To mitigate or to adapt: how to deal with optimism, pessimism and strategic ambiguity?

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To mitigate or to adapt: how to deal with optimism, pessimism and strategic ambiguity?*

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Abstract

We analyze the effect of strategic ambiguity and heterogeneous attitudes towards such ambiguity on optimal mitigation and adaptation. Pessimistic players tend to invest more in mitigation, while optimists favor adaptation. When adaptation is more expensive than mitigation, three types of equilibria can obtain depending on the level and distribution of ambiguity aversion: (*i*) a mitigation equilibrium, (*ii*) an adaptation equilibrium and (*iii*) a mixed equilibrium with both adaptation and mitigation. The interaction between ambiguity attitudes and wealth distribution plays a crucial role for the aggregate environmental policy: a wealth transfer from pessimistic to optimistic agents increases total mitigation. A similar result applies to the choice of an optimal tax on consumption, which is shown to increase in optimism, but decrease following a transfer of income towards the more optimistic players. Finally, we show that under strategic ambiguity, the introduction of a non-binding standard can impact agents' beliefs about their opponents' behavior and as a result lower total equilibrium mitigation. Our results highlight the necessity to consider attitudes towards strategic ambiguity in the design of economic policies targeting climate change. They might also shed some light on the slow rate of convergence of environmental policies across countries.

Keywords: Climate policy; Ambiguity; Heterogeneity; Choquet expected utility.

JEL Classification: D81, Q54, H23

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1 Introduction

Climate change is one of the major challenges our planet is currently facing. Global warming due to excessive emissions of green-house gasses into the atmosphere can have a profound and potentially irreversible impact on the environment and potentially catastrophic effects on health, life-expectancy, human activity, economic development and growth.

Mitigation and adaptation are the two main policies used to address climate change. Heal and Kristrom (2002) define mitigation as actions that reduce the flow of green-house gases into the atmosphere and so, change the probability distribution over future climate states. Adaptation refers to investment into processes, practices, or structures which moderate climate change damages and reduce the vulnerability of communities, regions, or countries to such environmental risks, Buob and Stephan (2011).

Mitigation and adaptation are commonly viewed as substitutes: more engagement in mitigation would improve environmental quality and thus reduce the necessity of adaptation. IPCC[1]'s latest recommendations and conclusions from international debates on climate change highlight that an effective climate policy should involve a mix of mitigation and adaptation actions (see Parry et al. (2007)).

Environmental policies and collective efforts to combat climate change, however, see a varying rate of success and face challenges, both with respect to their acceptance and to their implementation. Evaluating such policies and predicting their success is complicated by the presence of uncertainty, which is not easily quantifiable by means of objective probabilities. We will refer to such uncertainty as ambiguity.

Millner et al. (2013) distinguish two types of ambiguity: the first is due to the still limited scientific understanding of the natural processes related to climate change and thus, to the inability to make exact probabilistic predictions concerning the impact of climate change on economic outcomes. The second type of ambiguity concerns the behavior of economic agents in view of the threat of climate change. We discuss these two types of uncertainty below.

While it is well understood that human activity and, in particular, emission of green-house gasses and notably CO_2 into the atmosphere causes global warming, the precise magnitude of the temperature increase is a subject of scientific debate. Fig. 1 in Heal and Millner (2013, p. 24) provides 20 expert estimates of the density function for climate sensitivity, which have drastically different shapes and moments. Field et al. (2014) presents four different scenarios, which reveal climate sensitivities varying between +0.3 and +4.8 C. The resulting predictions of socioeconomic consequences are even less exact and show considerable variability. Weitzman (2010) emphasizes this uncertainty and illustrates the difference between policies targeted at the expected effects of global warming versus policies which put significant weight on extreme scenarios. Several studies have studied the impact of such uncertainty on policy choices. Lange and Treich (2008), Millner et al. (2013), Lemoine and Traeger (2016), Berger et al. (2017) and Etner et al. (2019) . They showed that changes in ambiguity, captured by the arrival of additional informations about the future environmental quality, may generate different behaviors depending on both the DM's attitude toward ambiguity and his environmental preferences. The recent study of Mavi and Querou (2020) showed that heterogeneity in perception (underestimation or overestimation in the probability of occurrence of climate

[1] Inter-governmental Panel of experts on Climate Change.

catastrophes) has a significant impact on the qualitative nature of behavioral adjustments and on the pattern of resource conservation.

The second type of uncertainty is related to the reaction of economic agents to the projected impacts of climate change on their future welfare. Environmental policies rely on the agents' willingness to contribute to public projects, such as mitigation, often at the cost, both of their private consumption and of engaging in private adaptation strategies. In presence of strategic interactions, optimal individual contributions depend on the efforts undertaken by the other agents in the society, which in turn, might be difficult to predict. This is true both on the individual, as well as on the country level. For instance, in spite of the commitment expressed by several countries to reduce their greenhouse gas emissions, following the Paris agreement, member countries are still not sure whether this commitment will be honored or not. Absent economic and political sanctions, countries thus face strategic ambiguity relative to the behavior of other cosignatories of the treaty. That such strategic considerations can have a significant impact is illustrated by Nordhaus (2013, p. 178, Fig. 26), who shows that effective mitigation could be achieved at a moderate cost when all countries participate, whereas a limited participation rate of 50% would render it prohibitively expensive.

Formally, strategic ambiguity refers to a situation in which a player is not able to form a precise probabilistic prediction about the behavior of his opponents in the game. Such ambiguity cannot be modelled within the standard concept of a Nash equilibrium, which relies on the expected utility theory developed byVon Neumann and Morgenstern (1945) and requires players to entertain correct probabilistic beliefs about the strategies chosen by their opponents. In the context of climate agreements such an assumption appears rather strong. Ambiguity about the behavior of others might be due to the novelty of the situation in which players are engaging, limited experience in similar past interactions with the players at hand, or to the fact that the game structure admits multiple predictions as to the outcome of the game. All three factors are relevant in the case of global agreements concerning climate change: the problem is relatively recent and past attempts at reaching a consensus have had limited success. The willingness of countries to participate at any given moment is often dictated by short-term political considerations and can drastically change at the end of a government mandate. Finally, while standard theoretical models of public good provision would predict lack of cooperation and a break-down of the treaty absent economic sanctions, the Paris agreement, which relies on self-commitment and evaluation by peers, implicitly presumes that the actors attach some positive weight to a cooperative outcome.

In the presence of strategic ambiguity, the players' attitudes towards such ambiguity will have an effect on equilibrium behavior. Optimistic agents will overweigh the possibility that their opponents are fully engaged in mitigation, whereas pessimists will put excessive weight on scenarios, in which contributions of others are low. Thus, heterogeneity in attitudes towards ambiguity will in general lead to differences in the optimal strategies chosen. Indeed, experimental studies show that perception of ambiguity can explain the deviation of observed behavior from Nash Equilibrium, Pulford and Colman (2007), Di Mauro and Castro (2011), and Kelsey and Le Roux (2015) and find that ambiguity attitudes differ largely across players, Eichberger et al. (2008), Ivanov (2011), Li et al. (2019). Interestingly, such heterogeneity has also been documented on a country-level: Hofstede (2001) identifies pessimism and optimism as cultural traits of societies. He proposes an Uncertainty Avoidance Index – a measure of pessimistic attitudes – which he applies on a country level. His data demonstrates large

differences in the optimism parameters across countries[2]. In as far as countries' decisions to contribute to global mitigation efforts are subject to such cultural traits, we can expect those to have an impact on the outcome of global climate agreements.

While country-level data on environmental policies, Holzinger et al. (2008a, 2011), show that environmental policies across countries converge, such convergence is slow and applies mostly to the set of issues regulated. In contrast, the type of policy instruments used, as well as the levels of taxes and standards implemented exhibit significant variation across countries (e.g., even within the EU), which is not explained by differences in income. Holzinger et al. (2008b) point out cultural similarity between countries, as one of the explanatory variables for the speed of convergence. In as far as optimism and pessimism can be seen as cultural traits, as suggested by Hofstede (2001), they might have an effect on the type and level of policies chosen by different countries. Furthermore, Holzinger et al. (2008b) highlight transnational communication as a facilitating factor for convergence of environmental policies. Since communication across countries can alleviate strategic ambiguity, our model shows that it will also reduce the impact of heterogeneous attitudes towards ambiguity on policy choices, thus implying a higher degree of convergence.

Theoretical advances in the field of decision theory taking into account ambiguity have allowed for a rigorous formalization of the notion of ambiguity in games. Notably, the Choquet expected utility with NEO-additive capacities, axiomatized by Chateauneuf et al. (2007), allows for a meaningful separation of ambiguity and ambiguity attitude and captures both ambiguity aversion (pessimism) as well as ambiguity seeking (optimism). A player's payoff is represented as a weighted sum of the expected payoff he would obtain under his objective belief without ambiguity and a convex combination of the best possible outcome given his strategy and the worst possible outcome given his strategy. The weight assigned to the expected payoff is the player's degree of confidence $(1-\delta)$, where δ is the perceived ambiguity. The weight α assigned to the best possible outcome captures the player's degree of optimism. This representation has the advantage to model heterogeneous attitudes with a minimal number of parameters and it is easy to interpret. It allows for a distinction between the players' probabilistic beliefs about the behavior of the other players in the game (which correspond to the standard interpretation of a Nash equilibrium) and the confidence that players entertain regarding these beliefs.

Eichberger and Kelsey (2014) provide an equilibrium concept for games with strategic ambiguity. This equilibrium has been applied to public good games, see Eichberger and Kelsey (2002), to models of oligopolies see Fontini (2005) as well as to coordination games Eichberger et al. (2009). In coordination games, ambiguity aversion or ambiguity loving behavior can serve as an equilibrium selection device. In public good games, it has been shown that the deviation from the Nash equilibrium depends on the nature of strategic interactions taking place, i.e., whether the game being played exhibits strategic substitutes or complements. In games of strategic substitutes with externalities such as public good provision and Cournot duopoly, an increase in ambiguity combined with pessimism can bring the equilibrium allocation closer to Pareto-optimality, while an increase in optimism increases the player's own payoff, but results in Pareto-inferior allocations, see Eichberger et al. (2009)

[2]Cozzi and Giordani (2011) relate optimism on a country level to investment in R&D and country-specific growth.

and Kelsey and Le Roux (2015).

In this paper, we study the impact of strategic ambiguity and attitudes towards strategic ambiguity on the choice of different agents to contribute to mitigation, or use resources for adaptation. We examine the impact of agent heterogeneity on the optimal policy choices and aggregate outcomes. We also provide some policy recommendations.

1.1 Framework and results

We consider a two-period model where individuals can invest simultaneously in two environmental policies: mitigation and adaptation.

In the first period, players can split their endowment between personal savings and mitigation that benefits all players. In the second period, their returns from savings can be used for consumption and adaptation. Ambiguity arises since players decide about their contributions to mitigation policy while holding uncertain beliefs about others' behavior.

We model such ambiguity by a NEO-additive capacity, in which players assign a weight of $(1-\delta)$, their degree of confidence, to the equilibrium strategy combination chosen by their opponents. The rest of the weight, the degree of ambiguity δ, is distributed between the strategy combination that results in the best possible outcome and the one resulting in the worst possible outcome. These are weighted by the degree of optimism α and the degree of pessimism $(1-\alpha)$.

We next use the equilibrium under ambiguity defined by Eichberger and Kelsey (2014) to determine the equilibrium contributions to mitigation and adaptation.

Our main results are the following. As is well known, in the case of ambiguity-neutrality, players consider mitigation and adaptation to be perfect substitutes and always choose the cheaper of the two policies. We show that under strategic ambiguity, this is only true as long as mitigation is at least as expensive as adaptation. In the more realistic scenario, in which adaptation is the more expensive strategy, we exhibit values of the parameters, for which a player would choose both mitigation and adaptation on the equilibrium path. The two strategies are no longer perfect substitutes, since adaptation occurs only after total mitigation has been observed and thus provides the player with some flexibility after the ambiguity has been resolved. Thus, a player who is not fully pessimistic will be willing to pay for such flexibility and choose positive levels of adaptation, even when the latter is more expensive. In the presence of optimism, prices of distinct economic policies can therefore exhibit arbitrage opportunities, even when objectively the two policies are perfect substitutes. In particular, societies in which income is relatively equally distributed, but optimism is relatively high will not mitigate and invest ex-post in adaptation even when adaptation is more expensive than mitigation. Thus, optimism can generate inefficiencies in policy choice.

