^S, $f^N < 0$. This case describes the adoption dynamics of a mitigation technology, which thus improves environmental quality for all agents (see Gupta and Gregg, 2012; Hallegatte, 2009, for instances of adaptation technologies with mitigation features). If we think of the agents as firms, instances of such technologies might be the installation of a water treatment plant on a common water basin or, equivalently, of a technology which reduces emissions or waste water usage. Other examples might draw from businesses dealing with the management of common environmental resources, such as fisheries or forestries (Olson, 1965).

3.1 Dynamic regimes

We first note that if d^N, d^S, f^S, $f^N < 0$, both the straight lines (6a) (where $\dot{x} = 0$) and (6b) (where $\dot{z} = 0$) have negative slope. Differently from the case with negative public effects, in this case $\dot{x} > 0$ below line (6a), whereas $\dot{x} < 0$ above it. Analogously, $\dot{z} > 0$ below line (6b), whereas $\dot{z} < 0$ above it. In contrast to the previous case, now the adoption dynamics is not self-reinforcing: more specifically, the incentive to adopt the environmental mitigation technology decreases if the share of agents adopting the technology in either group increases. This is the well known free riding problem, for which agents are not willing to contribute to a public good and would rather benefit from the contributions of others without paying the cost of their own contribution. In addition, the concavity of the well-being function with respect to the environmental quality accentuates the effect, as it makes any further improvement of the environment less desirable. Since the returns from the mitigation technology decrease with the share of adopters while the cost is constant, we may see why this context favours coexistence between strategies $\boldsymbol{A}$ and $\boldsymbol{NA}$. Indeed, as more and more agents adopt the mitigation technology, the well-being differential of such strategy falls to zero, allowing for a stationary state in which in the same region there are agents adopting strategy $\boldsymbol{A}$ and agents adopting $\boldsymbol{NA}$. Moreover, we remark that if the autonomous environmental quality $\overline{E}$ is sufficiently high in N and S, then the well-being differential is always negative, i.e. $\dot{x} < 0$ and $\dot{z} < 0$, leading agents to drop the mitigation technology and shift from $\boldsymbol{A}$ to $\boldsymbol{NA}$. In this case, the autonomous level of environmental quality is so high that no agent finds it convenient to increase it further by an amount equal to the private effect p^j, with $j = 0, 1$. This might also be due to the inefficiency of the mitigation technology (a low value of $\frac{p^j}{e^{C^j}-1}$). In formal terms, we may say that lines (6a) and (6b) move downwards if the autonomous environmental quality for region N or S is higher. For sufficiently high values of $\overline{E}^N$ and $\overline{E}^S$ or for sufficiently low values of p^N and p^S, we have that $\dot{x} < 0$ and $\dot{z} < 0$, respectively. The reverse applies when $\overline{E}^N$ and $\overline{E}^S$ are sufficiently low or p^N and p^S sufficiently high.

We find that the following proposition characterises the adoption dynamics when: d^N, d^S, f^S, $f^N < 0$.

Proposition 3 *Under the assumption that d^N, d^S, f^S, $f^N < 0$, the system 5 has the following features:*

(a) Every trajectory of the system approaches a stationary state.

(b) When the stationary state $(0,0)$ is attractive (see section 2.2), then it is globally attractive, i.e. there is no other attractive stationary state (see Figure 7).

(c) When the stationary state $(1,1)$ is attractive (see section 2.2), then it is globally attractive (see Figure 8).

(d) If there is no stationary state in the interior of $\boldsymbol{Q}$, then there exists only one attractive stationary state in the boundary of $\boldsymbol{Q}$; it may either be one of the vertices or lie on the interior of the edges of $\boldsymbol{Q}$.

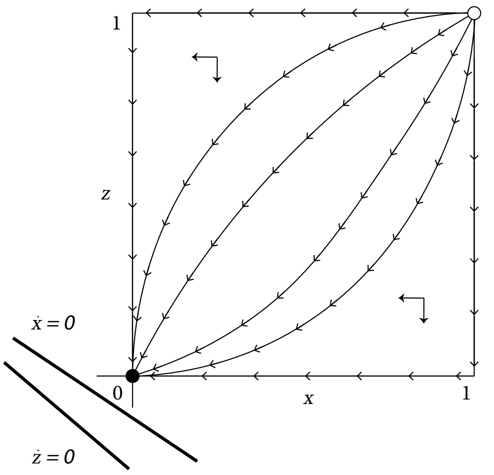

Figure 7: The non-adoption stationary state $(0,0)$ is globally attractive, whereas the full adoption one $(1,1)$ is repulsive.

