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ORIGINAL RESEARCH

Maladaptation in an unequal world: an evolutionary model with heterogeneous agents

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Abstract
Maladaptation is steadily increasing its presence in agenda and debates about climate change and its impacts. The term denotes actions undertaken, at the individual or collective level, to defend against the adverse effects of climate change or environmental degradation, but that ultimately exacerbate the underlying risk factors. In this paper, we investigate the effects of maladaptation in terms of well-being and inequality in a two-population (North–South) evolutionary model. While agents in the South often face higher vulnerability to environmental degradation and limited defense mechanisms compared to their Northern counterparts, the latter stand to endure greater economic losses, in absolute terms. Our model demonstrates that the diffusion of maladaptive choices could result in a Pareto-dominated steady state, influencing inequality levels positively or negatively based on the scale of maladaptation impacts relative to the existing environmental degradation. These findings stress the imperative of integrating environmental risk studies with maladaptive effects and dynamics. Additionally, they advocate for international discourse not only on climate change mitigation but also on adaptive measures among countries.

Keywords Maladaptation · Inequality · Negative externalities · Economic growth · North–South interactions

JEL Classification C70 · D62 · O13 · O40 · Q20

1 Introduction

Environmental degradation is attracting increasing attention in modern societies for its numerous undesirable effects (in terms of health damages, productivity loss, reparation costs, etc.). Climate change accelerates and magnifies environmental degradation, and its effects are going to be larger and come sooner than estimated in previous assessments (IPCC, 2022). While each inhabited region is going to be affected in a different way, many ecosystems across the world are going to degrade irreversibly. In this context, the demand and scope for effective adaptation is growing and IPCC acknowledges benefits and progress in adapta-

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tion implementation. However, there is an increasing awareness of both limits and potential negative effects of adaptation initiatives. Indeed, in some cases, environmental degradation stimulates behaviours perceived as rational at the individual level, i.e. capable of increasing personal well-being at least in the short run, which at the aggregate level or in the long run may generate a reduction in the well-being of the community or part of it. If so, such adaptive choices turn out to be "maladaptive" (Barnett and O'neill, 2010).

The literature has highlighted several cases in which adaptive strategies can have relevant adverse impacts for the environment. Air conditioning is a paradigmatic example in this regard, as it is one of the most common adaptive strategies to reduce distress caused by rising temperatures. To the extent that the increase in cooling demand exceeds the reduction in energy demand due to warmer winters, air conditioning ultimately contributes to global warming. Deschênes and Greenstone (2011) and Auffhammer and Aroonruengsawat (2011), for instance, find a positive relationship between electricity consumption and heat shocks in the U.S. residential sector. Similar results are obtained by Davis and Gertler (2015) for Mexico. More recently, Van Ruijven et al. (2019) estimate that global energy demand is projected to increase between 11 and 58 percent by 2050 due to global warming.

Other adaptation strategies that can generate increased energy consumption and growth in GHG emissions are snowmaking (Abegg et al., 2007), desalination and inter-basin water transfer projects (Barnett and O'neill, 2010), and pumping-based water efficiency schemes (Beilin et al., 2012). In other cases, adaptation processes do not cause a growth of GHG emissions, but still increase environmental pressures and the associated risks in other ways. The empirical literature provides a wide variety of case studies. In different contexts, from the United States and Australia (Hamin and Gurran, 2009), Great Britain (Fezzi et al., 2015) to Bangladesh (Pouliotte et al., 2009) negative consequences for emissions, freshwater and land fertility emerged as a result of changes in land use and plans due to adaptation against environmental risks. Increased use of fertiliser and pesticide as adaption strategies can generate new environmental risks (IPCC, 2018). The literature review by Müller et al. (2017) finds that some climate insurance schemes, by fostering the status quo or intensification in farming practices, can produce maladaptive outcomes. According to Magnan et al. (2016), the use of sandbags to reduce coastal erosion in Cape Town has released plastic into the sea with the consequent loss of recreational value of beaches. In other cases, adaptation choices do not need to produce additional environmental threats, but can exacerbate or generate new forms of exposure and vulnerability. In Mixteca Alta, Mexico, a mix of perverse economic and institutional factors is pushing smallholders to maladaptive cultivation practices, as they tend to substitute resilient with sensitive components in their cropping system and to reduced crop diversity making the system more rigid against the increasingly erratic weather conditions (Dobler-Morales et al., 2021). IPCC (2023) mentions the example of seawalls which can produce short-term gains but also long-term losses creating lock-ins of risk exposure.

In short, the number of case studies on maladaptation is rapidly growing (for rich literature reviews showing several real-world examples see also Eriksen et al. (2021) and Thomas and Warner (2019)). In contrast, theoretical works on the subject are still rare, though in recent years important progress has been made in the conceptualisation of maladaptation (Holling et al., 2002; Barnett and O'Neill, 2013; D'Alisa and Kallis, 2016; Schipper, 2020).

We contribute to this field of research with a theoretical model which analyses maladaptation through a distributional lens. For this purpose, this article focuses on the process of adopting maladaptive choices via an evolutionary model in which the interacting economic agents belong to two distinct populations. Evolutionary models have been adopted in different contexts to capture imitative behaviors of economic agents (e.g. Villani & Biancardi, 2019; Wang, Chen, & Szolnoki, 2019) also in presence of environmental dynamics (Xepapadeas, 2005; Bischi et al., 2013; Blanco and Lozano, 2015; Tilman et al., 2020; Antoci et al., 2021; Zhou et al., 2022; Ding et al., 2023). These eco-evolutionary games show the richness of possible dynamical outcomes which may arise when interactions among agents and between agents' strategies and the environment are modeled. We integrate this area of research adding the ex-ante existence of different population groups in order to identify potential distributive implications of environmental feedback effects of adaptation choices in a context of bounded rationality,[1]

In the present model agents decide whether to self-protect from environmental degradation or not depending on what the others do. The agents are divided in the two populations according to (1) their ability to self-protect against environmental degradation; (2) the negative environmental effects generated by their adaptation choices; (3) the relative cost of adaptation compared to their gross output. The paper, in particular, investigates the dynamics underlying the diffusion of (mal)adaptive strategies, and the possible feedback effects that the propagation of such strategies in the two populations may have on the well-being of agents belonging to the whole community. The objective of the present analysis is to highlight the conditions under which maladaptive choices can make both populations worse-off and/or can generate an increase in inequality between the two populations. Earlier empirical research found that distributive effects of maladaptation can be the result of inequalities in agency and political power which affect the distribution of benefits from climate adaptation creating source of increased vulnerability and marginalization (Johnson et al., 2023; Sovacool, 2018). We show that an increase in inequality can emerge even without introducing a political perspective to maladaptation (as, for instance, in Glover and Granberg (2021)), but as the mere result of the interactions of agents who differ in terms of adaptation effectiveness and affordability.

The paper is structured as follows. Section 2 discusses the related literature. Section 3 describes the model, Sect. 4 the dynamic regimes emerging from the analysis, Sect. 5 examines the well-being of the two populations at the steady states and the factors driving the well-being differential between them. Section 6 summarises the main results derived from the model and discusses possible directions for future research.