Agent heterogeneity impacts considerably the choice of environmental policies. Even in the case, when the two policies have identical prices, the maximal optimal amount invested in mitigation by a player depends negatively on his degree of optimism. In particular, we construct an equilibrium, in which pessimists only mitigate and optimists only adapt. When adaptation is the costlier of the two policies, everything else being equal, an agent who is more optimistic will invest less in mitigation compared to a more pessimistic one. The critical price of adaptation at which a more optimistic agent stops choosing adaptation is higher

than the corresponding one for a more pessimistic agent. Thus, we can exhibit equilibria, in which agents separate into mitigation and adaptation, depending on their attitude towards ambiguity.

In the case, in which the price of adaptation is sufficiently high and thus all agents prefer to invest in mitigation, the equilibrium exhibits some interesting properties. As one would expect, more optimistic players choose lower levels of mitigation than pessimistic ones. However, differently from the standard case, the total amount of mitigation depends crucially both on the total level of optimism in the society, and on the "wealth-weighted total level of optimism", i.e., on the distribution of wealth across players with different attitudes towards ambiguity. Interestingly, a wealth transfer from a more pessimistic to a more optimistic player results in an increase of the total level of mitigation. This is because optimists overweigh the possibility that their opponents contribute their total wealth to mitigation. When this maximal contribution decreases, they have to compensate by increasing their own mitigation efforts, which in turn increases total mitigation. Thus, societies identical in all other respects, but in which optimistic agents are relatively richer may be more successful in their mitigation efforts.

In order to provide some policy recommendations in presence of ambiguity, we study the effect of taxes and standards on equilibrium allocations. We show that the tax rate necessary to implement the socially optimal level of mitigation increases in the individual degrees of optimism. Intuitively, pessimistic players need less incentives in order to increase their mitigation level to the socially optimal one. It increases (decreases) in the perceived ambiguity when players are relatively optimistic (pessimistic). In-line with our findings above, societies in which optimistic agents are relatively richer, require lower tax levels to achieve the social optimum, provided that the transfer scheme is relatively flat in income and thus, does not cancel out the positive effect of the initial income distribution profile.

Under strategic ambiguity, we show that the introduction of a standard leads to a change in players' expectations by increasing contributions of the other players in the worst case scenario. This, in turn, leads to a reduction in the contribution of the players who are more pessimistic. For low levels of the standard, and especially, when the standard is not binding for all of the players, this effect is not necessarily offset by the increase in the mitigation efforts of the optimists brought about by the standard. Therefore, the introduction of a standard may in fact lead to a decrease in the total contribution to the mitigation policy and worsen environmental quality. The situation with strategic ambiguity thus differs from the standard case: if the social planner does not know the social optimum or if the optimal standard is not politically implementable, setting a lower standard as a compromise might have an effect opposite to the desired one.

1.2 Organization of the paper

The paper is organized as follows. Section 2 describes the economy, explains how we model strategic ambiguity and discusses the equilibrium. Section 3 is devoted to the analysis of the game. In section 4, we study the effect of taxes and standards on equilibrium allocations. Section 5 concludes.

2 Two-period model with mitigation and adaptation

2.1 The economy

Consider a two-period economy with n consumers. Consumer i receives an income y_i in period 1 and no endowment in period 2. In period 1, consumer i can use his income to either save (S_i) or to contribute to mitigation policy (m_i) that benefits all players: $y_i = m_i + S_i$. The interest rate on savings is r.

Consumers choose their mitigation efforts simultaneously. These choices become commonly known in the second period and affect global environmental quality according to $E_2 = E + M$, where $M = \sum_{i=1}^{N} m_i$ are the total mitigation efforts and E is the exogenously given environmental quality which obtains in absence of mitigation[3].

In period 2, consumer i observes the realized environmental quality E_2, collects the return on his savings, $(1+r) S_i$ and decides how to apportion them between consumption (c_i) and adaptation (a_i) to the prevailing environmental quality. Adaptation is a private good available at a cost ϕ. Thus, the budget constraint for period two is given by: $(1+r) S_i = c_i + \phi a_i$.

Consumer i's perceived environmental quality taking into account adaptation is:

$$e_i = E + M + a_i \tag{1}$$

We assume that i's utility from consumption and environmental quality is Cobb-Douglas:

$$U_i(c_i, e_i) = c_i e_i.$$

2.2 The Mitigation-Adaptation Game

We now model the economy described above as a game with the set of players being the set of consumers $I = \{1...n\}$. The strategy of a player is given by a tuple $(m_i, \hat{a}_i(\cdot,\cdot))$ where $m_i \in \tilde{M}_i = [0, y_i]$ is i's contribution towards mitigation and $\hat{a}_i(\cdot,\cdot)$ is i's adaptation strategy. Formally, let $\tilde{M}_{-i} = \times_{j \neq i} \tilde{M}_j$ be the set of vectors of contributions towards mitigation of all players other than i with representative element $\tilde{m}_{-i}$. The adaptation strategy of player i assigns a feasible level of adaptation to every vector of mitigations $(m_i, \tilde{m}_{-i}) \in \tilde{M}_i \times \tilde{M}_{-i}$:

$$\hat{a}_i(\cdot,\cdot) : \tilde{M}_i \times \tilde{M}_{-i} \rightarrow \left[0, \frac{(1+r)(y_i - m_i)}{\phi}\right]$$

Since adaptation brings only private benefits, i's payoff depends on the mitigation efforts of the others $\tilde{m}_{-i}$, but not on their adaptation decisions. Since environmental quality depends on the sum of the mitigation efforts, we will use the notation $m_{-i} = \sum_{j \neq i} m_j$ to represent the sum of the mitigation efforts of all players other than i. Thus, using the budget constraints for period 1 and 2, as well as equation (1), the payoff of player i, $U_i(c_i, e_i)$, can be rewritten as a function of strategies as:

$$U_i\left(m_i, \hat{a}_i(m_i, \tilde{m}_{-i}), \tilde{m}_{-i}\right) = (1+r)\left(y_i - m_i - \phi \hat{a}_i(m_i, \tilde{m}_{-i})\right)\left[E + m_i + m_{-i} + \hat{a}_i(m_i, \tilde{m}_{-i})\right].$$

[3] We follow John and Pecchenino (1994), Jouvet et al. (2005) and Raffin and Seegmuller (2014) to describe the evolution of the environmental quality over time. However, we assume that the parameter reflecting the efficiency of mitigation is equal to one contrary to the cited papers.

Consider first the adaptation decision. In period 2, the environmental quality $E+M=E+m_i+m_{-i}$ is assumed common knowledge. Thus, players face no uncertainty in regards to the payoff from adaptation. The optimal adaptation strategy is given by:

$$\begin{aligned} a_i^*\left(m_i,\tilde{m}_{-i}\right) &= \arg \max_{a_i\in\left[0,\frac{(1+r)(y_i-m_i)}{\phi}\right]} \left((1+r)\left(y_i-m_i\right)-\phi a_i\right)\left[E+m_i+m_{-i}+a_i\right] \\ a_i^*\left(m_i,\tilde{m}_{-i}\right) &= \begin{cases} 0 & \text{if } (1+r)\left(y_i-m_i\right)-\left(E+m_i+m_{-i}\right)\phi<0 \\ \frac{(1+r)(y_i-m_i)-(E+m_i+m_{-i})\phi}{2\phi} & \text{if } (1+r)\left(y_i-m_i\right)-\left(E+m_i+m_{-i}\right)\phi\geq 0 \end{cases} \end{aligned} \tag{2}$$

In words, adaptation is increasing in income and decreasing in the mitigation efforts of the player, m_i and in realized environmental quality, $E+m_i+m_{-i}$. In this sense, mitigation and adaptation are substitutes: adaptation becomes 0 if mitigation is sufficiently large.

We observe that a_i^* depends on $\tilde{m}_{-i}$ only through m_{-i}. We thus write, whenever convenient $a^*\left(m_i,m_{-i}\right)$. This, in turn, implies that $U_i\left(\cdot\right)$ depends on $\tilde{m}_{-i}$ only through m_{-i} and we also use the notation $U_i\left(m_i,a^*\left(\cdot\right),m_{-i}\right)$ whenever convenient[4].

Next consider the choice of mitigation effort by player i in period 1. Since mitigation efforts are chosen simultaneously, player i makes decisions about m_i while being potentially uncertain about his opponents' behavior. In particular, suppose that player i's best estimate about the mitigation efforts of the other players is given by $\tilde{m}_{-i}\in M_{-i}$. If i does not know well his opponents, if the situation of strategic interaction is novel and i has little experience with it, i might face ambiguity δ about this estimate. We will assume that the degree of ambiguity depends on the situation of strategic interaction and is thus common to all players. Player i will thus assign $\tilde{m}_{-i}$ a degree of confidence given by $(1-\delta)$, and put a positive weight of δ on the outcome of the interaction being different from $\tilde{m}_{-i}$.

The additional weight δ will be distributed towards those opponents' strategies that give i the best possible outcome when i is optimistic and towards those that lead to the worst possible outcome, when i is pessimistic. In general i's degree of optimism, α_i will determine this tradeoff. The degree of optimism α_i is assumed to be player-specific.

Formally, such ambiguous beliefs of player i are captured by a NEO-additive capacity on $\tilde{M}_{-i}$, as axiomatized by Chateauneuf et al. (2007).

Definition 1 *For a given degree of ambiguity $\delta\in[0,1]$, degree of optimism $\alpha_i\in[0,1]$ and an i-incomplete mitigation strategy $\tilde{m}_{-i}\in\tilde{M}_{-i}$, a NEO-additive-capacity ν_i on $\tilde{M}_{-i}$ is defined by $\nu_i\left(\varnothing\right)=0$, $\nu_i\left(\tilde{M}_{-i}\right)=1$ and*

$$\nu_i\left(A\mid\tilde{m}_{-i}\right)=\begin{cases}\delta\alpha_i+(1-\delta) & \text{if } \tilde{m}_{-i}\in A \\ \delta\alpha_i & \text{if } \tilde{m}_{-i}\notin A\end{cases}. \tag{3}$$

The Choquet integral is used to obtain an expected payoff with respect to a capacity, see Eichberger and Kelsey (2014). In the case of NEO-additive capacities as in (3), the Choquet integral takes the following form:

Remark 2 *Assuming that player i chooses an optimal adaptation strategy, $a_i^*\left(\cdot,\cdot\right)$, and for a given i-incomplete mitigation strategy $\tilde{m}_{-i}$, the Choquet expected payoff of player i with*

[4]The same remark applies to the function $V_i\left(\cdot\right)$ defined below.

respect to capacity (3) is given by:

$$\begin{aligned} V_i\left(m_i, \tilde{m}_{-i}\right) &= \int U_i\left(m_i, a_i^*\left(m_i, \tilde{m}'_{-i}\right), \tilde{m}'_{-i}\right) d\nu_i\left(\tilde{m}'_{-i} \mid \tilde{m}_{-i}\right) \\ &= (1-\delta)\, U_i\left(m_i, a_i^*\left(m_i, \tilde{m}_{-i}\right), \tilde{m}_{-i}\right) + \\ &\quad +\delta\alpha_i \max_{\tilde{m}_{-i}\in\tilde{M}_{-i}} U_i\left(m_i, a_i^*\left(m_i, \tilde{m}_{-i}\right), \tilde{m}_{-i}\right) + \delta\left(1-\alpha_i\right) \min_{\tilde{m}_{-i}\in\tilde{M}_{-i}} U_i\left(m_i, a_i^*\left(m_i, \tilde{m}_{-i}\right), \tilde{m}_{-i}\right) \\ &= (1-\delta)\, U_i\left(m_i, a_i^*\left(m_i, \tilde{m}_{-i}\right), \tilde{m}_{-i}\right) + \\ &\quad +\delta\alpha_i U_i\left(m_i, a_i^*\left(m_i, (y_j)_{j\neq i}\right), (y_j)_{j\neq i}\right) + \delta\left(1-\alpha_i\right) U_i\left(m_i, a_i^*\left(m_i, \mathbf{0}\right), \mathbf{0}\right) \end{aligned}$$

The payoff is composed of three parts: the first term comprises i's payoff given his own strategy and his best estimate about the strategy of his opponents, $\tilde{m}_{-i}$. The presence of ambiguity means that this payoff is discounted by $(1-\delta)$, i's degree of confidence. In particular, if $\delta = 0$, $V_i(\cdot,\cdot)$ coincides with $U_i(\cdot,\cdot)$. The response to ambiguity is partly optimistic represented by the weight α_i given to the best outcome, the case in which i's opponents invest all of their income in mitigation, and partly pessimistic represented by the weight $(1-\alpha_i)$ given to the worst outcome, the case in which i's opponents invest nothing in mitigation.