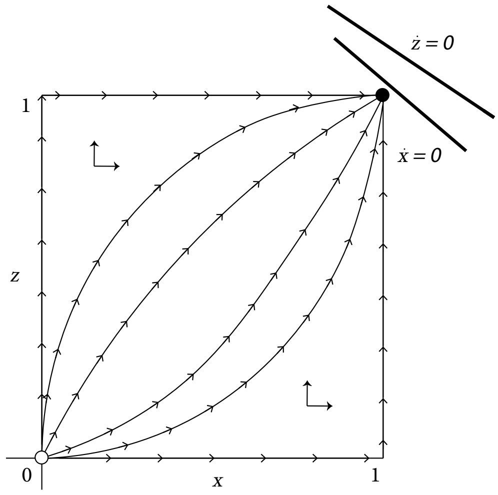

Figure 8: The full adoption stationary state $(1,1)$ is globally attractive, whereas the non-adoption one $(0,0)$ is repulsive.

(e) If $d^N d^S - f^N f^S > 0$, i.e. the domestic effects are larger than the foreign ones, the stationary state in the interior of $\boldsymbol{Q}$ (in which both strategies are played in both regions) is globally attractive, when it exists (see Figure 9).

(f) If $d^N d^S - f^N f^S < 0$, i.e. the domestic effects are smaller than the foreign ones, the stationary state in the interior of $\boldsymbol{Q}$ is a saddle point, when it exists. In addition, there exist two attractive stationary states lying in the edges of $\boldsymbol{Q}$: they may be the vertices $(0,1)$ and $(1,0)$ or lie in the interior of the edges $\boldsymbol{Q}_{h,k}$ (see Figures 10–13).

(g) If $p^N = p^S = 0$ (i.e. the private effect of strategy $\boldsymbol{A}$ is 0 in both regions), then non-adoption is individually convenient for all agents: $\Pi^N_{NA} > \Pi^N_A$ and $\Pi^S_{NA} > \Pi^S_A$, whatever the values of x and z are. This implies that $\dot{x} < 0$ and $\dot{z} < 0$ always hold and consequently $(0,0)$ is globally attractive (the classical free-riding problem arises for public goods provision).

Remark *The coordinates of the internal stationary state are:*

$$\overline{x} = \frac{d^S\left(\overline{E}^N - \frac{p^N}{e^{C^N}-1}\right) - f^N\left(\overline{E}^S - \frac{p^S}{e^{C^S}-1}\right)}{d^N d^S - f^S f^N} \tag{17a}$$

$$\overline{z} = \frac{d^N\left(\overline{E}^S - \frac{p^S}{e^{C^S}-1}\right) - f^S\left(\overline{E}^N - \frac{p^N}{e^{C^N}-1}\right)}{d^N d^S - f^S f^N} \tag{17b}$$

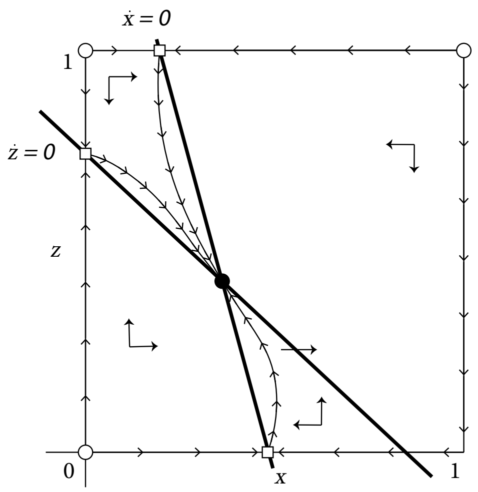

Figure 9: The internal steady state is an attractor. There are also three saddles on the sides and three repulsors on the vertices $(0,0)$, $(1,0)$, $(1,1)$.

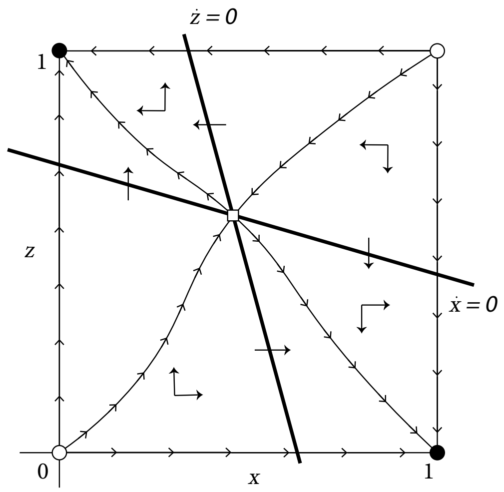

Figure 10: The internal point is a saddle, whereas the asymmetric states $(0,1)$ and $(1,0)$ are attractors. The non-adoption state $(0,0)$ and the full adoption one $(1,1)$ are repulsors.