2 Related literature

The model builds upon and connects two strands of the literature: (i) the one on self-protective choices, and (ii) the one on the environment-inequality nexus. The concept of maladaptation can be traced back to the literature on self-protective choices, originated in the '90 s from some seminal contributions Shogren and Crocker (1991) for instance distinguished between self-protection that reduces the chance and the severity of undesirable events and that which transfers them to others. The idea of counterproductive reactions to environmental threats was further developed by subsequent analytical studies (e.g. Antoci & Borghesi, 2012) which pointed out that the attempt to defend from environmental degradation may have perverse effects on the well-being of the economic agents. As such, these works can be considered as predecessors of the literature on maladaptation at a time in which the term "maladaptation" was still to be coined. The concept of maladaptation has successively made its way mainly in the literature on climate change. Introduced by Barnett and O'neill (2010)

[1] Some models in the literature analyse the interplay between mitigation and adaptation expenditures on environmental degradation (see e.g. Bahn 2010). However, in such works, negative externalities and inequality consequences of maladaptive choices in a context with heterogeneous economic agents are not explicitly taken into account.

as "*action taken ostensibly to avoid or reduce vulnerability to climate change that impacts adversely on, or increases the vulnerability of other systems, sectors or social groups*", the notion of maladaptation has been later disentangled into different meanings and manifestations and applied to different environmental threats. Eriksen et al. (2021) distinguish perverse adaptation measures according to the underlying reasons for the consequent increase in vulnerability: interventions of governments, NGOs and development agencies which reinforce vulnerability (for instance in case of elite capture), redistribute it (for instance infrastructural projects), or create new sources of vulnerability (as in the case of negative temporal rebound effects or resettlement policies). Analogously, Juhola et al. (2016) distinguish maladaptation types based on outcomes: rebounding vulnerability of targeted or implemented actors, shifting vulnerability to other actors, and creating common pool problems. Here, we use the term of maladaptation as in the third meaning proposed by Juhola et al. (2016), that is self-protection choices that dampen the effect of a global public bad (for instance climate change, global biodiversity loss, ocean acidification and so on) and increase the severity of the problem for the entire community. At the same time, the distribution of the outcomes is dynamically shaped by the combined effects of initial agents' heterogeneity and the results of their interactions and environmental feedback. In this sense, the model conceptualises maladaptation in a general framework which encompasses also the other specifications and, in line with the maladaptation literature, captures the intrinsically distributive nature of this phenomenon.

The present paper, therefore, extends the literature on the environment-inequality nexus in that the proposed modelling reflects some stylised facts identified by empirical literature in this research area. There is a consensus that poorer agents are more adversely affected by climate change, pollution, and other environmental hazards. At the local level, socially and economically disadvantaged people live in more marginal areas that are more exposed to environmental degradation (Barbier, 2010; Barbier and Hochard, 2018). At the global level, the impact of climate change on low- and middle-income regions is stronger and more severe than on richer regions (see, for example IPCC, 2007, p. 13). The latter have greater possibilities to adapt and react more effectively to environmental damages due to better access to knowledge, resources, technologies, credit and insurance markets (Barbier, 2010, 2015). Country rankings based on synthetic indicators mirrored this dichotomy. Countries with lower levels of *Sustainable Development Goals Index* tend to score higher in terms of *Climate Change Vulnerability Index*, based on vulnerability to weather-related natural disasters, sea level rise, and loss of agricultural productivity (Pigato, 2019). Similar patterns are shown by indicators elaborated within The Notre Dame Global Adaptation Initiative (ND-GAIN). *Vulnerability scores*, measuring a country's exposure, sensitivity, and ability to adapt to the negative impact of climate change, are lower for higher levels of income. Along the same lines, the *readiness scores*, which measures a country's ability to implement adaptation actions, declines moving from the group of upper income countries to that of low income countries.[2] It is worth noting that resource abundance may tend to exacerbate, rather than improve, the economic well-being of a population. This phenomenon, known as the "curse of natural resources", accounts for variations in both average income and economic growth levels, operating both at cross-country (Sachs and Warner, 2001) and within-country levels (James and Aadland, 2011). Various factors contribute to this negative correlation between resource abundance and economic performance. The literature highlights price effects that undermine the profitability of local manufacturing, subsequently reducing the competitiveness of export sectors (Sachs and Warner, 2001; Amiri et al., 2019). Additionally, some scholars emphasise the signifi-

[2] World wide rankings are available at https://gain.nd.edu/our-work/country-index/rankings/.

cance of low institutional quality as the primary factor in this relationship (Brunnschweiler and Bulte, 2008; Sala-i Martin and Subramanian, 2013; Amiri et al., 2019). Finally, the positive relationship between resource abundance or dependence and exposure to climate change impacts underscores the interaction between lower economic performance and vulnerability to climate change (Thomas and Twyman, 2005). In brief, poorer countries are disproportionately exposed to and impacted by the risks of climate change, and they have less capacity to adapt to these challenges. Both global and regional reports corroborate this dual burden (Hallegatte, 2016; IPCC, 2022). Similarly, a recent UNEP report (UNEP, 2023) estimates that adaptation costs and the related financial requirements, as a percentage of GDP, are higher for low-income countries compared to lower-middle or upper-middle-income countries.

3 The model

Let us assume that there are two countries at different stages of development, which differ from each other in terms of three elements: per capita gross output, exposure to environmental hazards, efficacy in reducing such exposure.[3] This narrative of the problem allows us to refer to the asymmetric capability of less developed countries and more developed ones to cope with environmental degradation. We name the wealthier country N and the poorer country S. Each agent in country k, k=N,S, has a gross output $\overline{Y}_k$, with

$$\overline{Y}_N > \overline{Y}_S > 0$$

The gross output $\overline{Y}_k$ is reduced by the damages that environmental degradation generates. Agents can choose whether to defend against environmental degradation or not. Following Antoci and Borghesi (2012), this translates into two strategies available to agents from both countries:

1. Adapting to environmental degradation (strategy D);
2. Not adapting to environmental degradation (strategy ND).

In order to adopt strategy D, agents have to incur into an additional cost equal to C^D. The strategy chosen by each agent from country k determines the final level of the net output:

$$Y_k^{ND} = \overline{Y}_k - \Omega_k^{ND}(P), \qquad \text{if the agent in country } k \text{ chooses ND} \tag{1}$$

$$Y_k^{D} = \overline{Y}_k - \Omega_k^{D}(P), \qquad \text{if the agent in country } k \text{ chooses D} \tag{2}$$

where P is an index of environmental degradation, and $\Omega_k^{ND}(P)$ and $\Omega_k^{D}(P)$ are damage functions measuring the economic damage suffered by each agent adopting strategies ND and D, respectively. The difference in net output yielded by the two strategies depends exclusively on the different form of the damage functions. In particular, we assume that for an agent from country k it holds that:

$$\Omega_k^{ND}(P) = \alpha_k P, \qquad \text{if the agent in the country } k \text{ chooses ND} \tag{3}$$

$$\Omega_k^{D}(P) = \frac{\alpha_k P}{1 + d_k}, \qquad \text{if the agent in the country } k \text{ chooses D} \tag{4}$$

where α_k weighs the negative impact of P on the economic activities of agents from country k and d_k weighs the efficacy of protecting against environmental degradation. In line with

[3] Other characterisations of this context are plausible. For instance, the two populations of agents can also be interpreted as two social groups (e.g. rich and poor individuals) within a single country.