The mitigation best-response of a player i is defined by

$$\rho_i\left(\tilde{m}_{-i}\right) = \arg\max_{m_i\in\tilde{M}_i} V_i\left(m_i, \tilde{m}_{-i}\right).$$

The equilibrium under ambiguity is defined as a strategy combination such that each player chooses an optimal adaptation strategy and a mitigation strategy which is a best-response to the mitigation efforts chosen by his opponents, see Eichberger and Kelsey (2014):

Definition 3 *(Equilibrium under ambiguity) An equilibrium of the game is given by a strategy combination $\left(m_i^*, a_i^*(\cdot,\cdot)\right)_{i\in I}$ such that for every player i, $a_i^*(\cdot,\cdot)$ is an optimal adaptation strategy as in (2) and such that for each player i, his mitigation strategy is a best response to the mitigation efforts chosen by his opponents: $m_i^* \in \rho_i\left(\tilde{m}_{-i}^*\right)$.*

3 Analysis of the game

In the previous section, we derived the optimal adaptation strategy of the players and defined the notion of an equilibrium. In this section, we analyze the properties of the best-responses and the equilibria in this game.

We assume that the player is forward-looking and thus knows the adaptation strategy he will adopt in the three possible scenarios he envisions: the worst-case scenario, when the other players contribute nothing to mitigation, the equilibrium path, and the best-case scenario, when the other players' contributions are equal to their total income. Thus, in general, the payoff function of the player will consist of (up to)[5] four segments:

$$V_i\left(m_i, m_{-i}\right) =$$

[5]Depending on the values of m_{-i} and the parameters, some of these segments might be irrelevant.

$$\begin{cases} V_i^{(1)}(m_i, m_{-i}) = \delta(1-\alpha_i)\frac{1}{\phi}\left(\frac{(1+r)(y_i-m_i)+(E+m_i)\phi}{2}\right)^2 + (1-\delta)\frac{1}{\phi}\left(\frac{(1+r)(y_i-m_i)+(E+m_i+m_{-i})\phi}{2}\right)^2 + \\ +\delta\alpha_i\frac{1}{\phi}\left(\frac{(1+r)(y_i-m_i)+\left(E+m_i+\sum_{j\neq i}y_j\right)\phi}{2}\right)^2,\ m_i \in \left[0, \frac{(1+r)y_i-\left(E+\sum_{j\neq i}y_j\right)\phi}{[(1+r)+\phi]}\right] \\ V_i^{(2)}(m_i, m_{-i}) = \delta(1-\alpha_i)\frac{1}{\phi}\left(\frac{(1+r)(y_i-m_i)+(E+m_i)\phi}{2}\right)^2 + (1-\delta)\frac{1}{\phi}\left(\frac{(1+r)(y_i-m_i)+(E+m_i+m_{-i})\phi}{2}\right)^2 + \\ +\delta\alpha_i(1+r)(y_i-m_i)\left[E+m_i+\alpha_i\delta\sum_{j\neq i}y_j\right],\ m_i \in \left[\frac{(1+r)y_i-\left(E+\sum_{j\neq i}y_j\right)\phi}{[(1+r)+\phi]}, \frac{(1+r)y_i-(E+m_{-i})\phi}{[(1+r)+\phi]}\right] \\ V_i^{(3)}(m_i, m_{-i}) = \delta(1-\alpha_i)\frac{1}{\phi}\left(\frac{(1+r)(y_i-m_i)+(E+m_i)\phi}{2}\right)^2 + (1+r)(y_i-m_i)\cdot \\ \cdot\left[(1-\delta+\delta\alpha_i)(E+m_i)+(1-\delta)m_{-i}+\alpha_i\delta\sum_{j\neq i}y_j\right],\ m_i \in \left[\frac{(1+r)y_i-(E+m_{-i})\phi}{[(1+r)+\phi]}, \frac{(1+r)y_i-E\phi}{[(1+r)+\phi]}\right] \\ V_i^{(4)}(m_i, m_{-i}) = (1+r)(y_i-m_i)\left[E+m_i+(1-\delta)m_{-i}+\alpha_i\delta\sum_{j\neq i}y_j\right],\ m_i \geq \frac{(1+r)y_i-E\phi}{[(1+r)+\phi]} \end{cases}$$

Here, the first segment $V_i^{(1)}(m_i, m_{-i})$ corresponds to the case where optimal adaptation is always strictly positive, the second segment, $V_i^{(2)}(m_i, m_{-i})$, has the player adapting only when the other players contribute their equilibrium levels of mitigation or nothing. In the third segment $V_i^{(3)}(m_i, m_{-i})$ strictly positive adaptation is optimal only when others do not mitigate and on the fourth segment, $V_i^{(4)}(m_i, m_{-i})$, no adaptation takes place. While the so-obtained payoff function is continuous, it is not differentiable on the boundaries between the segments.

The non-differentiability of the payoff function, as well as the fact that the first three segments can be either concave or convex, depending on the parameters makes the analysis of the best-response function tedious. Rather than providing the formal proofs (which are available from the authors upon request), we here describe the main properties of the best response of player i in terms of mitigation and adaptation. A formal description of the cases and properties discussed below is provided in the Appendix.

Four scenarios can be described depending on the ratio of the prices of adaptation and mitigation. Consider first the case in which $\frac{\phi}{1+r} < 1$, i.e., adaptation is cheaper than mitigation. For this case, it can be shown that optimal mitigation will always be 0: $\rho_i(m_{-i}) = 0$. Indeed, a player who chooses mitigation foregoes the possibility to "wait and see" the mitigation efforts of his opponents, and then optimally adapt his perceived environmental quality. By committing to mitigation, he exposes himself to the ambiguity of "investing too much" into the more expensive mitigation. Thus, postponing the decision until the relevant information is revealed is optimal and the player chooses no mitigation. The optimal adaptation in this case depends on the specific value of $\frac{\phi}{1+r}$, i.e., on which segment of the payoff function (1), (2) or (3) is relevant. Note that since at the time the adaptation decision are made, players perceive no ambiguity, optimal adaptation does not depend on ambiguity and ambiguity attitude.

The second scenario is the benchmark case, in which adaptation and mitigation have the same price, $\frac{\phi}{1+r} = 1$. In this case, optimal mitigation is not uniquely determined, the minimum being 0 and the maximum corresponding to the optimal adaptation level in the best-case scenario, when $m_i = 0$ and $m_{-i} = \sum_{j\neq i} y_j$:

$$\rho_i(m_{-i}) \in \left[0, \frac{y_i - \left(E + \sum_{j\neq i} y_j\right)\frac{\phi}{1+r}}{\left[1+\frac{\phi}{1+r}\right]}\right] \text{ for } \alpha_i\delta \neq 0.$$

The upper bound of $\rho_i(m_{-i})$ corresponds to a player, who mitigates just enough to make sure he will not have to adapt in the worst-case scenario and then, adjusts his adaptation level if he is "negatively surprised". Note that when players switch from being at least somewhat optimistic to an optimism parameter $\alpha_i = 0$ and then from being somewhat pessimistic, $\delta < 1$, to full pessimism, $\delta = 1$, the perceived adaptation necessary in the best-case scenario increases and thus, the maximal amount of optimal mitigation increases from:

$$\rho_i(m_{-i}) \in \left[0, \frac{y_i - (E + m_{-i})\frac{\phi}{1+r}}{\left[1 + \frac{\phi}{1+r}\right]}\right] \text{ for } \alpha_i = 0,\ \delta < 1$$

to

$$\rho_i(m_{-i}) \in \left[0, \frac{y_i - E\frac{\phi}{1+r}}{\left[1 + \frac{\phi}{1+r}\right]}\right] \text{ for } \alpha_i = 0,\ \delta = 1.$$

Hence, even in the case of equal prices for adaptation and mitigation, players with different attitudes towards ambiguity will exhibit different optimal levels of mitigation.

Next, consider the (admittedly more realistic) case, in which adaptation, while possible, is more expensive that mitigation, $\frac{\phi}{1+r} > 1$. In this scenario, the ambiguity of the player regarding others' contributions plays a non-trivial role: while investing in mitigation is cheaper, it exposes him to the possibility of having mitigated more than is optimal in the best-case scenario. In contrast, foregoing mitigation in favor of adaptation exposes him to the possibility of the worst-case scenario, in which others contribute nothing, while adaptation is expensive.

When $\frac{\phi}{1+r}$ is only slightly greater than 1, optimal mitigation will be strictly positive and in the interior of segment (2) implying that the player will have strictly positive levels of adaptation only in the worst-case scenario and on the equilibrium path, but not in the best-case scenario:

$$\begin{aligned}\rho_i(m_{-i}) \;=\; & \frac{\left[(1+\alpha_i\delta)\frac{\phi}{1+r} - (1-\alpha_i\delta)\right] y_i + \left[(1-\alpha_i\delta)\frac{\phi}{1+r} - (1+\alpha_i\delta)\right]\frac{\phi}{1+r}E}{-(1-\alpha_i\delta) + 2(1+\alpha_i\delta)\frac{\phi}{1+r} - (1-\alpha_i\delta)\left(\frac{\phi}{1+r}\right)^2} \\ & + \frac{(1-\delta)\frac{\phi}{1+r}\left[\frac{\phi}{1+r} - 1\right] m_{-i} - 2\frac{\phi}{1+r}\alpha_i\delta\sum_{j\neq i} y_j}{-(1-\alpha_i\delta) + 2(1+\alpha_i\delta)\frac{\phi}{1+r} - (1-\alpha_i\delta)\left(\frac{\phi}{1+r}\right)^2}\end{aligned} \tag{4}$$

As $\frac{\phi}{1+r}$ increases, making mitigation relatively cheaper, optimal mitigation increases as well. Furthermore, an increase in optimism drives optimal mitigation down.

As $\frac{\phi}{1+r}$ continues increasing, optimal mitigation eventually reaches first the boundary of segment (2),

$$\rho_i(m_{-i}) = \frac{y_i - (E + m_{-i})\frac{\phi}{1+r}}{\left[1 + \frac{\phi}{1+r}\right]}$$

with adaptation on the equilibrium path becoming 0, and then the interior of segment (3)

satisfying:

$$\rho_i(m_{-i}) = \frac{\left[\frac{\phi}{1+r}(2-\delta+\alpha_i\delta)-\delta(1-\alpha_i)\right]y_i+\left[\delta(1-\alpha_i)\frac{\phi}{1+r}-(2-\delta+\alpha_i\delta)\right]\frac{\phi}{1+r}E}{\left[2(2-\delta+\alpha_i\delta)\frac{\phi}{1+r}-\delta(1-\alpha_i)\left(\frac{\phi}{1+r}\right)^2-\delta(1-\alpha_i)\right]} \quad (5)$$
$$-\frac{2\frac{\phi}{1+r}\left((1-\delta)m_{-i}+\alpha_i\delta\sum_{j\neq i}y_j\right)}{\left[2(2-\delta+\alpha_i\delta)\frac{\phi}{1+r}-\delta(1-\alpha_i)\left(\frac{\phi}{1+r}\right)^2-\delta(1-\alpha_i)\right]}.$$

Once again, this best-response is increasing in $\frac{\phi}{1+r}$ and decreasing in optimism. Eventually, $\frac{\phi}{1+r}$ reaches a level at which the function $V_i^{(3)}(m_i, m_{-i})$ becomes convex and obtains its optimum on its upper boundary

$$\rho_i(m_{-i}) = \frac{y_i - E\frac{\phi}{1+r}}{\left[1+\frac{\phi}{1+r}\right]}$$

implying that adaptation becomes 0 in all cases.

Increasing the price of adaptation even further implies that optimal mitigation is in segment (4) and given by:

$$\rho_i(m_{-i}) = \frac{y_i - E - \alpha_i\delta\sum_{j\neq i}y_j - (1-\delta)m_{-i}}{2}. \quad (6)$$

While this expression does not depend on prices, the effect of optimism on mitigation continues to be negative.