Thus, if $d^N/f^N > f^S/d^S$, i.e. the stationary state is attractive, the internal stationary state exists if and only if:

$$0 < d^S \left(\overline{E}^N - \frac{p^N}{e^{C^N} - 1} \right) - f^N \left(\overline{E}^S - \frac{p^S}{e^{C^S} - 1} \right) < d^N d^S - f^S f^N$$

$$0 < d^N \left(\overline{E}^S - \frac{p^S}{e^{C^S} - 1} \right) - f^S \left(\overline{E}^N - \frac{p^N}{e^{C^N} - 1} \right) < d^N d^S - f^S f^N$$

which can be rewritten as:

$$f^N \left(\overline{E}^S - \frac{p^S}{e^{C^S} - 1} \right) < d^S \left(\overline{E}^N - \frac{p^N}{e^{C^N} - 1} \right) < d^N d^S - f^S f^N$$

$$f^S \left(\overline{E}^N - \frac{p^N}{e^{C^N} - 1} \right) < d^N \left(\overline{E}^S - \frac{p^S}{e^{C^S} - 1} \right) < d^N d^S - f^S f^N$$

These conditions require both numerator and denominator of coordinates (17) to be positive, with the former being greater than the latter. The condition that the numerators of (17) be lower than the related denominators restricts $\bar{x}$ and $\bar{z}$ to be lower than 1, thus making the point $(\bar{x}, \bar{z})$ belong to the interior of $\boldsymbol{Q}$.

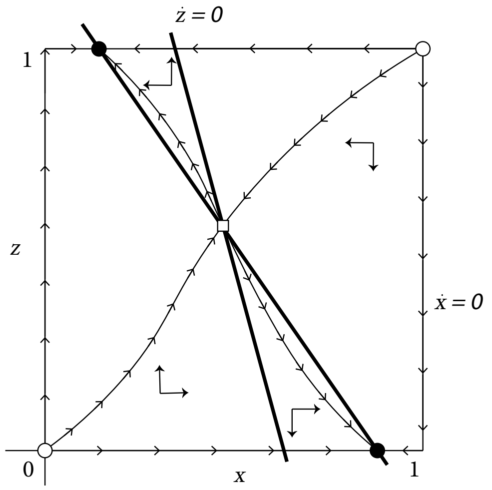

Figure 11: The internal fixed point is a saddle and both the non-adoption $(0, 0)$ and the full adoption $(1, 1)$ states are repulsors. Two attractors lie on the interiors of the bottom side and on the top side of $\boldsymbol{Q}$.

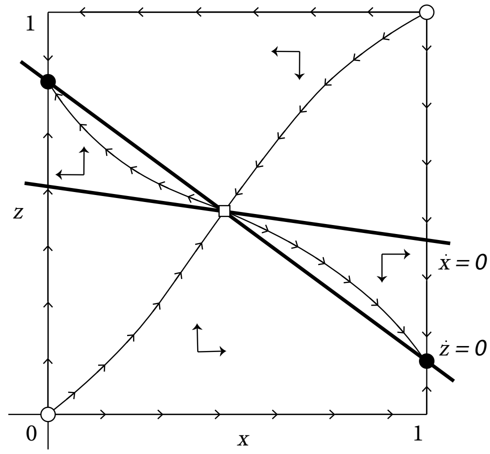

Figure 12: The internal fixed point is a saddle and both the non-adoption $(0, 0)$ and the full adoption $(1, 1)$ states are repulsors. Two attractors lie on the interiors of side to the left and on the side to the right of $\boldsymbol{Q}$.

3.2 Well-being in the context with positive externalities

We now examine the average level of well-being in the two regions when all public effects are positive: d^N, d^S, f^S, $f^N < 0$ (see (15) and (16) in the previous section for a comparison). The following proposition applies.