Strömberg (2007) and Barbier (2010), we assume that $d_N > d_S > 0$; that is, the economy of S is less effective in contrasting the adverse effects of environmental degradation. Under the stated conditions on the parameters, we have that:

$$\Omega_k^D(P) < \Omega_k^{ND}(P), \qquad k = N, S \tag{5}$$

Condition (5) states that the adverse effects of environmental degradation are stronger if an agent does not protect herself. More specifically, it holds that:

$$\frac{d\Omega_k^D(P)}{dP} < \frac{d\Omega_k^{ND}(P)}{dP}, \qquad k = N, S \tag{6}$$

Condition (6) specifies that as the environment degrades, i.e. P increases, adaptive choices become increasingly convenient, as the damage function increases less rapidly for agents adopting D. We assume that the level of environmental degradation is only affected by the strategy distribution in the two countries. In this case, the dynamics of P depends on the shares of agents $x(t)$ and $z(t)$ adopting strategy D at time t in country N and S, respectively:

$$P = \overline{P} + \beta_N \cdot x(t) + \beta_S \cdot z(t) \tag{7}$$

where $\overline{P} > 0$ is the environmental degradation when all agents in both countries adopt strategy ND, i.e. $x = z = 0$, whereas $\beta_N, \beta_S > 0$ measure the impact of adaptive choices of agents from N and S, respectively. The mechanism described by Eq. (7) characterises strategy D as a maladaptive strategy. Given the positive sign of parameters β_N and β_S, if the share of agents adopting strategy D increases, then the environmental degradation increases. We remark that if all agents successfully coordinated on strategy ND, they could be better off, as they would enjoy a lower value of P while not incurring into the increased cost of adopting D.

Recalling that agents adopting strategy D pay a cost $C^D > 0$, the payoff of an agent from country k is:

$$U_k = \begin{cases} U_k^{ND}(x, z) = \overline{Y}_k - \Omega_k^{ND}(P), & \text{for strategy ND} \\ U_k^{D}(x, z) = -C^D + \overline{Y}_k - \Omega_k^{D}(P), & \text{for strategy D} \end{cases} \tag{8}$$

whereas the time evolution of x and z is assumed to be described by replicator dynamics (see, for example Weibull, 1997):

$$\dot{x} = x(1-x)\,\Pi_N \tag{9a}$$

$$\dot{z} = z(1-z)\,\Pi_S \tag{9b}$$

where $\dot{x}$ and $\dot{z}$ are the time derivatives of x and z, respectively, and Π_k is the payoff differential in country k:

$$\Pi_k = U_k^D(x, z) - U_k^{ND}(x, z) = -C^D + \frac{\alpha_k d_k}{1 + d_k} P, \text{ with } k = N, S \tag{10}$$

Intuitively, the payoff differential is positive ($\Pi_k > 0$) if the cost C^D of adopting strategy D is lower than its benefits, represented by the damage differential:

$$\Omega_k^{ND}(P) - \Omega_k^D(P) = \frac{\alpha_k d_k}{1 + d_k} P \tag{11}$$

We note that this damage differential is always positive according to condition (5). By substituting equation (7) into (10) we obtain:

$$\Pi_k = -C^D + \frac{\alpha_k d_k}{1+d_k}\left(\overline{P} + \beta_N \cdot x + \beta_S \cdot z\right), \; k = N, S \tag{12}$$

According to dynamics (9a)–(9b), the share of agents in country k adopting strategy D increases when the payoff differential is positive ($U_k^D(x,z) - U_k^{ND}(x,z) > 0$), whereas it decreases in the opposite case ($U_k^D(x,z) - U_k^{ND}(x,z) < 0$). As noted by Levin et al. (2013), rationality depends on the context, and bounded rationality is a sensible assumption of human behaviour in social-ecological systems which are often complex adaptive systems. This may be the case in the context of global commons that typically result from a complex composition of choices of innumerable near and far away agents whose consequences accumulate gradually. For these reasons, we assume imitation dynamics based on the difference between the payoffs of strategies D and ND in each country.

4 Dynamic regimes

4.1 Steady states

The dynamical system (9a)–(9b) is defined in the square Q:

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

Each point (x, y) of the square Q represents a specific distribution of strategies D and ND, within the two populations considered. The vertices of the square $(x, y) = (0, 0), (1, 1), (0, 1), (1, 0)$ are the states where each of the two populations "specialises" by adopting only one of the two possible strategies.

In order to find the steady states of system (9a)–(9b), we study the points in which $\dot{x} = 0$ and $\dot{z} = 0$. We find that $\dot{x} = 0$ holds when all agents in N adopt the same strategy, i.e. for $x = 0$, $x = 1$. Furthermore, $\dot{x} = 0$ holds if the two strategies D and ND yield the same payoff, which occurs on all couplets (x, z) belonging to the straight line:

$$z = f_N(x) := \frac{1+d_N}{\alpha_N \beta_S d_N} C^D - \frac{\overline{P}}{\beta_S} - \frac{\beta_N}{\beta_S} \cdot x \tag{13}$$

along which the two strategies yield the same payoff for agents in N, i.e. $U_N^D(x,z) = U_N^{ND}(x,z)$. It is easy to check that the share of agents in N adopting strategy D increases ($\dot{x} > 0$) above the line (13), whereas it decreases ($\dot{x} < 0$) below it.

Analogously, $\dot{z} = 0$ holds when all agents in S adopt the same strategy, i.e. for $z = 0$, $z = 1$, and in all couplets (x, z) belonging to the straight line:

$$z = f_S(x) := \frac{1+d_S}{\alpha_S \beta_S d_S} C^D - \frac{\overline{P}}{\beta_S} - \frac{\beta_N}{\beta_S} \cdot x \tag{14}$$

along which $U_S^D(x,z) - U_S^{ND}(x,z) = 0$. In analogy with country N, the share of agents adopting D in S increases above the line (14) and decreases below it. We note that the lines (13) and (14) have the same slope: $f_N'(x) = f_S'(x) = -\frac{\beta_N}{\beta_S} < 0$. Furthermore, $f_N(0) = f_S(0)$ holds for:

$$\frac{\alpha_S d_S}{1+d_S} = \frac{\alpha_N d_N}{1+d_N} \tag{15}$$

We shall see that (15) proves to be a necessary condition for the existence of steady states internal to Q. Indeed, we now summarise the steady states, i.e. the states (x, y) in which $\dot{x} = \dot{z} = 0$:

1. All vertices (0, 0), (1, 1), (0, 1), (1, 0) of Q; each of them represents a scenario in which a single strategy is adopted in both populations.
2. The intersection points (when they exist) between the line (13) and the sides of Q with either $z = 0$ or $z = 1$.
3. The intersection points (when they exist) between the line (14) and the sides of Q with either $x = 0$ or $x = 1$.
4. The points, when they exist, internal to the square region Q and belonging to both lines (13) and (14). According to the above analysis, no internal steady state exists if (15) is not satisfied. In the non robust case in which (15) holds, the lines (13) and (14) coincide and all the points belonging to the intersection between them and the interior of the square Q are steady states. For simplicity, in the following analysis we shall not consider such a non robust case.

4.2 Stability properties of the steady states

The following proposition concerns the stability of the steady states (0, 0), (0, 1), (1, 0), (1, 1). The proof is straightforward and will be omitted.

Proposition 1 *The Jacobian matrix of the system* (9a)–(9b) *evaluated at the steady state* $(x, z) = (i, j)$, $i = 0, 1$ *and* $j = 0, 1$, *is:*

$$\begin{pmatrix} (1-2i)\left[U_N^D(i,j) - U_N^{ND}(i,j)\right] & 0 \\ 0 & (1-2j)\left[U_S^D(i,j) - U_S^{ND}(i,j)\right] \end{pmatrix} \tag{16}$$

and has eigenvalues:

$$(1-2i)\left[U_N^D(i,j) - U_N^{ND}(i,j)\right]$$

and

$$(1-2j)\left[U_S^D(i,j) - U_S^{ND}(i,j)\right]$$

The analysis of the sign of the eigenvalues given in Proposition 1 allows us to illustrate the stability properties of the steady states (0, 0), (0, 1), (1, 0), (1, 1). In what follows we will denote with $Q_{x=0}$ the side of Q where $x = 0$, and with $Q_{x=1}$ the side where $x = 1$. Similar interpretations apply to $Q_{z=0}$ and $Q_{z=1}$. All sides of this square are invariant; namely, if the pair (x, z) initially lies on one of the sides, then the whole correspondent trajectory also lies on that side.