In general, we have:

Proposition 4 *For $\frac{\phi}{1+r} > 1$, $\delta \in [0,1]$ and $\alpha_i \in [0,1]$ and given mitigation efforts m_{-i}, the optimal mitigation of player i within each segment is weakly increasing in the price ratio $\frac{\phi}{1+r}$ and weakly decreasing in the degree of optimism α_i. Furthermore, the reservation price levels $\frac{\phi}{1+r}$ below which player i chooses adaptation in all conceivable scenarios (segment (i)); chooses strictly positive adaptation in the worst-case scenario and on the equilibrium path (segment (ii)); chooses a strictly positive level of adaptation only in the worst-case scenario (segment (iii)); and never chooses adaptation (segment (iv)) are increasing in the degree of optimism α_i.*

Proposition 4 confirms the intuition that optimists will be less willing to contribute to mitigation and more likely to adapt. The analysis of the best-response of a player implies that the game of mitigation and adaptation under ambiguity can have equilibria in which players with distinct attitudes towards ambiguity choose not only different levels of mitigation and adaptation, but also different strategies towards dealing with climate change. In particular, our analysis suggests that more optimistic players will be choosing lower levels of mitigation, but will also be less likely to invest in mitigation at all, preferring the adaptation strategy, which gives them more flexibility. This could occur, even when adaptation is relatively more costly. In contrast, pessimists will favor mitigation.

This separation between optimists and pessimists is most marked for full optimists, $\alpha_i = 1$ and full pessimists, $\alpha_i = 0$, $\delta = 1$, see Claim 4 in the Appendix. In this special case, even if adaptation is more expensive, $\frac{\phi}{1+r} > 1$, optimal mitigation for full optimists will never exceed $\frac{(1+r)y_i - \left(E + \sum_{j \neq i} y_j\right)\phi}{(1+r)+\phi}$, implying strictly positive levels of adaptation on the equilibrium path, whereas, for $\frac{\phi}{1+r} > 1$ optimal mitigation for full pessimists will never fall below $\frac{(1+r)y_i - E\phi}{(1+r)+\phi}$, implying no adaptation on the equilibrium path.

In the following, we illustrate three types of equilibria which can occur: first, an equilibrium in which all players choose mitigation, second, an equilibrium, in which all players choose adaptation and third, "mixed" equilibria in which some players choose mitigation and others adaptation.

3.1 Mitigation equilibria

We first concentrate on an equilibrium of the static game in which all players invest only in mitigation. This requires the optimal adaptation efforts to be constant at 0 regardless of the choice of mitigation strategies and in particular, even if everyone chooses 0 mitigation. This would be the case if the cost of adaptation is particularly high, the environmental quality is relatively high, or the incomes are relatively low. In particular, as explained in the previous section, the existence of such an equilibrium can only be ensured if players are not too optimistic. Notably, the case of full optimism for some player, $\alpha_i = 1$, is excluded by the condition below. Provided these conditions are satisfied, the payoff of all players can be represented by $V_i^{(4)}(m_i, m_{-i})$. To characterize the equilibrium, we denote by $y = \sum_{i=1}^n y_i$ the total income of the society and by $\alpha = \sum_{i=1}^n \alpha_i$ the total degree of optimism.

Proposition 5 *Suppose that for all $i \in \{1...n\}$,*

$$\frac{\phi}{1+r} > \max \left\{ \begin{array}{c} \frac{(2-\delta(1-\alpha_i))+\sqrt{2(2-\delta(1-\alpha_i))}}{\delta(1-\alpha_i)}, \frac{[2-\delta(1-\alpha_i)]+\sqrt{(2-\delta(1-\alpha_i))^2+(4-3\delta+\delta\alpha_i)^2}}{4-\delta-3\alpha_i\delta}, \\ \frac{y_i+E+\alpha_i\delta\sum_{j\neq i} y_j+(1-\delta)m_{-i}}{y_i+E-\alpha_i\delta\sum_{j\neq i} y_j-(1-\delta)m_{-i}} \end{array} \right\}.$$

The unique interior Nash equilibrium under ambiguity of the static game is given by:

$$\begin{aligned} m_i^*(\delta, \alpha_i) &= \frac{\left[2 + (1-\delta)\left(n - 2 + \delta\sum_{j\neq i}\alpha_j\right)\right] y_i - (1+\delta)E}{[1+\delta+n(1-\delta)](1+\delta)} + \\ &+ \frac{-[(1-\delta)+\delta\alpha_i[2+(1-\delta)(n-2)]]\sum_{j\neq i} y_j + (1-\delta)\delta\sum_{j\neq i}\alpha_j\sum_{k\neq i,j} y_k}{[1+\delta+n(1-\delta)](1+\delta)} \end{aligned}$$

$$a^*\left(m_i^*(\delta,\alpha_i), \mathbf{0}\right) = a^*\left(m_i^*(\delta,\alpha_i), m_{-i}^*(\delta,\alpha_i)\right) = a^*\left(m_i^*(\delta,\alpha_i), (y_j)_{j\neq i}\right) = 0$$

provided that $m_i^*(\delta, \alpha_i) \in [0, y_i]$ for each i.

It satisfies the following properties

(i) $\frac{\partial m_i^*(\delta,\alpha_i)}{\partial \alpha_i} < 0$, $\frac{\partial^2 m_i^*(\delta,\alpha_i)}{\partial\alpha_i \partial\sum_{j\neq i} y_j} < 0$ *and* $\frac{\partial m_i^*(\delta,\alpha_i)}{\partial \alpha_j} > 0$ *for all i and all $j \neq i$;*

(ii) $\frac{\partial m_i^*(\delta,\alpha_i)}{\partial y_i} > 0$, $\frac{\partial m_i^*(\delta,\alpha_i)}{\partial E} < 0$.

Total mitigation is given by

$$M^*(\delta, \alpha_i) = \frac{y(1-\delta\alpha) + \delta y \sum_{i=1}^{n} \alpha_i \frac{y_i}{y} - nE}{1+\delta+n(1-\delta)} \tag{7}$$

with

(iii) $\frac{\partial M^*(\delta,\alpha_i)}{\partial \alpha_i} < 0$ *for every* i*;*

(iv) $\frac{\partial M^*(\delta,\alpha_i)}{\partial \delta} \gtrless 0$ *iff* $\sum_{i=1}^{n} \alpha_i \sum_{j\neq i} y_j \lessgtr \frac{n-1}{n+1}[y - nE]$ *and in particular, for* $y > nE$*,*

$\left.\frac{\partial M^*(\delta,\alpha_i)}{\partial \delta}\right|_{(\alpha_i=0)_{i\in\{1\dots n\}}} > 0$ *and*

$\left.\frac{\partial M^*(\delta,\alpha_i)}{\partial \delta}\right|_{(\alpha_i=1)_{i\in\{1\dots n\}}} < 0.$

Note that the contribution to mitigation depends negatively on the individual degree of optimism. Hence, we expect from this expression that an extreme pessimist with $\alpha_p = 0$, will contribute more than a player with a strictly positive degree of optimism $\alpha_o > 0$. Intuitively, the pessimist attributes a strictly positive weight δ to the optimist choosing 0 mitigation. Since mitigation efforts are substitutes, he compensates by increasing his own mitigation effort. A symmetric argument holds for the optimist. Note that this effect is stronger, the larger the income share of player i's opponents. Indeed, the larger $\sum_{j\neq i} y_j$, the larger is the difference in the expected contributions of i's opponents in the best- and the worst case scenario and thus, the larger the change in the optimal strategy of i in response to an increase in his optimism.

In contrast, the individual contribution to mitigation of a player depends positively on the optimism of the other players. Indeed, as his opponents become more optimistic, their contributions decrease, which in turn provides an incentive for the player to increase his own contribution. The last term of $m_i^*(\delta, \alpha_i)$ indicates that this effect is stronger for those opponents, whose income share is smaller. As explained above, their strategy will vary more in response to their optimism, which in turn implies a larger variation on the side of i's best-response, everything else being equal.

The total mitigation inherits these properties and depends negatively on each individual degree of optimism, as well as on total ambiguity α. In as far as the levels of optimism and pessimism in a society can be seen as a cultural trait as in Hofstede (2001), this result is thus consistent with the findings of Holzinger et al. (2011) that divergence between countries in the type and intensity of environmental policies can be attributed to cultural characteristics.

In turn, the effect of ambiguity on total mitigation depends on the optimism-profile of the population. For purely pessimistic players, increasing ambiguity leads to an increase in contributions, whereas the converse is true for pure optimism. When income is equally distributed, a decrease in ambiguity (e.g., allowing agents to communicate), thus reduces the impact of heterogeneous attitudes towards ambiguity on contributions. As δ tends to 0, individual contributions of agents with identical incomes are equalized – convergence occurs.

In general, the sign of the effect of ambiguity depends on the term $\sum_{i=1}^{n} \alpha_i \sum_{j\neq i} y_j$, which can be rewritten as: $y\left(\alpha - \sum_{i=1}^{n} \frac{y_i}{y}\alpha_i\right)$. In particular, the second term in the brackets can be interpreted as the wealth-weighted optimism of the society.

Proposition 6 *For a given total level of optimism α and a given total level of income y, a wealth transfer from individual i to individual j increases total mitigation if and only if $\delta > 0$ and $\alpha_i < \alpha_j$.*

Interestingly, when players are heterogeneous with respect to their optimism, total mitigation depends not just on the total income in the society, but also on the income distribution. This is in stark contrast to the classical result of Bergstrom and Varian (1985) that in an interior equilibrium the equilibrium level of the public good remains unchanged after a wealth redistribution. Notably, transferring income to more optimistic players increases total mitigation. While at first glance counterintuitive, this result is easy to understand: the lower contributions of optimistic players are due to their expectation that others would contribute their entire income to mitigation. Reducing these maximal contributions provides incentives for optimists to in turn increase theirs. Note that this dependence on the income distribution disappears once ambiguity vanishes $\delta = 0$.

This result suggests that even societies which are identical in every other respect (including their total degree of optimism) will exhibit different total mitigation efforts if they have different income distributions. In particular, the society, in which more optimistic individuals tend to be richer will invest more in mitigation as long as the relevant equilibrium is one in which only mitigation takes place.

3.2 Adaptation equilibria

Here we consider the case in which each player plans on contributing nothing to mitigation. We first consider the case, in which mitigation is at least as expensive as mitigation, $\phi \leq 1+r$.

Proposition 7 *Let $\frac{\phi}{1+r} \leq 1$ and $E < y_i$, then the game has an equilibrium in which:*

- *each player i chooses 0-mitigation, $m_i^* = 0$;*
- *each player i chooses a strictly positive amount of adaptation on the equilibrium path $a_i^*(m_i = 0, m_{-i} = 0) = \frac{(1+r)y_i - \phi E}{2\phi}$;*
- *off the equilibrium path, optimal adaptation is*

$$a_i^*\left(0, (y_j)_{j\neq i}\right) = \begin{cases} \frac{(1+r)y_i - \phi\left(E + \sum_{j\neq i} y_j\right)}{2\phi} & \text{if } \frac{\phi}{1+r} < \frac{y_i}{\left(E + \sum_{j\neq i} y_j\right)} \\ 0 & \text{if } \frac{\phi}{1+r} \geq \frac{y_i}{\left(E + \sum_{j\neq i} y_j\right)} \end{cases}$$

Furthermore, when $\frac{\phi}{1+r} < 1$, this is the unique equilibrium of the game.

Observe that in this case, equilibrium adaptation is negatively related to the initial environmental quality E and to the relative price of adaptation $\frac{\phi}{1+r}$. Higher values of E lead to less adaptation, but whenever $y_i > E$ and $\frac{\phi}{1+r} < 1$, as in the statement of the proposition, optimal adaptation is strictly positive for all players on the equilibrium path.

When $\frac{\phi}{1+r} \leq 1$, adaptation is cheaper than mitigation and since the optimal level of adaptation does not depend on ambiguity perception and attitude, the resulting equilibrium

allocation is both individually and socially optimal. Yet, the perception of ambiguity combined with relatively high levels of optimism can lead to an equilibrium, in which all players choose no mitigation, and engage in adaptation even when it is the more expensive of the two policies:

Proposition 8 *Let* $\frac{\phi}{1+r} > 1$. *Suppose that for every* i,

$$\frac{\phi}{1+r}E < y_i < \sum_{j \neq i} y_j.$$

For each i, *let* κ_i *be a constant,* $\kappa_i \in (0,1)$. *Then, there is an* $\bar{\epsilon} > 0$ *such that for any* $\epsilon \in (0, \bar{\epsilon})$, *whenever* $\delta = 1 - \epsilon$ *and for all* $i \in \{1...n\}$, $\alpha_i = 1 - \kappa_i \epsilon$ *the unique equilibrium of the game is the one described in Proposition 7. Furthermore,* $a_i^*(m_i = 0, m_{-i} = 0) > 0$, *whereas* $a_i^*\left(0, (y_j)_{j \neq i}\right) = 0$ *for all* i.