Proposition 4 *Assume* d^N, d^S, f^S, $f^N < 0$. *In such context, it holds:*

(a) The stationary state $(0, 0)$ *is Pareto-dominated (in both regions) by any attractive stationary state with* $x > 0$ *and/or* $z > 0$. *When* $(0, 0)$ *is attractive*[6]*, it may be Pareto-dominated by other stationary states* [7].

(b) The stationary state $(1, 1)$ *Pareto dominates (in both regions) any other stationary state when it is attractive (remember that, in such case, no other stationary state can be attractive). Furthermore, even if it is unstable, it Pareto dominates the stationary state in the interior of* $\boldsymbol{Q}$*, when it exists.*

[6]As stated in **Proposition 3**, point (b), in this case $(0, 0)$ is globally attractive.

[7]This occurs, for instance, when $\frac{p^N}{e^{C^N}-1} < \overline{E}^N < \frac{p^N-d^N-f^N}{e^{C^N}-1}$ and $\frac{p^S}{e^{C^S}-1} < \overline{E}^S < \frac{p^S-d^S-f^S}{e^{C^S}-1}$ hold. Indeed, in this case $(0, 0)$ is attractive but is Pareto-dominated by $(1, 1)$.

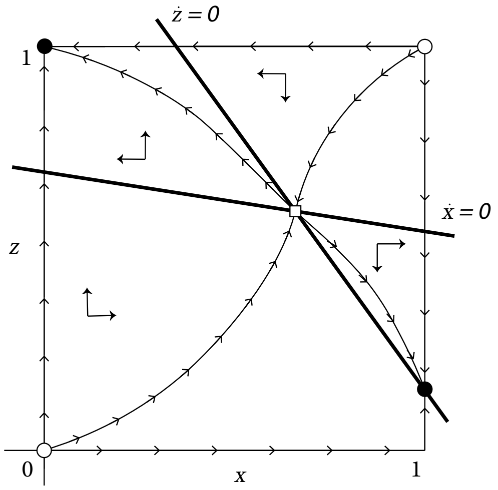

Figure 13: In this case, one attractor lies on the asymmetric state $(0, 1)$ and another lies on the interior of the right-hand of square $\boldsymbol{Q}$. The internal point is a saddle and both the non-adoption $(0, 0)$ and the full adoption $(1, 1)$ states are repulsors.

Remark *From the well-being analysis above, in the context in which the stationary state* $(\overline{x}, \overline{z})$ *in the interior of* $\boldsymbol{Q}$ *is attractive, we have that* $(\overline{x}, \overline{z})$ *Pareto-dominates* $(0, 0)$ *but is Pareto-dominated by* $(1, 1)$*; however, the latter stationary state cannot be reached because it is not attractive.*

These results are reversed with respect to the case with negative public effects. Indeed, in the previous case $(0, 0)$ Pareto-dominates all stationary states in most cases, although it is not attractive. The selfish nature of the maladaptation technology leads agents towards adoption, although it results in a lower level of well-being for all. The technology is thus over-adopted with respect to the Pareto-optimum. With positive public effects, we have that $(0, 0)$ is Pareto-dominated by all other stationary states whereas $(1, 1)$ Pareto-dominates them when it is attractive. All agents benefit from the mitigation technology adopted by others, but they are less willing to pay its cost as they do not internalise the well-being of other. In this case, the technology is under-adopted, as the full adoption scenario would be the Pareto optimum. This last result is in line with the results by Shogren and Crocker (1991).

4 Discussion and conclusions

In this work, we excluded altruistic consideration on the part of agents towards either same-region and cross-region agents. In other terms, we assumed that the actions of agents are only driven by self-interest considerations. We then studied the case of two regions whose agents may adopt an environmental adaptation technology which yields a private benefit to the adopter, while also transferring a negative or positive externality both to agents in the same region and to agents in the other one. We defined same-region externalities as domestic public effects and cross-region externalities as foreign public effects. The model here proposed is very broad, so that a complete analysis of all possible specifications is beyond the scope of this chapter. Instead, we focused on two salient characterisations. On the one hand, we analysed the case of a maladaptation technology, whose domestic and foreign public effects are both negative. In this case, an adopter shifts the environmental load to agents from both regions. A common example of this kind of technologies is air conditioning (Lundgren and Kjellstrom, 2013). On the other hand, we analysed the case of a mitigation technology, whose domestic and foreign public effects are both positive. In this case, each adopter is improving the well-being of agents from both regions. In analogy with the previous example, we may think of home insulation, as it allows each household to reduce both heating and air conditioning, benefiting the environment on a global scale. Our results show that for the maladaptation technology the social optimum is represented by the non-adoption scenario, unless the efficiency of the technology is extremely high (greater than the autonomous level of environmental quality). However, Pareto-dominated states may be reached, because agents do not internalise the externalities of the technology. In this case, we talk of over-adoption of the maladaptation technology. The reverse occurs with a mitigation technology, which would have a full adoption scenario as its Pareto-optimum. However, an intermediate state (in which only some agents are adopters) is *typically* reached, since the returns on adoption decrease for each additional adopter. Also in this case, agents do not take into account the (positive) externalities of adoption on other agents, this time leading to under-adoption of the technology with respect to the Pareto-dominant state. Finally, under the hypothesis of a maladaptation technology, with negative public effects, we analysed the effects of an environmental dumping strategy. This represents a stronger characterisation of maladaptation, as it requires that in the more developed region both the domestic and the foreign public effect are relatively low (null, in the extreme case) with respect to the public effects in the less developed region. Although it is intuitive that the agents from the less developed region would be worse off in this case, the implications for agents from the more developed region are not straightforward. Indeed, according to relative magnitude of foreign effects in the two regions, the well-being of agents from the more developed region could either increase or decrease.