Stability of the steady state (0, 0)

The eigenvalue in direction of $Q_{z=0}$ of the Jacobian matrix (16), evaluated at (0, 0), is strictly negative if and only if (iff, hereafter):

$$C^D > \frac{\alpha_N d_N}{1 + d_N} \overline{P} \tag{17}$$

The eigenvalue in direction of $Q_{x=0}$ is strictly negative iff:

$$C^D > \frac{\alpha_S d_S}{1 + d_S} \overline{P} \tag{18}$$

Stability of the steady state (0, 1)

The eigenvalue in direction of $Q_{z=1}$ of the Jacobian matrix (16), evaluated at (0, 1), is strictly negative iff:

$$C^D > \frac{\alpha_N d_N}{1+d_N}\left(\overline{P}+\beta_S\right) \tag{19}$$

The eigenvalue in direction of $Q_{x=0}$ is strictly negative iff:

$$C^D < \frac{\alpha_S d_S}{1+d_S}\left(\overline{P}+\beta_S\right) \tag{20}$$

Stability of the steady state (1, 0)

The eigenvalue in direction of $Q_{z=0}$ of the Jacobian matrix (16), evaluated at (1, 0), is strictly negative iff:

$$C^D < \frac{\alpha_N d_N}{1+d_N}\left(\overline{P}+\beta_N\right) \tag{21}$$

The eigenvalue in direction of $Q_{x=1}$ is strictly negative iff:

$$C^D > \frac{\alpha_S d_S}{1+d_S}\left(\overline{P}+\beta_N\right) \tag{22}$$

Stability of the steady state (1, 1)

The eigenvalue in direction of $Q_{z=1}$ of the Jacobian matrix (16), evaluated at (1, 1), is strictly negative iff:

$$C^D < \frac{\alpha_N d_N}{1+d_N}\left(\overline{P}+\beta_N+\beta_S\right) \tag{23}$$

The eigenvalue in direction of $Q_{x=1}$ is strictly negative iff:

$$C^D < \frac{\alpha_S d_S}{1+d_S}\left(\overline{P}+\beta_N+\beta_S\right) \tag{24}$$

Stability properties of the steady states in the interior of the edges of *Q*

We note that the right sides of the inequalities from (17) to (24) define the threshold values for which changes in the stability properties of the steady states occur as the parameter C^D varies (bifurcation values). The following propositions concern the stability properties of the steady states belonging to the interior of the edges of the square Q, i.e. those where both adoption choices coexist in N while all agents in S play the same strategy, or vice-versa. The proofs are straightforward and will be omitted.

Proposition 2 *The Jacobian matrix of the system* (9a)–(9b) *evaluated at the steady states* $(i, \overline{z})$ *in the interior of the edges* $Q_{x=i}$ $(i = 0, 1)$ *is:*

$$\begin{pmatrix} (1-2i)\left[U_N^D(i,\overline{z})-U_N^{ND}(i,\overline{z})\right] & 0 \\ \overline{z}(1-\overline{z})\frac{\partial\left[U_S^D(i,\overline{z})-U_S^{ND}(i,\overline{z})\right]}{\partial x} & \overline{z}(1-\overline{z})\frac{\partial\left[U_S^D(i,\overline{z})-U_S^{ND}(i,\overline{z})\right]}{\partial z} \end{pmatrix} \tag{25}$$

where $\overline{z}$ is the value of z at the steady state, and has the eigenvalues:

$$\overline{z}(1-\overline{z})\frac{\partial\left[U_S^D(i,\overline{z})-U_S^{ND}(i,\overline{z})\right]}{\partial z}=\overline{z}(1-\overline{z})\frac{\alpha_S d_S}{1+d_S}\beta_S>0 \tag{26}$$

in direction of $Q_{x=i}$, and

$$(1-2i)\left[U_N^D(i,\overline{z})-U_N^{ND}(i,\overline{z})\right] \tag{27}$$

in direction of the interior of Q.

Proposition 3 *The Jacobian matrix of the system (9a)–(9b) evaluated at the steady states $(\overline{x}, j)$ in the interior of the edges $Q_{z=j}$ $(j=0,1)$ is:*

$$\begin{pmatrix} \overline{x}(1-\overline{x})\frac{\partial\left[U_N^D(\overline{x},j)-U_N^{ND}(\overline{x},j)\right]}{\partial x} & \overline{x}(1-\overline{x})\frac{\partial\left[U_N^D(\overline{x},j)-U_N^{ND}(\overline{x},j)\right]}{\partial z} \\ 0 & (1-2j)\left[U_S^D(\overline{x},j)-U_S^{ND}(\overline{x},j)\right] \end{pmatrix} \tag{28}$$

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

$$\overline{x}(1-\overline{x})\frac{\partial\left[U_N^D(\overline{x},j)-U_N^{ND}(\overline{x},j)\right]}{\partial x}=\overline{x}(1-\overline{x})\frac{\alpha_N d_N}{1+d_N}\beta_N>0 \tag{29}$$

in direction of $Q_{z=j}$, and

$$(1-2i)\left[U_S^D(\overline{x},j)-U_S^{ND}(\overline{x},j)\right]\quad (\textit{in direction of the interior of } Q) \tag{30}$$

We note that both Jacobian matrices (25) and (28) have at least one positive eigenvalue (the one in direction of the side of Q); therefore, the steady states in the interior of the sides of Q cannot be attractive. In particular, they are either saddle points (if the eigenvalue in direction of the interior of Q is negative) or repellers.

5 Interpretation of results

According to the results illustrated in the Sect. 4, we have that almost all the trajectories starting in the interior of the square Q converge to one of the vertices (0, 0), (0, 1), (1, 0), (1, 1).[4] Proposition 1 gives the conditions allowing for the stability of such steady states. According to this proposition, the steady state (0, 0) (in which all agents adopt the non-defensive strategy ND in both countries) is (locally) attractive if the cost C^D is high enough; that is, if the following condition holds:

$$C^D>\max\left\{\frac{\alpha_N d_N}{1+d_N}\overline{P},\frac{\alpha_S d_S}{1+d_S}\overline{P}\right\} \tag{31}$$

We recall that parameter C^D measures the cost difference between the maladaptive strategy D and the non-defensive one ND, whereas parameter $\overline{P}$ is the environmental degradation when all agents choose strategy ND. Finally, we also recall that α_k, $k=N,S$, measures the economic damage for each unit of environmental degradation, whereas d_k measures the efficacy of strategy D in reducing the damage due to environmental degradation.

[4] The unique trajectories not converging to a vertex of Q are those belonging to the one-dimensional stable arms of the saddle points in the interior of the sides of Q (when existing).