Condition $y_i < \sum_{j \neq i} y_j$ will be satisfied for all i, when income inequality is not too large and holds in particular, whenever all agents have equal income. Proposition 8 suggests that in such societies excessive optimism would not only impede mitigation (even when environmental quality is low), but also lead to individuals investing strictly positive amounts ex-post in the more expensive adaptation policy on the equilibrium path.

3.3 Mixed-Policy equilibria

The two equilibria described above represent extreme cases, in which one of the two policies, mitigation or adaptation is considered optimal by all individuals in the society.

Interestingly, with heterogeneous attitudes towards ambiguity, it is also possible to construct equilibria, in which optimistic and pessimistic players choose distinct policies. In particular, even with identical cost of mitigation and adaptation, we can find an equilibrium, in which pessimists only mitigate and optimists only adapt. This implies that in the presence of agent heterogeneity, prices of distinct economic policies can exhibit arbitrage opportunities, even when effectively the two policies are perfect substitutes. Such arbitrage is due to the strategic ambiguity perceived by the players: adaptation provides the benefit of flexibility in view of such ambiguity and thus, positive levels of adaptation can be sustained even when adaptation is the more expensive policy.

3.3.1 A first illustrative example: Equal prices of mitigation and adaptation

Using this example, we illustrate the existence of an equilibrium in which pessimists only mitigate and optimists only adapt when costs of mitigation and adaptation are identical. Suppose that there are two types of players n_p pessimists with $\alpha_p = 0$ and $n_o = n - n_p$ optimists with $\alpha_o > 0$. The following proposition shows the existence of an equilibrium in which optimists invest only in adaptation, whereas pessimists only contribute to mitigation:

Proposition 9 *Let* $\phi = (1+r)$. *If* $E \in (0, y_p)$ *and* $\frac{y_o - E}{y_p - E} > \frac{n_p}{n_p + 1}$. *Then, the game has an equilibrium in which the pessimists' strategy is* $\left(m_p^*, a_p^*(\cdot,\cdot)\right)$ *and the optimists' strategy is* $(m_o^*, a_o^*(\cdot,\cdot))$ *such that:*

(*i*) All pessimists choose a strictly positive amount to mitigation

$$m_p^* = \frac{y_p - E}{n_p + 1}$$

no adaptation on the equilibrium path,

$$a_p^* \left(m_p^* = \frac{y_p - E}{n_p + 1}, m_{-i}^* = (n_p - 1) \frac{y_p - E}{n_p + 1} \right) = 0$$

and strictly positive adaptation off-equilibrium when their opponents contribute 0 to mitigation:

$$a_p^* \left(m_p^* = \frac{y_p - E}{n_p + 1}, 0 \right) = \frac{y_p - E}{2 (n_p + 1)} > 0$$

(*ii*) All optimists choose no mitigation, $m_o^* = 0$, strictly positive adaptation on the equilibrium path:

$$a_o^* \left(m_o^* = 0, m_{-i}^* = n_p \frac{y_p - E}{n_p + 1} \right) = y_o - E - n_p \frac{y_p - E}{(n_p + 1)}$$

strictly positive adaptation off-equilibrium, in case their opponents contribute 0 to mitigation:

$$a_o^* (m_o^* = 0, 0) = \frac{y_o - E}{2} > 0$$

and

$$a_o^* (m_o^* = 0, m_{-i} = y_{-i}) = \max \left\{ y_o - E - n_p \frac{y_p - E}{(n_p + 1)} - (n_o - 1) y_o, 0 \right\}$$

off-equilibrium, in case their opponents contribute their entire endowment to mitigation.

When the price of mitigation and adaptation is the same, it might not appear surprising that agents would choose different technologies to counteract climate change in equilibrium. However, in the presence of ambiguity, such separation can also occur when adaptation is more expensive than mitigation. This is illustrated in our second example.

3.3.2 A second illustrative example: Mitigation is cheaper than adaptation

For the purposes of the following example, we assume that mitigation is the cheaper of the two strategies, $\frac{\phi}{1+r} > 1$, and we construct an equilibrium in which pessimists only mitigate and optimists only adapt.

Proposition 10 *Suppose that* $y_p > E$,

$$y_o < \frac{E (1 + \delta - n_p \delta) + n_p y_p}{(1 + \delta + n_p (1 - \delta))} \frac{[\delta + n_p (1 - \delta)] E + y_p}{[\delta + n_p (1 - \delta)] y_p + E}$$

and[6] $\frac{\phi}{(1+r)} \in \left(\frac{[\delta + n_p(1-\delta)] y_p + E}{[\delta + n_p(1-\delta)] E + y_p}, \frac{E(1+\delta-n_p\delta) + n_p y_p}{(1+\delta+n_p(1-\delta)) y_o} \right)$. *Then, the game has an equilibrium in which the pessimists' strategy is* $\left(m_p^*, a_p^* (\cdot, \cdot) \right)$ *and the optimists' strategy is* $(m_o^*, a_o^* (\cdot, \cdot))$ *such that:*

[6] Note that $\frac{[\delta + n_p(1-\delta)] y_p + E}{[\delta + n_p(1-\delta)] E + y_p} > 1$ and thus, the condition implies $\frac{\phi}{1+r} > 1$.

(*i*) The pessimists choose a strictly positive amount of mitigation m_p^* :

$$m_p^* = \frac{y_p - E}{1 + \delta + n_p (1 - \delta)} > 0$$

and 0-adaptation, both on and off the equilibrium path: $a_p^* \left(m_p^*, m_{-i} = 0\right) = a_p^* \left(m_p^*, m_o^*\right) = 0$.

(*ii*) The optimists choose no mitigation $m_o^* = 0$, strictly positive amount of adaptation on the equilibrium path and off-the equilibrium path in case their opponents choose 0 mitigation:

$$a_o^* \left(m_o^* = 0, m_{-i} = n_p \frac{y_p - E}{2}\right) = (1 + r) y_o - \phi \left(E + n_p \frac{y_p - E}{1 + \delta + n_p (1 - \delta)}\right) > 0$$

$$a_o^* \left(m_o^* = 0, m_{-i} = 0\right) = (1 + r) y_o - \phi E > 0$$

while optimal adaptation when their opponents choose maximal mitigation effort is given by:

$$a_o^* \left(m_o^* = 0, m_{-i} = n_p y_p + (n_o - 1) y_o\right) = \max \left\{(1 + r) y_o - \phi \left[n_p y_p + (n_o - 1) y_o\right], 0\right\}$$

As explained previously, when adaptation becomes more expensive, an optimist might still prefer it to mitigation, because it provides him with flexibility in case his opponent invests his entire endowment in mitigation. Were this scenario to occur, the optimist could enjoy the increased environmental quality at no cost. This scenario is however irrelevant for the pessimist: were he to undertake 0 mitigation, strictly positive adaptation will be necessary in the worst-case scenario. Since adaptation is more expensive, he prefers a strictly positive investment in mitigation and chooses no adaptation.

Note that in this scenario the impact of income distribution on total mitigation is very different than in the case of a mitigation equilibrium. In particular, as long as the parameters continue to satisfy the conditions of Proposition 10, transferring income from optimists towards pessimists results in an increase of total mitigation and a decrease in adaptation, thus increasing the cost efficiency of the policy mix.

4 Introduction of taxes and standards

In this section, we study the effect of the introduction of taxes and standards on the equilibrium contributions towards mitigation. We will show that strategic ambiguity combined with heterogeneous degrees of optimism has a non-trivial effect on the optimal tax on consumption and may distort the functioning of a standard.

4.1 Introduction of taxes

We start by introducing a tax on private consumption in equilibrium allocations. For the purposes of the discussion, we concentrate on the mitigation equilibrium discussed in Section 3.

Let τ be the tax rate on consumption and t_i be the lump-sum transfer i obtains in equilibrium. The total tax revenue is given by

$$T = \tau (y - M) = \sum_{i=1}^{n} t_i$$

and coincides with the total amount of transfers.

We assume that player i's transfer is a decreasing function of his relative wealth:

$$t_i = \left(\frac{1+\gamma}{n} - \gamma \frac{y_i}{y} \right) T$$

where $\gamma \geq 0$ is an exogenously given redistribution coefficient. When $\gamma = 0$, the transfer structure is flat and each player obtains $\frac{1}{n}$ of the total tax income. For $\gamma > 0$, players who are richer receive lower subsidies.

Each player i will maximize the following Choquet expected utility function taking transfers as given:

$$V_i^{(4)} (m_i, m_{-i}, \tau) = \frac{(1+r)}{(1+\tau)} (y_i - m_i + t_i) \left[E + m_i + (1-\delta) m_{-i} + \alpha_i \delta \sum_{j \neq i} (y_j + t_j) \right]$$

Note that the utility function of i being non-linear in the transfer, even a lump-sum transfer will have a non-trivial effect on the choice of the player to mitigate.

The following proposition characterizes total mitigation in an equilibrium in which all players mitigate:

Proposition 11 *Suppose that the policy maker imposes a tax on private consumption with τ the tax rate. Then:*

(i) Total mitigation is given by:

$$M (\delta, (\alpha_i)_{i=1}^n, \tau) = \frac{y \left(1 - \alpha\delta + \tau \left[1 - \frac{\alpha\delta}{n} (n - 1 - \gamma) - \frac{\gamma\delta}{y} \sum_i \alpha_i y_i \right] \right) - nE + \delta \sum_i \alpha_i y_i}{\left[2 + (1-\delta)(n-1) + \tau \left[1 - \frac{\alpha\delta}{n} (n - 1 - \gamma) - \frac{\gamma\delta}{y} \sum_i \alpha_i y_i \right] \right]}$$

(ii) Total mitigation increases in τ: $\frac{\partial M^* \left(\delta, (\alpha_i)_{i=1}^n, \tau \right)}{\partial \tau} > 0$

(iii) When $\delta > 0$, there exists a $\bar{\gamma} > 0$ (with $\bar{\gamma}$ possibly ∞) such that whenever $\gamma < \bar{\gamma}$, for a given total level of optimism α and a given total income y, total mitigation increases in wealth-weighted optimism, $\frac{\partial M^* \left(\delta, (\alpha_i)_{i=1}^n, \tau \right)}{\partial \left(\sum_i \alpha_i \frac{y_i}{y} \right)} > 0$.

Not surprisingly, increasing the tax leads to higher total mitigation efforts. In Section 3.1, we showed that a wealth transfer from a pessimist to an optimist increases total mitigation. The same effect is documented in part (iii) of the proposition – total mitigation increases in

wealth-weighted optimism as long as γ is relatively low. However, for high values of γ, this effect can be offset by the income redistribution caused by transfers.

The social-planner wishes to set the tax in such a way as to maximize actual total welfare. Thus, social welfare does not take into account perceived ambiguity[7], but only actually realized payoffs and is given by:

$$W(M) = \sum_{i=1}^{n} (1+r)(y-M)[E+M].$$

The socially optimal total level of mitigation is thus $M^S = \frac{y-E}{2}$. Thus, the social planner has to set the tax τ in such a way that

$$M(\delta, (\alpha_i)_{i=1}^n, \tau) = M^S.$$

Proposition 12 *Suppose that $y_i > E$ for all $i \in \{1...n\}$. The tax rate which achieves the socially-optimal total level of mitigation is given by:*

$$\tau^S(\delta, (\alpha_i)_{i=1}^n) = \frac{(n-1)[y(1-\delta) + E(1+\delta)] + 2\alpha\delta y - 2\delta\sum_i \alpha_i y_i}{\left[1 - \frac{\alpha\delta}{n}[n-1-\gamma] - \frac{\gamma\delta}{y}\sum_i \alpha_i y_i\right]}$$

This tax rate is

(i) strictly increasing in the individual degree of optimism: $\frac{\partial\tau^S\left(\delta,(\alpha_i)_{i=1}^n\right)}{\partial\alpha_i} > 0$ for all $i \in \{1...n\}$;

(ii) strictly decreasing in δ at $\alpha_i = 0$ for all $i \in \{1...n\}$ and strictly increasing in δ at $\alpha_i = 1$ for all $i \in \{1...n\}$. Furthermore, $\frac{\partial\tau^S\left(\delta,(\alpha_i=\bar{\alpha})_{i=1}^n\right)}{\partial\delta} = 0$ iff $\bar{\alpha} = \frac{(y-E)}{2y+(y+E)(n-1)} \in (0,1)$ and $\frac{\partial\tau^S\left(\delta,(\alpha_i=\tilde{\alpha})_{i=1}^n\right)}{\partial\delta} \underset{(<)}{>} 0$ iff $\tilde{\alpha} \underset{(<)}{>} \bar{\alpha}$.