This last result is particularly interesting, although its plausibility should be verified by further research. Indeed, instances of such negative feedbacks could provide greater insight on the cost-benefit analysis of many maladaptation strategies available to the more developed regions. In addition, further research should try to map the specifications which are not illustrated in this work. Interesting dynamics could arise, for example, if the public effects had different signs according to whether they are domestic or foreign. In particular, a case in which all domestic public effects are null or positive, while all foreign effects are negative would depict a situation in which all adopters shift the environmental burden to foreign agents, although they increase the well-being of same-region individuals. In this case, it is not intuitive which state the system would reach. Another relevant case would be represented by technological differences between the two regions allowing the agents from the more developed region to adopt a mitigation technology, whereas agents in the less developed region could only adopt a maladaptation technology. Well-being analysis could highlight which region is relatively more affected by the negative externalities and which state is more likely to be reached. All similar research directions, focusing on translating real phenomena and dynamics into the model, would provide a fine extension to this work and a contribution to the understanding of the relationship between regions and countries at different stages of development and their environmental quality.

A Proofs of the propositions in text

Proof of Proposition 1 The proof of point (b) is straightforward and follows immediately from the local stability analysis (which can be found in Mathematical Appendix B). To prove point (a) we have to show that limit cycles cannot exist (see e.g. Lefschetz, 1963, pp. 230 ff). This is obviously the case when the internal stationary state $(\overline{x}, \overline{z})$, with $0 < \overline{x}, \overline{z} < 1$, does not exist or, if it does, is a saddle point. If $(\overline{x}, \overline{z})$ is a source, then $d^N d^S - f^S f^N > 0$ (see (22) in appendix B, that is the straight line (6a) (where $\dot{x} = 0$) crosses from above the straight line (6b) (where $\dot{z} = 0$). In such case, it is easy to see that the regions in $\boldsymbol{Q}$ where $\dot{x}$ and $\dot{z}$ have the same sign are positively invariant, so that no oscillatory behaviour of trajectories can occur. This implies, by the Poincaré-Bendixson Theorem, that any trajectory starting in $\boldsymbol{Q}$ approaches a stationary state. This concludes the proof of the proposition.

Proof of Proposition 2 To prove point (a) of proposition 2, we have to show that the average payoff in N, evaluated at $(0, 0)$, is higher than at any point $(\bar{x}, \bar{z})$ along the line $\Delta\Pi^N(x, z) = 0$ (where $\dot{x} = 0$) and along the side $Q_{x=0}$. The average level of well-being in $(0, 0)$ is:

$$\widetilde{\Pi}^N(0,0) = \Pi^N_{NA}(0,0) = \ln \overline{E}^N$$

Let us now take a point $(\bar{x}, \bar{z}) \in \left\{\Delta\Pi^N(x, z) = 0\right\}$. We have that both strategies yield the same level of well-being: $\Pi^N_A(\bar{x}, \bar{z}) = \Pi^N_{NA}(\bar{x}, \bar{z})$, which implies:

$$\widetilde{\Pi}^N(\bar{x}, \bar{z}) = \Pi^N_{NA}(\bar{x}, \bar{z}) = \ln \left(\overline{E}^N - d^N \cdot \bar{x} - f^N \cdot \bar{z}\right)$$