The steady state (1, 1) (in which all agents adopt the defensive strategy D in both countries) is attractive if C^D is sufficiently low, that is, if the following condition holds:

$$C^D < \min\left\{\frac{\alpha_N d_N}{1+d_N}\left(\overline{P}+\beta_N+\beta_S\right), \frac{\alpha_S d_S}{1+d_S}\left(\overline{P}+\beta_N+\beta_S\right)\right\} \tag{32}$$

We note that the steady states (0, 0) and (1, 1) can be simultaneously (locally) attractive. In this case, which steady state the system converges to depends on the initial distribution of strategies $(x(0), z(0))$. If it is sufficiently close to a steady state, then the trajectory starting from $(x(0), z(0))$ will approach such steady state. This bistability scenario occurs if both the following conditions hold:

$$\frac{\alpha_N d_N}{1+d_N}\left(\overline{P}+\beta_N+\beta_S\right) > C^D > \frac{\alpha_N d_N}{1+d_N}\overline{P}$$
$$\frac{\alpha_S d_S}{1+d_S}\left(\overline{P}+\beta_N+\beta_S\right) > C^D > \frac{\alpha_S d_S}{1+d_S}\overline{P}$$

Also the asymmetric steady states (0, 1) and (1, 0), in which the populations of the two countries specialise in different strategies (either D or ND), can be attractive. In particular, (0, 1) is attractive if the following condition holds:

$$\frac{\alpha_N d_N}{1+d_N}\left(\overline{P}+\beta_S\right) < C^D < \frac{\alpha_S d_S}{1+d_S}\left(\overline{P}+\beta_S\right) \tag{33}$$

The condition becomes intuitive recalling that (0, 1) is an asymmetric steady state in which all agents in N adopt strategy ND, while the agents from S adopt strategy D. In this case, the environmental degradation P is equal to $\overline{P}+\beta_S$, so that the terms to the left and to the right of inequality (33) are the damage differential for N and S, respectively. The condition for the stability of (0, 1) thus requires the costs of adopting strategy D to be lower than the benefits only for country S, leading to a share $x = 0$ adopting the self-protective strategy in country N. Analogously (1, 0) is attractive if the following condition holds:

$$\frac{\alpha_S d_S}{1+d_S}\left(\overline{P}+\beta_N\right) < C^D < \frac{\alpha_N d_N}{1+d_N}\left(\overline{P}+\beta_N\right) \tag{34}$$

This condition is the reverse of the previous one and its interpretation is indeed specular. As the costs of adopting strategy D are higher than its benefits for S, whereas they are lower than its benefits for N, only the population of the latter ends up adopting the maladaptive strategy. We note that the steady states (0, 1) and (1, 0) cannot be simultaneously attractive. On the one hand, (0, 1) is attractive only if the following inequality holds:

$$\frac{\alpha_N d_N}{1+d_N} < \frac{\alpha_S d_S}{1+d_S} \tag{35}$$

On the other hand, (1, 0) is attractive only if the opposite condition holds. We remark that the terms to the left and to the right of condition (35) describe the difference in the damages deriving from the adoption of strategies ND and D per unit of environmental degradation for N and S, respectively (see equations (3) and (4)). Moreover, it is relevant to observe that the damage differential of a country k deriving from adopting strategy D depends positively on both the impact coefficient α_k and on self-protection efficacy d_k. It is intuitive that a higher efficacy would increase the damage differential. It is less intuitive, perhaps, that a higher impact coefficient has the same effect. This is due to the fact that a country that suffers more from environmental degradation has more to gain from adopting a strategy which dampens this adverse effect. Figure 1a illustrates a bistable dynamic regime in which only the steady

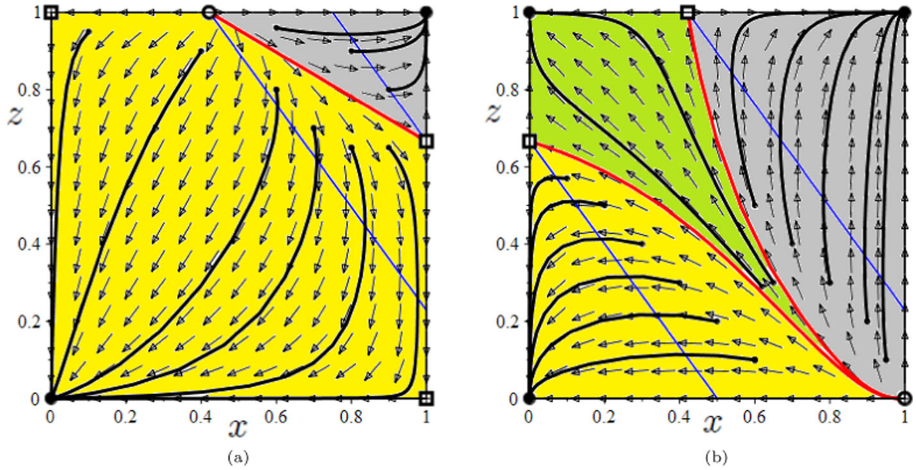

Fig. 1 Panel a: Steady states (0, 0) and (1, 1) are the only attractors of the system. Parameter values: $\alpha_S = 0.3$, $\alpha_N = 0.23$, $\beta_S = 0.3$, $\beta_N = 0.4$, $d_S = 0.5$, $d_N = 0.9$, $C_D = 0.16$, $\overline{P} = 1$; Panel b: Three attractive steady states emerge: (0, 0), (1, 1) and (0, 1). Parameter values: the same as in panel a, the only difference is that $\alpha_S = 0.4$. The full circles on the boundary of the square Q are used to represent attractive steady states, the empty circles for repulsive steady states and the empty squares for saddle points. The small full circles in the interior of Q identify the starting points of trajectories represented in the figures. The blue lines depict the nullclines of the dynamical system

states (0, 0) and (1, 1) are attractive. Figure 1b illustrates a dynamic regime in which (0, 0), (1, 1), and (0, 1) are attractive. Starting from the parameter setting in Figs. 1a, 2a-b show how the dynamic results change with variations in the parameters d_N and d_S, and α_N and α_S, respectively. We note that α_k and d_k, $k = N, S$, play a similar role in defining the dynamics of the model. Thus, focusing on the α_k parameters, we observe that:

1. sufficiently low values of both α_N and α_S make (0, 0) (where all agents adopt the non-defensive strategy ND) the unique attractive steady state of the model (and therefore all the trajectories starting in the interior of the square Q approach it in the long-run);
2. sufficiently high values of both α_N and α_S make (1, 1) (where all agents adopt the defensive strategy D) the unique attractive steady state of the model;
3. intermediate values of the parameters α_N and α_S, as well as sufficiently heterogeneous values of these, make the stability results more articulated allowing for the coexistence of two or three attractive steady states.

6 Well-being and inequality

We are now interested in studying the well-being of the two populations in the steady states of the dynamical system (9a)–(9b). To do so, we define the average well-being of country k as the average of the utility of agents adopting D and the ones adopting ND, weighted by their shares in the population. The average well-being in N and S is thus given respectively by:

$$\widetilde{U}_N(x, z) := x \cdot U_N^D(x, z) + (1 - x) \cdot U_N^{ND}(x, z) \tag{36}$$

$$\widetilde{U}_S(x, z) := z \cdot U_S^D(x, z) + (1 - z) \cdot U_S^{ND}(x, z) \tag{37}$$

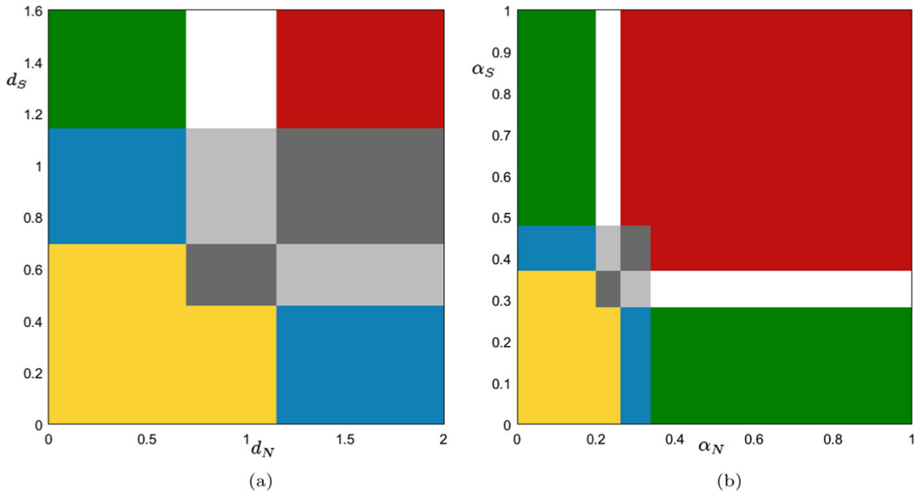

Fig. 2 2D bifurcation diagrams in the (d_N, d_S)-parameter plane (Panel a) and in the (α_N, α_S)-parameter plane (Panel b). Color legend: a) yellow: the (unique) attractive steady state is (0, 0); b) red: the attractive steady state is (1, 1); c) dark grey: the attractive steady states are (0, 0) and (1, 1); d) light grey: the attractive steady states are (0, 0), (1, 1) and an asymmetric steady state (either (0, 1) or (1, 0)); e) white: the attractive steady states are (1, 1) and an asymmetric steady; f) blue: the attractive steady states are (0, 0) and an asymmetric steady state; g) green: no symmetric steady state is an attractor and only one of the two asymmetric steady states is an attractor