(iii) for given total wealth y, total optimism α and $\delta > 0$, strictly decreasing in the wealth-weighted optimism, $\frac{\partial\tau^S\left(\delta,(\alpha_i=\bar{\alpha})_{i=1}^n\right)}{\partial\left(\sum_i \alpha_i y_i\right)} < 0$ iff

$$\gamma < \frac{2\left[1 - \frac{\alpha\delta}{n}(n-1)\right]}{\left[(n-1)\left[(1-\delta) + \frac{E}{y}(1+\delta)\right] + 2\alpha\delta\left(1 - \frac{1}{n}\right)\right]}.$$

Proposition 12 characterizes the optimal tax rate in the presence of ambiguity and identifies the effects of ambiguity and ambiguity attitude. The optimal tax rate increases in the individual degrees of optimism. Intuitively, pessimistic players need less incentives in order to increase their mitigation level to the socially optimal one. It increases (decreases) in the perceived ambiguity when players are relatively optimistic (pessimistic).

[7]This can be because the social planner only cares about objective realized ex-post payoffs, or because he is unable to measure ambiguity attitudes at the individual level, but can only obtain aggregate measures such as the total level of optimism or the wealth-weighted optimism.

Finally, as discussed above, an income distribution skewed towards optimism leads to higher total mitigation. Thus, societies in which optimistic agents are relatively richer, will require lower tax levels to achieve the social optimum. This result however, does not hold if the society has a relatively high redistribution coefficient γ. Even if optimists are initially richer than pessimists, for high values of γ, transfers might skew the income distribution towards pessimism and reverse the effect. In this case, policy makers who usually cannot condition transfers on individual ambiguity attitudes will face a trade-off between providing incentives to increase mitigation and the goal of income redistribution as captured by γ.

For the purposes of the analysis in this section, we focused on the mitigation equilibrium described in Section 3.1. This analysis is appropriate, whenever the price of adaptation is sufficiently high so that the effective price ratio of adaptation versus mitigation, $\frac{\phi\left(1+\tau^S\left(\delta,(\alpha_i)_{i=1}^n\right)\right)}{(1+r)}$, in combination with the post-transfer incomes, $y_i + t_i$ satisfy the conditions of Proposition 5. In this case, the optimal level of mitigation will be established upon the introduction of the tax $\tau^S\left(\delta,(\alpha_i)_{i=1}^n\right)$, regardless of the type of equilibrium the economy would exhibit in absence of taxes. In particular, by effectively increasing the price of adaptation, the introduction of a tax on consumption may lead to a transition from the inefficient adaptation equilibrium exhibited in Proposition 8 to a socially-optimal mitigation equilibrium. In contrast, when adaptation remains the relatively cheaper option even post-taxes, i.e., $\frac{\phi\left(1+\tau^S\left(\delta,(\alpha_i)_{i=1}^n\right)\right)}{(1+r)} < 1$, no mitigation will take place, even when consumption is taxed, and this will be the efficient outcome for the economy at hand.

An interesting case arises when adaptation is cheaper before taxes, $\frac{\phi}{1+r} < 1$, but becomes sufficiently more expensive after taxes so that for $\frac{\phi\left(1+\tau^S\left(\delta,(\alpha_i)_{i=1}^n\right)\right)}{(1+r)}$ the mitigation equilibrium obtains. In this scenario, it is optimal both from an individual and from a social point of view to not raise taxes on consumption and to rely only on adaptation. If, however, adaptation is unobservable by the social planner, or if mitigation is the only strategy for which he can take credit, he might nevertheless implement a tax, thus distorting the optimal allocation in favor of the costlier policy.

4.2 Introduction of a standard

In the last section, we illustrated how a taxation policy needs to be adapted in the presence of strategic ambiguity. In this section, we turn to the introduction of a standard which stipulates a minimal level of contributions to mitigation, m_s.

For the purposes of the analysis, we will assume that there are two consumers[8], $n = 2$, one of which has an optimism parameter α_p and the other an optimism parameter $\alpha_o > \alpha_p$. We will refer to the former as the "pessimist" and to the latter as the "optimist". Assume that both agents have identical income $\tilde{y}$.

Note that the introduction of a standard m_s changes the expectations of the players concerning the worst-case scenario: instead of 0, they now consider m_s as the minimal contribution of the other players. Thus, the payoff function in a mitigation equilibrium becomes:

[8]The main insights of Proposition 13 below can be extended to an arbitrary population size with two types of player, but at the cost of sacrificing tractability.

$$V_i^{(4)}(m_i, m_{-i}, m_s) = (\tilde{y} - m_i)(E + m_i + (1-\delta) m_{-i} + \delta(1-\alpha_i) m_s + \delta\alpha_i \tilde{y})$$

whereas the best response function is given by:

$$\rho_i(m_{-i}, m_s) = \max\left\{\frac{\tilde{y} - E - (1-\delta) m_{-i} - \delta(1-\alpha_i) m_s - \delta\alpha_i \tilde{y}}{2}, m_s\right\} \tag{8}$$

The following proposition characterizes the mitigation equilibrium with a standard which occurs when the cost of adaptation ϕ is sufficiently high.

Proposition 13 *Suppose that* $\frac{[2(\alpha_o-\alpha_p)-\delta(1-\delta\alpha_p)]}{a_o-a_p}\frac{\tilde{y}}{E} > 1$ *and* $\delta > 0$. *The equilibrium contributions of the pessimists and the optimists in the mitigation equilibrium with standard* m_s *are given by:*

$$m_o^*(\delta, \alpha_o, m_s) = \begin{cases} \frac{(1+\delta-2\delta\alpha_o+\delta(1-\delta)\alpha_p)\tilde{y}-(1+\delta)E+\delta[2\alpha_o-\alpha_p(1-\delta)-(1+\delta)]m_s}{(1+\delta)(3-\delta)} & m_s \leq \frac{(1+\delta-2\delta\alpha_o+\delta(1-\delta)\alpha_p)\tilde{y}-(1+\delta)E}{[(1+\delta)(3-\delta)-\delta[2\alpha_o-\alpha_p(1-\delta)-(1+\delta)]]} \\ m_s & m_s \geq \frac{(1+\delta-2\delta\alpha_o+\delta(1-\delta)\alpha_p)\tilde{y}-(1+\delta)E}{[(1+\delta)(3-\delta)-\delta[2\alpha_o-\alpha_p(1-\delta)-(1+\delta)]]} \end{cases}$$

$$m_p^*(\delta, \alpha_p, m_s) = \begin{cases} \frac{[(1+\delta)-2\delta\alpha_p+\delta(1-\delta)\alpha_o]\tilde{y}-(1+\delta)E-\delta[\alpha_o(1-\delta)+(1+\delta)-2\alpha_p]m_s}{(1+\delta)(3-\delta)} & m_s \leq \frac{(1+\delta-2\delta\alpha_o+\delta(1-\delta)\alpha_p)\tilde{y}-(1+\delta)E}{[(1+\delta)(3-\delta)-\delta[2\alpha_o-\alpha_p(1-\delta)-(1+\delta)]]} \\ \frac{\tilde{y}[1-\delta\alpha_p]-E-[(1-\delta)+\delta(1-\alpha_p)]m_s}{2} & m_s \in \left[\frac{(1+\delta-2\delta\alpha_o+\delta(1-\delta)\alpha_p)\tilde{y}-(1+\delta)E}{[(1+\delta)(3-\delta)-\delta[2\alpha_o-\alpha_p(1-\delta)-(1+\delta)]]}, \frac{\tilde{y}(1-\delta\alpha_p)-E}{3-\delta\alpha_p}\right] \\ m_s & m_s > \frac{\tilde{y}(1-\delta\alpha_p)-E}{3-\delta\alpha_p} \end{cases}$$

Total mitigation in equilibrium

$$M(\delta, \alpha_p, \alpha_o, m_s) = m_o^*(\delta, \alpha_o, m_s) + m_p^*(\delta, \alpha_p, m_s)$$

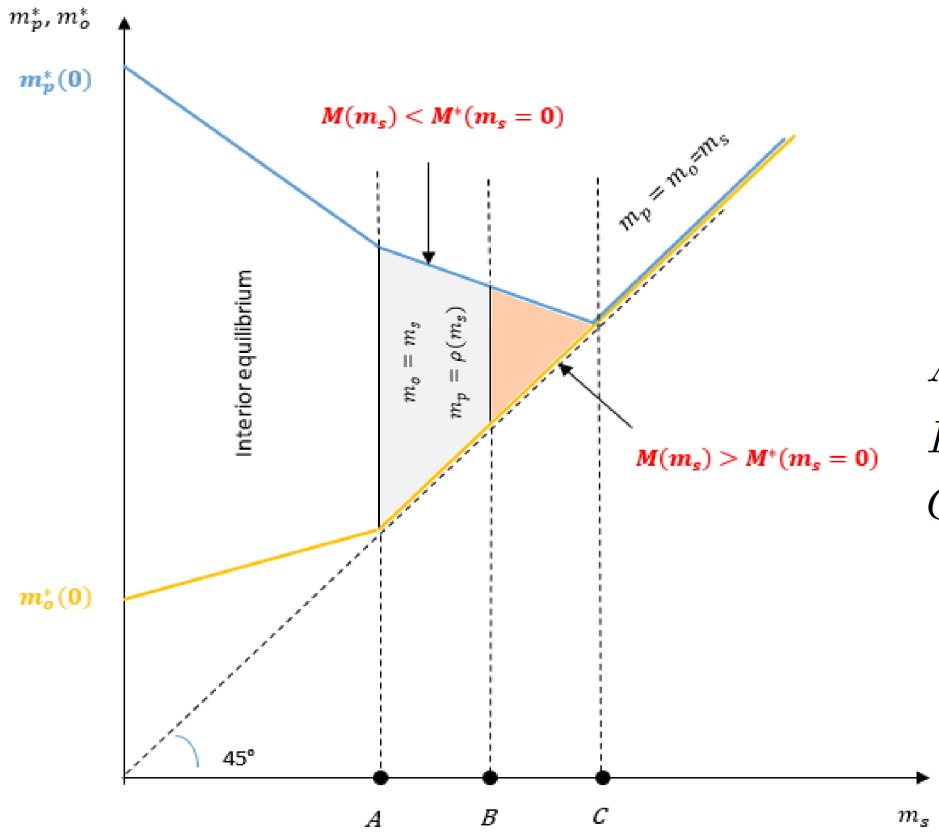
(i) decreases in m_s whenever $m_s < \frac{(1+\delta-2\delta\alpha_o+\delta(1-\delta)\alpha_p)\tilde{y}-(1+\delta)E}{[(1+\delta)(3-\delta)-\delta[2\alpha_o-\alpha_p(1-\delta)-(1+\delta)]]}$ with $\frac{\partial M(\delta,\alpha_p,\alpha_o,m_s)}{\partial m_s} = -\frac{\delta(2-\alpha_o-\alpha_p)}{(3-\delta)}$;

(ii) increases in m_s whenever $m_s > \frac{(1+\delta-2\delta\alpha_o+\delta(1-\delta)\alpha_p)\tilde{y}-(1+\delta)E}{[(1+\delta)(3-\delta)-\delta[2\alpha_o-\alpha_p(1-\delta)-(1+\delta)]]}$ with $\frac{\partial M(\delta,\alpha_p,\alpha_o,m_s)}{\partial m_s} = \frac{1+\delta\alpha_p}{2}$;

(iii) exceeds total mitigation in the absence of a standard, $M(\delta, \alpha_p, \alpha_o, 0)$ if and only if

$$m_s > \frac{\left(1+\delta+\delta\alpha_p-\delta^2\alpha_p-2\delta\alpha_o\right)\tilde{y}-(1+\delta)E}{(1+\delta\alpha_p)(3-\delta)}.$$

We illustrate the results of Proposition 13 in the graph **??** for the case of $\alpha_o = 1$ and $\alpha_p = 0$.



$$A = \frac{(1-\delta)y-(1+\delta)E}{3+\delta}$$
$$B = \frac{(1-\delta)y-(1+\delta)E}{3-\delta}$$
$$C = \frac{y-E}{3}$$

As explained above, in the absence of a standard, pessimist's mitigation efforts exceed that of the optimist. With the introduction of a standard ($m_s \geqslant 0$), the pessimist will revise his belief about the worst-case scenario. This revision will be manifested in attributing a strictly positive weight to the opponent contributing m_s instead of 0. Therefore, the pessimist will reduce his mitigation efforts. In contrast, the optimist' s contribution increases with m_s. However, as shown in part (i) of Proposition 13, the pessimist's optimal strategy $m_p^*(\cdot, m_s)$ decreases faster in m_s than $m_o^*(\cdot, m_s)$ increases, thus leading to a decrease in total mitigation. Differently from the case of no ambiguity, the introduction of a non-binding standard can have a negative effect on overall environmental quality. Therefore, this result may justify the reason why some countries apply a stricter internal standard that the one set in international agreements, as is e.g., the case of Germany in the EU, see Holzinger et al. (2011).