Therefore, if $\bar{x}$ and/or $\bar{z} > 0$, it follows that: $\widetilde{\Pi}^N(0, 0) > \widetilde{\Pi}^N(\bar{x}, \bar{z})$. This means that the average well-being in the non-adoption state $(0, 0)$ is higher than in any stationary state in the interior of $\boldsymbol{Q}$ and in any stationary state in the interior of the sides $Q_{z=h}$ $(h = 1, 2)$. Furthermore, it is easy to check that $(0, 0)$ always Pareto-dominates any stationary state with $z > 0$ in the side $Q_{x=0}$. In order to prove point (c), we now show that $(0,0)$ Pareto-dominates any stationary state in the side $Q_{x=1}$ if $\overline{E}^N > \frac{p^N - d^N}{e^{C^N}-1}$. It can be easily verified that $(1,0)$ always Pareto-dominates any other stationary state in the side $Q_{x=1}$. Therefore, we simply have to compare well-being in $(0,0)$ with the one in $(1,0)$. By very simple computations, we obtain that, if $\overline{E}^N > \frac{p^N - d^N}{e^{C^N}-1}$, then $(0,0)$ Pareto-dominates $(1,0)$. With similar arguments, it is easy to check that $(1,1)$ is Pareto-dominated by all the other stationary states when $\overline{E}^N > \frac{p^N - d^N}{e^{C^N}-1}$. To prove that analogous results hold for the well-being of region S, it suffices to apply the same arguments.

Proof of Proposition 3 The proof of point (b) is straightforward and follows immediately from graphical analysis: if $(0,0)$ is attractive, then it must lie above the straight lines (6a) and (6b). Consequently, in the interior of $\boldsymbol{Q}$, it holds $\dot{x} < 0$ and $\dot{z} < 0$, which implies the global attractiveness of $(0,0)$. With similar arguments, point (c) can be proved. In order to prove point (e), it suffices to check that when $d^N/f^N > f^S/d^S$, the internal stationary state is locally attractive (see **Proposition 6**). Graphical analysis then allows to see that no other attractive stationary state can exist. It remains to show that limit cycles cannot exist. To do so, we note that the straight line (6a), along which $\dot{x} = 0$, crosses the straight line (6b), along which $\dot{z} = 0$, from above. In such case, the regions of $\boldsymbol{Q}$ where $\dot{x}$ and $\dot{z}$ have opposite signs are positively invariant; this implies that no oscillatory behaviour of trajectories may occur and consequently that the internal stationary state is globally attractive by the Poincaré-Bendixson Theorem. We now prove point (f): if $d^N/f^N < f^S/d^S$, the internal stationary state is a saddle point (see section 2.2); consequently, no limit cycle may exist. Furthermore, we note that the straight line (6a) crosses the straight line (6b) from below. In such case, the regions of $\boldsymbol{Q}$ where $\dot{x}$ and $\dot{z}$ have opposite sign are positively invariant and, in each of these regions, the trajectories approach a stationary state lying on the boundary of $\boldsymbol{Q}$. Finally, the proof of points (a), (d) and (g) is straightforward.

Proof of Proposition 4 To prove point (a) of the proposition, we first consider the average well-being in N, which in $(0,0)$ is equal to:

$$\widetilde{\Pi}^N(0,0) = \Pi^N_{NA}(0,0) = \ln \overline{E}^N$$

Let us now consider a point $(\bar{x},\bar{z}) \in \boldsymbol{Q}$. If $(\bar{x},\bar{z})$ is a stationary state belonging to the curve $\Delta\Pi^N(x,z) = 0$, then it holds that $\Pi^N_A(\bar{x},\bar{z}) = \Pi^N_{NA}(\bar{x},\bar{z})$, and consequently we have:

$$\widetilde{\Pi}^N(\bar{x},\bar{z}) = \Pi^N_{NA}(\bar{x},\bar{z}) = \ln\left(\overline{E}^N - d^N \cdot \bar{x} - f^N \cdot \bar{z}\right)$$