We shall limit our analysis to the comparison of well-being levels evaluated at the steady states $(0, 0)$, $(0, 1)$, $(1, 0)$, $(1, 1)$, which are the only ones that can be attractive.

The well-being levels at the steady states $(0, 0)$, $(1, 1)$, $(0, 1)$, $(1, 0)$ are given by:

$$(0,0):\begin{cases}\widetilde{U}_N(0,0)=U_N^{ND}(0,0)=\overline{Y}_N-\alpha_N\overline{P}\\ \widetilde{U}_S(0,0)=U_S^{ND}(0,0)=\overline{Y}_S-\alpha_S\overline{P}\end{cases} \tag{38}$$

$$(1,1):\begin{cases}\widetilde{U}_N(1,1)=U_N^{D}(1,1)=-C^D+\overline{Y}_N-\dfrac{\alpha_N}{1+d_N}\left(\overline{P}+\beta_N+\beta_S\right)\\ \widetilde{U}_S(1,1)=U_S^{D}(1,1)=-C^D+\overline{Y}_S-\dfrac{\alpha_S}{1+d_S}\left(\overline{P}+\beta_N+\beta_S\right)\end{cases} \tag{39}$$

$$(0,1):\begin{cases}\widetilde{U}_N(0,1)=U_N^{ND}(0,1)=\overline{Y}_N-\alpha_N\left(\overline{P}+\beta_S\right)\\ \widetilde{U}_S(0,1)=U_S^{D}(0,1)=-C^D+\overline{Y}_S-\dfrac{\alpha_S}{1+d_S}\left(\overline{P}+\beta_S\right)\end{cases} \tag{40}$$

$$(1,0):\begin{cases}\widetilde{U}_N(1,0)=U_N^{D}(1,0)=-C^D+\overline{Y}_N-\dfrac{\alpha_N}{1+d_N}\left(\overline{P}+\beta_N\right)\\ \widetilde{U}_S(1,0)=U_S^{ND}(1,0)=\overline{Y}_S-\alpha_S\left(\overline{P}+\beta_N\right)\end{cases} \tag{41}$$

Note that:

$$\widetilde{U}_k(0,0)>\widetilde{U}_k(1,1),\text{with } k=N,S$$

if and only if:

$$C^D>\frac{\alpha_k d_k}{1+d_k}\overline{P}-\frac{\alpha_k}{1+d_k}\left(\beta_N+\beta_S\right) \tag{42}$$

In other terms, the steady state (0, 0) yields a higher utility than (1, 1) if the cost of adopting strategy D is greater than its benefits in terms of damage reduction, balanced for the increased level of environmental degradation $\frac{\alpha_k}{1+d_k}(\beta_N + \beta_S)$. Stated differently, condition (42) requires the costs of coping with additional degradation to offset the benefits from a reduced environmental damage. This can occur when the value of C^D, or any of the impact coefficients β_N, β_S are sufficiently high. It is easy to check that the local attractiveness of the steady state (0, 0) (see condition (31)) implies the Pareto-dominance of (0, 0) on the steady state (1, 1). Furthermore, (0, 0) may Pareto-dominate (1, 1) even if the former is not attractive while the latter is (see condition (32)). In this last case, agents from both countries would be better off if nobody adopted the maladaptive strategy D, defending against environmental degradation but ultimately fuelling it. However, as long as strategy D is individually convenient, agents will end up in the Pareto-dominated equilibrium (1, 1). This poses a dilemma to the policy maker, since enforcing a norm to abandon an attractive state of the system can be very hard, making the norm ultimately ineffective.

We can also compare the well-being in (0, 0) against the well-being in the asymmetric steady states (0, 1), (1, 0), in which the population of one country unanimously adopts the self-protecting strategy D, whereas in the other country no one does. Let us consider the steady state (0, 1). The Non-adoption strategy ND in both countries is Pareto-dominant if:

$$\widetilde{U}_N(0,0) > \widetilde{U}_N(0,1)$$
$$\widetilde{U}_S(0,0) > \widetilde{U}_S(0,1)$$

which holds true when:

$$\alpha_N \left(\overline{P} + \beta_S\right) > \alpha_N \overline{P} \tag{43}$$
$$C^D > \frac{\alpha_S d_S}{1+d_S}\overline{P} - \frac{\alpha_S}{1+d_S}\beta_S \tag{44}$$

Condition (43) is always satisfied, while condition (44) holds if the steady state (0, 0) is attractive (see condition (31)). Very similar steps allow to show that the steady state (0, 0) Pareto-dominates the steady state (1, 0), when the former is attractive.

Figure 3 shows the basins of attraction of steady states (0, 0) and (1, 1) at different parameter values in the bistable regime. As the figure shows (see panels (a)-(b)), an increase in the parameters α_N and α_S (measuring the negative effects of environmental degradation in each country) shrinks the basin of attraction of the socially optimal steady state (0, 0), thus reducing the likelihood that the system will eventually converge to it. The same occurs with an increase in the parameters d_N and d_S which measure the capacity of each country to self-protect from environmental degradation (see panels (c)-(d)). A similar result emerges also with a reduction in the maladaptation cost C^D and in the parameter $\overline{P}$ (measuring environmental degradation in (0, 0), that is, when none adopts maladaptive strategies, see Fig. 4).

Let us now look at the inequality in the payoff of the two populations. First of all, we recall that the payoff of an agent is constituted by the gross output $\overline{Y}_k$, the damage term $\Omega_k(P)$, and the cost C^D (in case of adoption of strategy D). We stress that the only variable part of the payoff is thus identified in the damage term, while the gross output and the adoption cost are fixed. This leads us to the consideration that any change in the inequality in well-being between agents of N and S can be ascribed to a variation in the differential of environmental damage. In particular, we find that the following proposition holds.