When the standard reaches a certain value $\left(m_s \geqslant \frac{(1-\delta)y-1+\delta)E}{3+\delta}\right)$, denoted by point A in the graph, the unconstrained optimal mitigation of the optimist becomes lower than the standard and so the optimist will be forced to contribute m_s. The pessimist will play a best-response to the strategy of his opponent (m_s), given by $\rho_p(m_s) = \frac{y-E-m_s}{2}$. As shown in part (ii) of Proposition 13, for such values of m_s, the total level of mitigation is increasing. However, it remains lower than total mitigation in the absence of a standard until m_s reaches point B, at which $m_s = \frac{(1-\delta)y-(1+\delta)E}{3-\delta}$. Beyond this level, total mitigation continues to increase and is strictly larger than that at $m_s = 0$.

Finally, when the standard is sufficiently high $\left(m_s \geqslant \frac{y-E}{3}\right)$, represented by point C in

the graph, even the pessimist's unconstrained optimal contribution becomes lower than m_s. Both players then contribute exactly m_s in equilibrium.

The fact that total mitigation decreases for low values of m_s is due to the fact that the standard increases the expectations of partially pessimistic players about the contributions of their opponents. This effect is thus present, whenever the two types of players are not fully optimistic, i.e., $\alpha_o + \alpha_p < 2$. This implies that in those cases in which a social planner is uncertain about the exact optimal level of m_s or if this optimal level is not politically feasible, choosing a low but positive standard might lead to worse outcomes rather than foregoing regulation at all.

In contrast, when adaptation is the more expensive policy, but $\frac{\phi}{1+r}$ is close to 1, and α_p is close to 0, one can construct equilibria, in which the more pessimistic player chooses a level of mitigation given by

$$m_p^* = \max\left\{\frac{\tilde{y} - E - (1 - \alpha_p\delta)\, m_s - \alpha_p\delta\tilde{y}}{2}, m_s\right\}$$

and does not adapt, whereas the more optimistic player chooses $m_o^* = m_s$ and an optimal adaptation strategy as described in (2). It is easy to see that in this case, increasing the standard m_s always leads to an increase in total mitigation. When the standard is non-binding for the pessimist, an increase in m_s by 1 unit increases total mitigation by a factor of $\frac{1+\alpha_P\delta}{2} \leq 1$. In particular, the positive effect increases with the degree of ambiguity δ and the degree of optimism α_p – this is because $\alpha_p\delta_p$ is the weight assigned to the optimist choosing maximal mitigation. Thus, an increase in $\alpha_p\delta_p$ makes the best-response of the pessimist less sensitive to both the standard and to the mitigation chosen by the optimist. Thus, while the optimist's strategy reacts to an increase in the standard by a factor of 1, the pessimist's response changes only by a factor $-\frac{1+\alpha_p\delta}{2}$. In the extreme case when $\alpha_p = 0$, the total effect equals $\frac{1}{2}$ and exactly coincides with that in a game without ambiguity.

5 Conclusion

In this paper, we asses the impact of ambiguity and ambiguity attitudes on the optimal design of a climate policy. We use NEO-additive beliefs to capture players' uncertainty about the strategies chosen by their opponents. This representation allows for a distinction between the perception of ambiguity and agents attitudes towards it : optimism and pessimism.

To our knowledge, this paper is the first project to consider strategic ambiguity in an environmental model. We believe that such a combination is very intuitive in the context of global agreements concerning climate change.

Our results prove that ambiguity attitudes play a crucial role in the choice of environmental policies. Indeed, pessimists are more inclined towards mitigation policy, while optimists favor adaptation. Thus, the observed policy mix will crucially depend on the distribution of ambiguity attitudes in the population. Notably, the distribution of wealth across individuals with different attitudes towards ambiguity will have a non-trivial effect on the total amount of mitigation in equilibrium.

Our findings rationalize the fact that societies similar in all other respects except for their optimism profile might choose different combination of policies in view of climate change,

some of which might appear irrational given market prices. The effect of regulation also crucially depends on the perception of and attitudes towards strategic ambiguity. Notably optimal tax policies depend both on the total optimism, as well as on the distribution of wealth across agents with different levels of optimism. Setting non-binding standards can have adverse effects on total mitigation in presence of heterogeneous attitudes towards strategic ambiguity. Our results thus emphasize the necessity to consider attitudes towards strategic ambiguity in the design of economic policies targeting climate change. They could be used to better understand the observed differences in environmental regulations across countries as well as the speed and patterns of convergence of environmental policies in supranational entities such as the EU.

Several questions remain to be addressed in future research. First, it would be of interest to endogenize optimism by allowing for an evolutionary dynamics based on actually realized payoffs. We conjecture that depending on the criterion of imitation, society can be dominated by different types of players and therefore can reach different environmental states. Second, it would be worthwhile to test our theoretical results in an experimental framework by measuring individual ambiguous beliefs and correlating them with best-responses in a public-good game. Finally, one might ask what policies can be implemented if one allows for a repetition of the static game analyzed here. This would be of particular interest in view of the Paris agreement which does not provide any political or economic sanctions to the signatories who do not follow up on their commitments.

6 Appendix

6.1 Analysis of the best-response of a player:

Case 1: Always adaptation: Suppose that $\frac{\phi}{1+r} < 1$. Then at any m_{-i}, i chooses no mitigation, $\rho_i(m_{-i}) = 0$. The optimal adaptation strategy satisfies

$a^*(0, \mathbf{0}) > 0, \ , \ a^*(0, m_{-i}) > 0, \ a^*\left(0, (y_j)_{j\neq i}\right) > 0$ if $\frac{\phi}{1+r} < \frac{y_i}{\left(E+\sum_{j\neq i} y_j\right)}$;

$a^*(0, \mathbf{0}) > 0, \ , \ a^*(0, m_{-i}) > 0, \ a^*\left(0, (y_j)_{j\neq i}\right) = 0$ if $\frac{\phi}{1+r} \in \left(\frac{y_i}{\left(E+\sum_{j\neq i} y_j\right)}, \frac{y_i}{(E+m_{-i})}\right]$;

$a^*(0, \mathbf{0}) > 0, \ a^*(0, m_{-i}) = a^*\left(0, (y_j)_{j\neq i}\right) = 0$ if $\frac{\phi}{1+r} \in \left(\frac{y_i}{(E+m_{-i})}, \frac{y_i}{E}\right]$;

$a^*(0, \mathbf{0}) = a^*(0, m_{-i}) = a^*\left(0, (y_j)_{j\neq i}\right) = 0$ if $\frac{\phi}{1+r} \in \left(\frac{y_i}{E}, 1\right)$.

Case 2: Adaptation and mitigation as perfect substitutes: Let $\frac{\phi}{1+r} = 1$ and

(i) Some optimism: If $\alpha_i > 0$, at any m_{-i}, i any level of mitigation in the set $\rho_i(m_{-i}) = \left[0, \max\left\{\frac{y_i - E - \sum_{j\neq i} y_j}{2}, 0\right\}\right]$ is optimal and for a given $m_i^* \in \rho_i(m_{-i})$ the corresponding optimal adaptation is $a^*(m_i^*, \mathbf{0}) > 0, \ , \ a^*(m_i^*, m_{-i}) > 0, \ a^*\left(m_i^*, (y_j)_{j\neq i}\right) \geq 0$.

(ii) Realism: If $\delta = 0$, then at any m_{-i}, i any level of mitigation in the set $\rho_i(m_{-i}) = \left[0, \max\left\{\frac{y_i - E - m_{-i}}{2}, 0\right\}\right]$ is optimal and for a given $m_i^* \in \rho_i(m_{-i})$ the corresponding optimal adaptation is $a^*(m_i^*, m_{-i}) \geq 0$.

(iii) Some pessimism: If $\delta > 0$ and $\alpha_i = 0$, then at any m_{-i}, i any level of mitigation in the set $\rho_i(m_{-i}) = \left[0, \max\left\{\frac{y_i - E - m_{-i}}{2}, 0\right\}\right]$ is optimal and for a given $m_i^* \in \rho_i(m_{-i})$ the corresponding optimal adaptation is $a^*(m_i^*, \mathbf{0}) > 0$, $a^*(m_i^*, m_{-i}) \geq 0$.

(iv) Full pessimism: If $\alpha_i = 0$ and $\delta = 1$, then at any m_{-i}, i any level of mitigation in the set $\rho_i(m_{-i}) = \left[0, \max\left\{\frac{y_i - E}{2}, 0\right\}\right]$ is optimal and for a given $m_i^* \in \rho_i(m_{-i})$ the corresponding optimal adaptation is $a^*(m_i^*, \mathbf{0}) \geq 0$.

Case 3: Simultaneous mitigation and adaptation: Let $\frac{\phi}{1+r} > 1$, $y_i - \left(E + \sum_{j\neq i} y_j\right)\frac{\phi}{1+r} > 0$ and

$$\frac{y_i + E + \alpha_i\delta\left[(1+r)+\phi\right]\sum_{j\neq i} y_j + (1-\delta)\left[(1+r)+\phi\right]m_{-i}}{y_i + E} > \max\left\{\begin{array}{c} \frac{(2-\delta(1-\alpha_i))+\sqrt{2(2-\delta(1-\alpha_i))}}{\delta(1-\alpha_i)}, \\ \frac{[2-\delta(1-\alpha_i)]+\sqrt{(2-\delta(1-\alpha_i))^2+(4-3\delta+\delta\alpha_i)^2}}{4-\delta-3\alpha_i\delta} \end{array}\right\}$$

Then,

(i) High level of optimism and low contribution by the opponent: if $\frac{\phi}{1+r} \in \left(1, \frac{(1+\alpha_i\delta)+\sqrt{1-2\delta+\delta^2+4\alpha_i\delta}}{\delta(1-\alpha_i)}\right)$ and

$$m_{-i} \leq 2\frac{\left[\frac{\phi}{1+r} - 1\right](y_i + E) - \alpha_i\delta\left[1 + \frac{\phi}{1+r}\right]\sum_{j\neq i} y_j}{\left[\left[(2-\delta-\alpha_i\delta)\right] - 2(1+\alpha_i\delta)\frac{\phi}{1+r} + \delta(1-\alpha_i)\left(\frac{\phi}{1+r}\right)^2\right]}$$

the optimal mitigation strategy is in the interval $\left(\frac{(1+r)y_i-\left(E+\sum_{j\neq i}y_j\right)\phi}{(1+r)+\phi},\frac{(1+r)y_i-(E+m_{-i})\phi}{(1+r)+\phi}\right)$ and is given by:

$$\begin{aligned}\rho_i(m_{-i}) &= \rho_i^{(2)}(m_{-i}) := \frac{\left[(1+\alpha_i\delta)\phi-(1-\alpha_i\delta)(1+r)\right](1+r)y_i}{-(1-\alpha_i\delta)(1+r)^2+2(1+\alpha_i\delta)(1+r)\phi-(1-\alpha_i\delta)\phi^2}\\ &+\frac{\left[(1-\alpha_i\delta)\phi-(1+\alpha_i\delta)(1+r)\right]\phi E}{-(1-\alpha_i\delta)(1+r)^2+2(1+\alpha_i\delta)(1+r)\phi-(1-\alpha_i\delta)\phi^2}\\ &+\frac{(1-\delta)\phi\left[\phi-(1+r)\right]m_{-i}-2\phi(1+r)\alpha_i\delta\sum_{j\neq i}y_j}{-(1-\alpha_i\delta)(1+r)^2+2(1+\alpha_i\delta)(1+r)\phi-(1-\alpha_i\delta)\phi^2}\end{aligned}$$

whereas the optimal adaptation satisfies $a^*(m_i^*,\mathbf{0})>0$, $a^*(m_i^*,m_{-i})>0$, $a^*\left(m_i^*,(y_j)_{j\neq i}\right)=0$.