Therefore, since d^N, d^S, f^S, $f^N < 0$, if either $\bar{x}$ or $\bar{z} > 0$, we have that: $\widetilde{\Pi}^N(0,0) < \widetilde{\Pi}^N(\bar{x},\bar{z})$. Thus, average payoff in $(0,0)$ is lower than in any stationary state in the interior of $\boldsymbol{Q}$ and in any stationary state in the interior of the sides $Q_{z=k}$ $(k = 1,2)$. Furthermore, it is easy to check that $(0,0)$ is always Pareto-dominated by any stationary state in the side $Q_{x=0}$. It remains to prove that $(0,0)$ is Pareto-dominated by any attractive stationary state in the side $Q_{x=1}$. Easy algebraic manipulations show that $\widetilde{\Pi}^N(0,0) < \widetilde{\Pi}^N(1,1)$ if and only if $\overline{E}^N < \frac{p^N - d^N - f^N}{e^{C^N} - 1}$. The latter condition is always satisfied if $(1,1)$ is attractive (see section 2.2). In the same way, it can be checked that $\widetilde{\Pi}^N(0,0) < \widetilde{\Pi}^N(1,0)$ when $(1,0)$ is attractive. Finally, it is left to prove that $(0,0)$ is Pareto-dominated by any attractive stationary state $(1,\overline{z})$ lying in the interior of $Q_{x=1}$. As already seen above, the well-being in $(0,0)$ is lower than in any stationary state, so that $\widetilde{\Pi}^N(0,0) = \Pi^N_{NA}(0,0) < \Pi^N_{NA}(1,\bar{z})$. Furthermore, we note that if $(1,\overline{z})$ is attractive, then the curve $\Delta\Pi^N(x,z) = 0$ must lie on the right of it (see **Proposition 5**); consequently, on the left of $\Delta\Pi^N(x,z) = 0$, it holds that $\Delta\Pi^N(x,z) > 0$. This implies that $\Pi^N_{NA}(1,\bar{z}) < \Pi^N_A(1,\bar{z})$. Therefore, $\widetilde{\Pi}^N(0,0) < \widetilde{\Pi}^N(1,\bar{z})$, being $\widetilde{\Pi}^N(1,\bar{z}) = \Pi^N_A(1,\bar{z})$. The corresponding results for S can be proved following the same steps. To check the remaining part of point (a), we simply have to solve the inequality $\widetilde{\Pi}^N(0,0) < \widetilde{\Pi}^N(1,1)$ and draw from the stability results in section 2.2 about the stationary state $(0,0)$. The proof of point (b) follows very similar steps.

B Stability properties of the stationary states

We here study the stability of the stationary states beyond the vertices of the region $\boldsymbol{Q}$, in order to understand toward which the system may converge. Indeed, the attractive states are of particular interest, as they are the only states that can actually be reached by the system. We recall that the condition for a stationary state to be attractive is that both the eigenvalues of the Jacobian matrix evaluated on it are negative[8].

B.1 Stability properties of the stationary states in the interior of the edges of $\boldsymbol{Q}$

The following proposition concerns the stability properties of the stationary states belonging to the interior of the edges of the square $\boldsymbol{Q}$, i.e. those where both adoption choices coexist in N while all agents in S play the same strategy or vice versa.

Proposition 5 *The Jacobian matrix of the system* (5) *evaluated at the stationary states in the interior of the edges* $Q_{x=h}$ *(*$h = 0,\ 1$*) is:*

$$\begin{pmatrix} (1-2h)\Delta\Pi^N(h,\overline{z}) & 0 \\ \overline{z}(1-\overline{z})\frac{\partial\Delta\Pi^S(h,\overline{z})}{\partial x} & \overline{z}(1-\overline{z})\frac{\partial\Delta\Pi^S(h,\overline{z})}{\partial z} \end{pmatrix} \tag{18}$$

where $\overline{z}$ *is the value of* z *at the stationary state, and has the eigenvalues:* $\overline{z}(1-\overline{z})\frac{\partial\Delta\Pi^S(h,\overline{z})}{\partial z}$ *(in direction of* $Q_{x=h}$*) and* $(1-2h)\Delta\Pi^N(h,\overline{z})$ *(in direction of the interior of* $\boldsymbol{Q}$*). The Jacobian matrix of the system (5) evaluated at the stationary states in the interior of the edges* $Q_{z=h}$ *(*$h = 0,\ 1$*) is:*

$$\begin{pmatrix} \overline{x}(1-\overline{x})\frac{\partial\Delta\Pi^N(\overline{x},h)}{\partial x} & \overline{x}(1-\overline{x})\frac{\partial\Delta\Pi^N(\overline{x},h)}{\partial z} \\ 0 & (1-2h)\Delta\Pi^S(\overline{x},h) \end{pmatrix} \tag{19}$$

where $\overline{x}$ *is the value of* x *at the stationary state, and has the eigenvalues:*

[8] If the eigenvalues are both positive, then the state is repulsive and cannot be reached by system (unless it coincides with its initial condition). If they have opposite signs, instead, the state is a saddle and can only be reached if the initial condition of the system lies on its stable branch.