Proposition 4 *Inequality in* (0, 0) *is lower than in* (1, 1)*, that is*

$$\widetilde{U}_N(0,0) - \widetilde{U}_S(0,0) < \widetilde{U}_N(1,1) - \widetilde{U}_S(1,1) \tag{45}$$

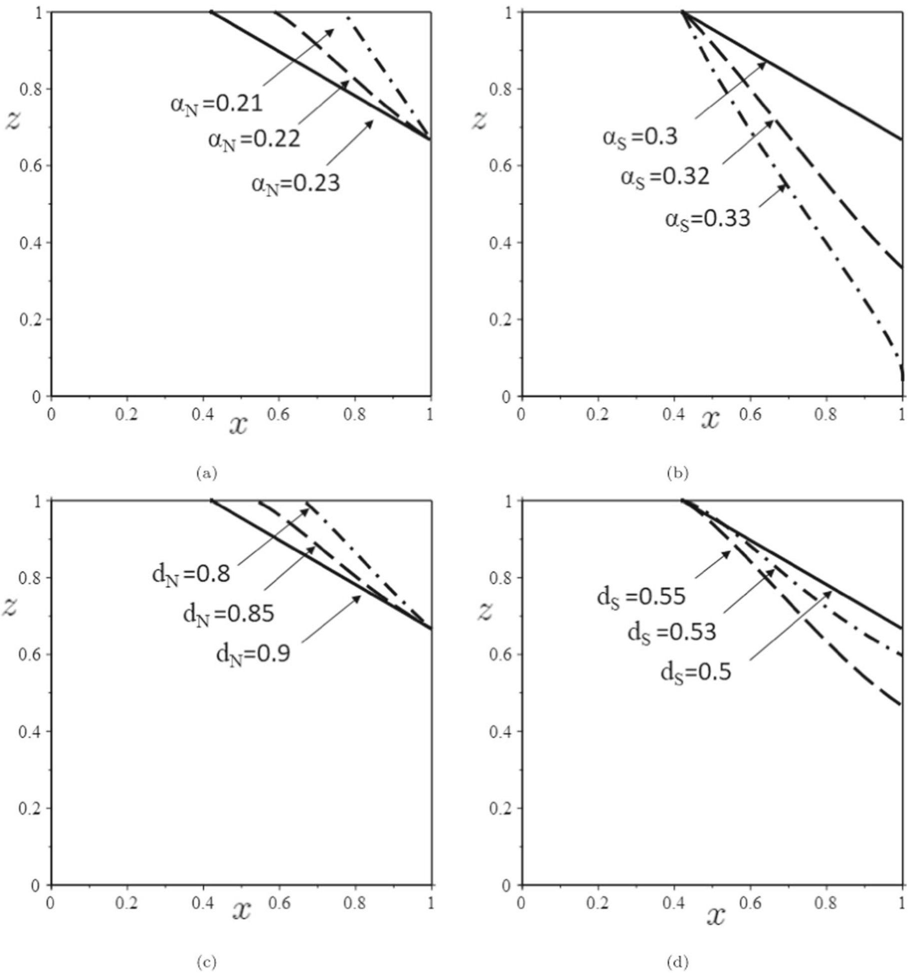

Fig. 3 Basins of attraction for different parameter values. Baseline: $\alpha_N = 0.23$, $\alpha_S = 0.3$, $\beta_N = 0.4$, $\beta_S = 0.3$, $d_N = 0.9$, $d_S = 0.5$, $C^D = 0.16$, $\overline{P} = 1$

if and only if:

$$\frac{\beta_N + \beta_S}{\overline{P}} > \frac{\alpha_S - \alpha_N}{\frac{\alpha_S}{1+d_S} - \frac{\alpha_N}{1+d_N}} - 1 \tag{46}$$

Proof The above proposition can be proved by substituting:

$$\widetilde{U}_N(0,0) - \widetilde{U}_S(0,0) = \overline{Y}_N - \overline{Y}_S + (\alpha_S - \alpha_N)\overline{P} \tag{47}$$

and

$$\widetilde{U}_N(1,1) - \widetilde{U}_S(1,1) = \overline{Y}_N - \overline{Y}_S + \left(\frac{\alpha_S}{1+d_S} - \frac{\alpha_N}{1+d_N}\right)\left(\overline{P} + \beta_N + \beta_S\right) \tag{48}$$

into inequality (45) and solving it. □

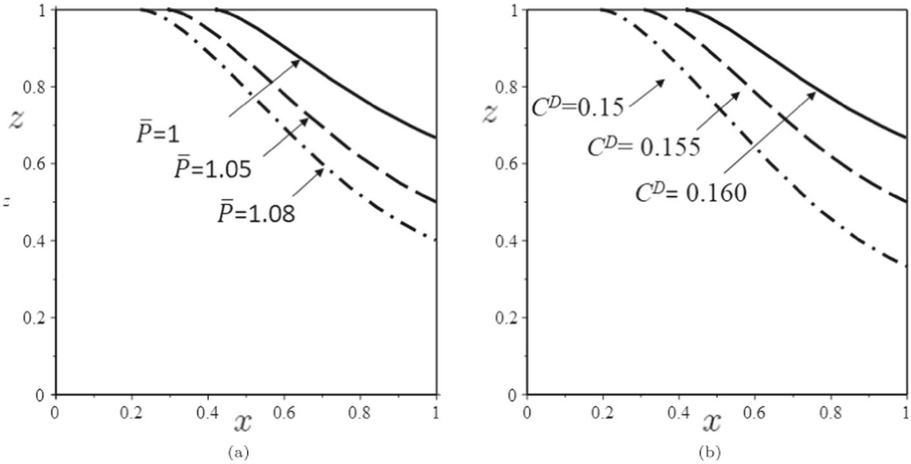

Fig. 4 Basins of attraction for different parameter values. Baseline: $\alpha_N = 0.23$, $\alpha_S = 0.3$, $\beta_N = 0.4$, $\beta_S = 0.3$, $d_N = 0.9$, $d_S = 0.5$, $C^D = 0.16$, $\overline{P} = 1$

Note that equation (46) always holds when the term on its right hand side is non-positive. We have:

$$\frac{\alpha_S - \alpha_N}{\frac{\alpha_S}{1+d_S} - \frac{\alpha_N}{1+d_N}} > 1 \tag{49}$$

if and only if

$$\frac{\alpha_N d_N}{1 + d_N} < \frac{\alpha_S d_S}{1 + d_S}$$

that is, if condition (35) holds.[5]

We recall that the above inequality requires that the damage differential of N due to the adoption of strategy D must be lower than the one of S. If this condition holds, then condition (46) holds only for sufficiently high values of the ratio $(\beta_N + \beta_S) / \overline{P}$. This occurs when negative externalities of agents adopting self-protective strategy D are much higher than autonomous degradation $\overline{P}$. Under these circumstances, inequality is bound to increase moving from $(0, 0)$ to $(1, 1)$, as human action makes environmental degradation increase more sharply and thus causes the gap in well-being between agents from N and S to widen, by virtue of condition (46).

7 The general case

In this work we employed a specification of the model whose simplicity allows for a more concise illustration of the phenomenon. However, we remark that a more general modelisation does not alter our results, which are robust to other formal specifications. Although the complete study of the general case is beyond the scope of this work, we here show that the results hold also if only the following assumption is made on the payoff functions $U_k^D(P)$

[5] Note that, since $d_S < d_N$, if $\alpha_S > \alpha_N$ then condition (35) is certainly met. In other words, the latter condition is always satisfied if the South suffers a higher economic impact from environmental degradation and has a lower capacity to defend.

and $U_k^{ND}(P)$:

$$\frac{dU_k^{ND}(P)}{dP} < \frac{dU_k^{D}(P)}{dP} < 0,\ k = N, S \tag{50}$$

We recall that this condition requires that the payoff of agents adopting ND decreases more rapidly than that of agents adopting D, when the level of environmental degradation P increases. Assuming that P is a function of x and z, with partial derivatives $\frac{\partial P(x,z)}{\partial x} > 0$ and $\frac{\partial P(x,z)}{\partial z} > 0$ (that is, P is increasing in x and z), we have that $\dot{x} = 0$ for $x = 0$, $x = 1$, and along the curve satisfying the equation:

$$U_N^D(P) - U_N^{ND}(P) = 0 \tag{51}$$

Analogously, it holds that $\dot{z} = 0$ for $z = 0$, $z = 1$, and along the curve satisfying the equation:

$$U_S^D(P) - U_S^{ND}(P) = 0 \tag{52}$$

The two equations (51) and (52) implicitly define two functions: $z = f_N(x)$ and $z = f_S(x)$, with equal slope:

$$f_k'(x) = -\frac{\frac{d\left[U_k^D(P) - U_k^{ND}(P)\right]}{dP}\cdot\frac{\partial P(x,z)}{\partial x}}{\frac{d\left[U_k^D(P) - U_k^{ND}(P)\right]}{dP}\cdot\frac{\partial P(x,z)}{\partial z}} = -\frac{\frac{\partial P(x,z)}{\partial x}}{\frac{\partial P(x,z)}{\partial z}} < 0,\ j\text{=}D\text{,}ND$$

Therefore, the graph of function $z = f_N(x)$ is a translation (either upward or downward) of the graph of $z = f_S(x)$. This implies that, just as in the model analysed in this work, there are generally no steady states internal to square Q, in which strategies D and ND coexist in both countries.

As concerns the steady states internal to the sides of Q (where the two strategies coexist in only one of the countries), we have that the Jacobian matrix evaluated at $(i, \bar{z})$, with $i = 0, 1$ and $1 > \bar{z} > 0$, is given by:

$$\begin{pmatrix} (1-2i)\left\{U_N^D\left[P(i,\bar{z})\right] - U_N^{ND}\left[P(i,\bar{z})\right]\right\} & 0 \\ \bar{z}(1-\bar{z})\frac{\partial\left\{U_S^D[P(i,\bar{z})] - U_S^{ND}[P(i,\bar{z})]\right\}}{\partial x} & \bar{z}(1-\bar{z})\frac{\partial\left\{U_S^D[P(i,\bar{z})] - U_S^{ND}[P(i,\bar{z})]\right\}}{\partial z} \end{pmatrix}$$

and has a positive eigenvalue in the direction of the side of Q with $x = i$:

$$\bar{z}(1-\bar{z})\frac{\partial\left\{U_S^D\left[P(i,\bar{z})\right] - U_S^{ND}\left[P(i,\bar{z})\right]\right\}}{\partial z} > 0\ \text{(by virtue of (50))}$$

Analogously, the Jacobian matrix evaluated at the steady states $(\bar{x}, j)$, with $j = 0, 1$ and $1 > \bar{x} > 0$, is given by:

$$\begin{pmatrix} \bar{x}(1-\bar{x})\frac{\partial\left\{U_N^D[P(\bar{x},j)] - U_N^{ND}[P(\bar{x},j)]\right\}}{\partial x} & \bar{x}(1-\bar{x})\frac{\partial\left\{U_N^D[P(\bar{x},j)] - U_N^{ND}[P(\bar{x},j)]\right\}}{\partial z} \\ 0 & (1-2j)\left\{U_S^D\left[P(\bar{x},j)\right] - U_S^{ND}\left[P(\bar{x},j)\right]\right\} \end{pmatrix}$$

and has a positive eigenvalue in direction of the side of Q on the side with $z = j$:

$$\bar{x}(1-\bar{x})\frac{\partial\left\{U_N^D\left[P(\bar{x},j)\right] - U_N^{ND}\left[P(\bar{x},j)\right]\right\}}{\partial x} > 0\ \text{(by virtue of (50))}$$

Therefore, also in this more general context, we find that only the vertices (0, 0), (0, 1), (1, 0), and (1, 1) can be attractive and that all trajectories starting from the interior of Q converge to one of such vertices, excluding the ones belonging to the stable manifolds of the steady states $(i, \bar{z})$ and $(\bar{x}, j)$ above-mentioned, when they exist and are saddle points. The less general specification adopted in this work is thus meant to provide an easier interpretative framework.

8 Discussion and conclusions

In this work we studied of the interconnection between inequality in the capacity to adopt adaptive strategies and inequality in well-being, highlighting the role that environmental degradation plays in this relation. In addition, we explicitly modelled the heterogeneity of agents, making the environmental damage they suffer, the efficacy, and affordability of their responses dependent on the groups they belong to. We recall that we chose a country-wise exemplification to illustrate our model only for the relevance of the issue at hand and for its descriptive efficacy. Other instances in which two groups are differentiated according to their capacity to cope with adversities would be equally valid, and so our results. As proved in the Sect. 7, the model specification chosen does not affect the results, which are robust to a more general formulation of the problem.

Two major conclusions can be drawn from our analysis. Firstly, the non-adoption case, in which no agent in either country adopts the maladaptive self-protective strategy, is Pareto-optimal whenever it is attractive, i.e. it is individually beneficial. This represents the case in which the cost of adoption of the maladaptive strategy is too high to make it convenient for any agent, thus preventing agents from generating the negative externalities related to such strategy. Intuitively, no agent would thus be better off adopting the Pareto-dominated maladaptive strategy. However, our analysis shows that non-adoption could be Pareto-optimal even if it is not attractive. This happens when the adoption cost of the maladaptive strategy is sufficiently low for at least the wealthier agents and its negative externalities are sufficiently high to make every agent worse off. In this case maladaptive strategies make the system reach a Pareto-dominated steady state. This undesirable outcome could be overcome if agents successfully coordinated on non-adoption or if an institution were established or a policy enforced to prevent agents from adopting maladaptive strategies.

Secondly, we also found that the inequality between the different groups of agents may decrease or increase depending on the ratio between autonomous environmental degradation and that generated by agents adopting strategy D (see condition (46)). If maladaptation has severe environmental consequences (i.e. it causes environmental degradation to remarkably increase with respect to the case in which none maladapts), then inequality will increase as we move from full non-adaptation $(0, 0)$ to full adaptation $(1, 1)$. Indeed, even if agents from the relatively less developed country adopt the maladaptive strategy, the fact that they are also more vulnerable to environmental degradation makes inequality increase. In the full adoption scenario, the environment is further degraded by the negative externalities coming from all agents, which goes to disproportionally increase the burden on the most vulnerable. On the contrary, if the environmental consequences of maladaptation are relatively low with respect to existing pollution, then inequality may decrease as we move to full adaptation. In this case, although the richer agents have a higher capacity to defend from environmental degradation, they also have more to lose from environmental degradation which makes them suffer higher losses. Stated differently, the reduction of inequality observed in this case is not the result of a progressive redistribution policy but it simple mirrors the fact that everybody gets poorer thus reducing the initial gap between agents.

These results therefore suggest the need to systematically integrate the study of indirect adaptation effects and their distributional potential into climate risk assessments and interventions. Efforts in this direction can be important to build an awareness of possible maladaptive outcomes and to push policy makers and practioners to consider them. They also open the debate on how to distribute not only climate change mitigation, but also how to distribute adaptation actions.

We remark that this paper describes the dynamics and well-being consequences of maladaptive strategies, but it does not model the introduction of maladaptive strategies in a group which does not have any already. An expansion of this model might indeed implement a cross-group imitation, discounting the payoff difference by a factor relating to the fact that imitators and imitated agents belong to different groups. Moreover, we did not include within-group heterogeneity since it did not seem to directly affect our results. However, relevant insights might be drawn from an analysis that studies both cross-group and stratified within-group externalities. Finally, in this work we were concerned with the degradation of an environmental variable which affected both groups, as it occurs, for instance, in the case of climate change. Maladaptive strategies could also increase environmental pressure at the local, rather than at the global level, e.g. a lake. Analogously, maladaptation might degrade and environmental indicator from which only a socially homogenous group benefits (e.g. in terms of income, education, or other socio-demographic variables). An analysis of the interaction of *local* degradation with respect to a *global* one would make for a compelling extension of this work, with a focus on the dynamics of maladaptive strategies affecting the former and/or the latter.

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Declarations

Conflict of interest No competing interests to declare.

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