$\overline{x}(1-\overline{x})\frac{\partial\Delta\Pi^N(\overline{x},h)}{\partial x}$ *(in direction of* $Q_{z=h}$*)* *and* $(1-2h)\Delta\Pi^S(\overline{x},h)$ *(in direction of the interior of* $\boldsymbol{Q}$*).*

Proof. Straightforward. ■

We remark that, given a stationary state in an edge $Q_{h=k}$, $h = x, z$ and $k = 0, 1$, the sign of its eigenvalue in direction of $Q_{h=k}$ is negative if and only if the stationary states at the extrema of $Q_{h=k}$ which are the vertices of $\boldsymbol{Q}$, have positive eigenvalues in direction of $Q_{h=k}$.

The conditions for the attractiveness of the steady states within the edges of $\boldsymbol{Q}$ deserve further comment. Indeed, the attractiveness conditions (18) and (19) require that:

$$\frac{\partial\Delta\Pi^N(\overline{x},i)}{\partial x} < 0 \tag{20a}$$

$$\frac{\partial\Delta\Pi^S(i,\overline{z})}{\partial z} < 0 \tag{20b}$$

Inequalities (20) describe a nonlinear dynamics of strategies $\boldsymbol{A}$ and $\boldsymbol{NA}$ in N and S, respectively, similar to the "elitist"narratives in Antoci et al. (2018). Since the well-being differential of adopting strategy $\boldsymbol{A}$ decreases with the share of adopters, strategy $\boldsymbol{A}$ yields the highest payoffs when only a minority of agents adopts it. As strategy $\boldsymbol{A}$ diffuses, so the incentive to adopt it decreases, to the point that agents become indifferent toward the technology. Intuitively, the presence of this dynamics in (only) one of the two regions is necessary in order to have coexistence of strategies in such region and a pure population strategy in the other region.

B.2 Stability properties of stationary states in the interior of $\boldsymbol{Q}$

The following proposition deals with the stability of stationary states in the interior of the square $\boldsymbol{Q}$, in which a positive share of agents adopts each strategy in both regions.

Proposition 6 *The Jacobian matrix of the system (5) evaluated at a stationary state* $(\overline{x}, \overline{z})$ *in the interior of* $\boldsymbol{Q}$ *(i.e.* $0 < \overline{x}, \overline{z} < 1$*) is:*

$$\begin{pmatrix} \overline{x}(1-\overline{x})\frac{\partial \Delta\Pi^N(\overline{x},\overline{z})}{\partial x} & \overline{x}(1-\overline{x})\frac{\partial \Delta\Pi^N(\overline{x},\overline{z})}{\partial z} \\ \overline{z}(1-\overline{z})\frac{\partial \Delta\Pi^S(\overline{x},\overline{z})}{\partial x} & \overline{z}(1-\overline{z})\frac{\partial \Delta\Pi^S(\overline{x},\overline{z})}{\partial z} \end{pmatrix} \tag{21}$$

where the sign of the determinant of (21) is equal to the sign of the expression:

$$d^N d^S - f^S f^N \tag{22}$$

and the trace of (21) is equal to:

$$d^N(e^{C^N} - 1)\overline{x}(1-\overline{x}) + d^S(e^{C^S} - 1)\overline{z}(1-\overline{z}) \tag{23}$$

Proof. Straightforward. ■

According to the above proposition, we have that if expression (22) is strictly negative, then the internal stationary state is a saddle (i.e. it is unstable). If it is positive, then the stationary state may be a source (i.e. a repulsor) or a sink (i.e. an attractor). In the context in which expression (22) is strictly positive, the condition d^N, $d^S > 0$ (< 0) is a sufficient condition for the repulsiveness (attractiveness) of the internal stationary state. Moreover, if the determinant is negative, then the stationary state is a saddle, whereas it is attractive when the determinant is positive and the trace is negative. The trace is given by the sum:

$$\overline{x}(1-\overline{x})\frac{\partial \Delta\Pi^N(\overline{x},\overline{z})}{\partial x} + \overline{z}(1-\overline{z})\frac{\partial \Delta\Pi^S(\overline{x},\overline{z})}{\partial z}$$

This means that in order for the trace to be negative, at least one of the partial derivatives above must be negative, meaning that in the corresponding region strategy $\boldsymbol{A}$ has an elitist dynamics as previously defined.

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