(ii) High level of optimism and high contribution by the opponent: if $\frac{\phi}{1+r}\in\left(1,\frac{(1+\alpha_i\delta)+\sqrt{1-2\delta+\delta^2+4\alpha_i\delta}}{\delta(1-\alpha_i)}\right)$ and

$$m_{-i}\geq 2\frac{-\left[\frac{\phi}{1+r}-1\right](y_i+E)+\alpha_i\delta\left[1+\frac{\phi}{1+r}\right]\sum_{j\neq i}y_j}{\left[-\left[(2-\delta-\alpha_i\delta)\right]+2(1+\alpha_i\delta)\frac{\phi}{1+r}-\delta(1-\alpha_i)\left(\frac{\phi}{1+r}\right)^2\right]}$$

the optimal mitigation strategy is given by

$$\rho_i(m_{-i})=\frac{(1+r)y_i-(E+m_{-i})\phi}{(1+r)+\phi}$$

and optimal adaptation satisfies: $a^*(m_i^*,\mathbf{0})>0$, $a^*(m_i^*,m_{-i})=0$, $a^*\left(m_i^*,(y_j)_{j\neq i}\right)=0$.

(iii) Intermediate level of optimism and low contribution by the opponent:
If $\frac{\phi}{1+r}\in\left(\frac{(1+\alpha_i\delta)+\sqrt{1-2\delta+\delta^2+4\alpha_i\delta}}{\delta(1-\alpha_i)},\frac{(2-\delta(1-\alpha_i))+\sqrt{2(2-\delta(1-\alpha_i))}}{\delta(1-\alpha_i)}\right)$,

$$m_{-i}\leq\frac{\left[\frac{\phi}{1+r}-1\right](y_i+E)-\alpha_i\delta\left[1+\frac{\phi}{1+r}\right]\sum_{j\neq i}y_j}{(1-\delta)\left[1+\frac{\phi}{1+r}\right]}$$

and if either

$$m_{-i}\geq 2\frac{\left[\frac{\phi}{1+r}-1\right](y_i+E)-\alpha_i\delta\left[\frac{\phi}{1+r}+1\right]\sum_{j\neq i}y_j}{\left[-\delta(1-\alpha_i)\left(\frac{\phi}{1+r}\right)^2+2(1+\alpha_i\delta)\frac{\phi}{1+r}-(2-\delta-\alpha_i\delta)\right]}$$

or $\frac{\phi}{1+r}>\frac{1+2\sqrt{\alpha_i\delta}+\alpha_i\delta}{1-\alpha_i\delta}$, then the optimal mitigation strategy is in the interval $\left(\frac{(1+r)y_i-(E+m_{-i})\phi}{(1+r)+\phi},\frac{(1+r)y_i-E\phi}{(1+r)+\phi}\right)$ and is given by:

$$\begin{aligned}\rho_i(m_{-i}) &= \rho_i^{(3)}(m_{-i}) := \frac{\left[\frac{\phi}{1+r}(2-\delta+\alpha_i\delta)-\delta(1-\alpha_i)\right]y_i+\left[\delta(1-\alpha_i)\frac{\phi}{1+r}-(2-\delta+\alpha_i\delta)\right]\frac{\phi}{1+r}E}{\left[2(2-\delta+\alpha_i\delta)\frac{\phi}{1+r}-\delta(1-\alpha_i)\left(\frac{\phi}{1+r}\right)^2-\delta(1-\alpha_i)\right]}\\ &-\frac{2\frac{\phi}{1+r}\left((1-\delta)m_{-i}+\alpha_i\delta\sum_{j\neq i}y_j\right)}{\left[2(2-\delta+\alpha_i\delta)\frac{\phi}{1+r}-\delta(1-\alpha_i)\left(\frac{\phi}{1+r}\right)^2-\delta(1-\alpha_i)\right]}\end{aligned}$$

and optimal adaptation satisfies: $a^*\left(m_i^*, \mathbf{0}\right) > 0$, $a^*\left(m_i^*, m_{-i}\right) = 0$, $a^*\left(m_i^*, \left(y_j\right)_{j\neq i}\right) = 0$.

(iv) Intermediate level of optimism and high contribution by the opponent: if $\frac{\phi}{1+r} \in \left(\frac{(1+\alpha_i\delta)+\sqrt{1-2\delta+\delta^2+4\alpha_i\delta}}{\delta(1-\alpha_i)}, \frac{(2-\delta(1-\alpha_i))+\sqrt{2(2-\delta(1-\alpha_i))}}{\delta(1-\alpha_i)}\right)$,

$$m_{-i} \geq \frac{\left[\frac{\phi}{1+r}-1\right]\left(y_i+E\right)-\alpha_i\delta\left[1+\frac{\phi}{1+r}\right]\sum_{j\neq i}y_j}{\left(1-\delta\right)\left[1+\frac{\phi}{1+r}\right]}$$

and if either

$$m_{-i} \geq 2\frac{\left[\frac{\phi}{1+r}-1\right]\left(y_i+E\right)-\alpha_i\delta\left[\frac{\phi}{1+r}+1\right]\sum_{j\neq i}y_j}{\left[-\delta\left(1-\alpha_i\right)\left(\frac{\phi}{1+r}\right)^2+2\left(1+\alpha_i\delta\right)\frac{\phi}{1+r}-\left(2-\delta-\alpha_i\delta\right)\right]}$$

or $\frac{\phi}{1+r} > \frac{1+2\sqrt{\alpha_i\delta}+\alpha_i\delta}{1-\alpha_i\delta}$, then the optimal mitigation strategy is given by $\frac{(1+r)y_i-E\phi}{(1+r)+\phi}$ and optimal adaptation is $a^*\left(m_i^*, \mathbf{0}\right) = a^*\left(m_i^*, m_{-i}\right) = a^*\left(m_i^*, \left(y_j\right)_{j\neq i}\right) = 0$;

(v) Low level of optimism:

If

$$\frac{\phi}{1+r} \in \left(\begin{array}{c} \max\left\{\begin{array}{c} \frac{(2-\delta(1-\alpha_i))+\sqrt{2(2-\delta(1-\alpha_i))}}{\delta(1-\alpha_i)}, \\ \frac{[2-\delta(1-\alpha_i)]+\sqrt{(2-\delta(1-\alpha_i))^2+(4-3\delta+\delta\alpha_i)^2}}{4-\delta-3\alpha_i\delta} \end{array}\right\}, \\ \frac{y_i+E+\alpha_i\delta\sum_{j\neq i}y_j+(1-\delta)m_{-i}}{y_i+E-\alpha_i\delta\sum_{j\neq i}y_j-(1-\delta)m_{-i}} \end{array}\right),$$

then the optimal mitigation strategy is given by $\frac{(1+r)y_i-E\phi}{(1+r)+\phi}$ and optimal adaptation is $a^*\left(m_i^*, \mathbf{0}\right) = a^*\left(m_i^*, m_{-i}\right) = a^*\left(m_i^*, \left(y_j\right)_{j\neq i}\right) = 0$.

Case 4: Only mitigation, no adaptation: If $y_i - E - \alpha_i\delta\sum_{j\neq i}y_j - \left(1-\delta\right)m_{-i} > 0$ and

$$\frac{\phi}{1+r} > \max\left\{\begin{array}{c} \frac{(2-\delta(1-\alpha_i))+\sqrt{2(2-\delta(1-\alpha_i))}}{\delta(1-\alpha_i)}, \frac{[2-\delta(1-\alpha_i)]+\sqrt{(2-\delta(1-\alpha_i))^2+(4-3\delta+\delta\alpha_i)^2}}{4-\delta-3\alpha_i\delta}, \\ \frac{y_i+E+\alpha_i\delta\sum_{j\neq i}y_j+(1-\delta)m_{-i}}{y_i+E-\alpha_i\delta\sum_{j\neq i}y_j-(1-\delta)m_{-i}} \end{array}\right\}$$

then the optimal mitigation strategy is given by

$$\rho_i\left(m_{-i}\right) = \rho_i^{(4)}\left(m_{-i}\right) := \frac{y_i - E - \alpha_i\delta\sum_{j\neq i}y_j - \left(1-\delta\right)m_{-i}}{2}$$

and optimal adaptation is $a^*\left(m_i^*, \mathbf{0}\right) = a^*\left(m_i^*, m_{-i}\right) = a^*\left(m_i^*, \left(y_j\right)_{j\neq i}\right) = 0$.

The following claims follow directly from the cases discussed above:

Claim 1: When $\frac{\phi}{1+r} > 1$, and whenever $\rho_i^{(2)}\left(m_{-i}\right)$ is the optimal mitigation strategy, $\frac{\partial\rho_i^{(2)}(m_{-i})}{\partial\left(\frac{\phi}{1+r}\right)} > 0$ and $\frac{\partial\rho_i^{(2)}(m_{-i})}{\partial\alpha_i} < 0$.

Claim 2: When $\frac{\phi}{1+r} > 1$, $\frac{\partial\rho_i^{(3)}(m_{-i})}{\partial\left(\frac{\phi}{1+r}\right)} > 0$ whenever $\rho_i^{(3)}\left(m_{-i}\right)$ is the optimal mitigation strategy and $\frac{\partial\rho_i^{(3)}(m_{-i})}{\partial\alpha_i} < 0$ whenever $y_i + E - \sum_{j\neq i}y_j > 0$.

Claim 3: When $\frac{\phi}{1+r} > 1$, $\frac{\partial \rho_i^{(4)}(m_{-i})}{\partial \alpha_i} < 0$.

Claim 4: When $\alpha_i = 1$ and $\delta = 1$, optimal mitigation cannot exceed $\frac{(1+r)y_i - \left(E + \sum_{j \neq i} y_j\right)\phi}{(1+r)+\phi}$. When $\alpha_i = 0$, $\delta = 1$, and $\frac{\phi}{1+r} > 1$, optimal mitigation is at least $\frac{(1+r)y_i - E\phi}{(1+r)+\phi}$.

Claim 5: As α_i increases, both the upper boundaries relevant for parts (i)–(v) of Case 3, as well as the lower boundaries relevant for parts (ii) –(v) of Case 3 and Case 4 increase. Thus, the best-response of a more optimistic player will exhibit lower levels of mitigation and higher levels of adaptation.

Proof of Proposition 4:

The proof of the proposition follows directly from Claims 1, 2, 3 and 5.

Proof of Proposition 5:

To prove the existence of this equilibrium, we will consider the Choquet expected utility given by segment (4), $V_i^{(4)}(m_i, m_{-i})$ where players invest exclusively in mitigation:

$$V_i^{(4)}(m_i, m_{-i}) = (1+r)(y_i - m_i)\left[E + m_i + (1-\delta)m_{-i} + \alpha_i \delta \sum_{j \neq i} y_j\right]$$

The first order derivative with respect to m_i leads to the following best-response function:

$$\rho_i(m_{-i}) = \min\left\{y_i, \max\left\{\frac{y_i - E - (1-\delta)m_{-i} - \alpha_i \delta \sum_{j \neq i} y_j}{2}, 0\right\}\right\} \tag{9}$$

Denoting by $M = \sum_{i=1}^n m_i$, in an interior equilibrium

$$m_i = \frac{y_i - E - \alpha_i \delta \sum_{j \neq i} y_j - (1-\delta)M}{1+\delta}$$

Summing both sides over i, and solving the resulting equation, we obtain that total mitigation can be written as:

$$M^*(\delta, \alpha_i) = \frac{\sum_{i=1}^n y_i - nE - \delta \sum_{i=1}^n \alpha_i \sum_{j \neq i} y_j}{(1+\delta) + n(1-\delta)} \tag{10}$$

Using the definitions of y and α, we thus obtain (7).

$$y\left(\alpha - \sum_{i=1}^n \frac{y_i}{y}\alpha_i\right)$$

By replacing M by (10) in (9), we get:

$$\begin{aligned} m_i^*(\delta, \alpha_i) &= \frac{\left[2 + (1-\delta)\left(n - 2 + \delta \sum_{j \neq i} \alpha_j\right)\right] y_i - (1+\delta)E}{[1 + \delta + n(1-\delta)](1+\delta)} \\ &+ \frac{(1-\delta)\delta \sum_{j \neq i} \alpha_j \sum_{k \neq i,j} y_k - [(1-\delta) + \delta\alpha_i[2 + (1-\delta)(n-2)]] \sum_{j \neq i} y_j}{[1 + \delta + n(1-\delta)](1+\delta)} \end{aligned}$$

Properties (i) – (iii) are then obvious. To obtain (iv), note that

$$\frac{\partial M^{*}\left(\delta,\alpha_{i}\right)}{\partial\delta}=\left(\frac{\left(n-1\right)y-n\left(n-1\right)E+\left(1+n\right)\sum_{i=1}^{n}\alpha_{i}\sum_{j\neq i}y_{j}}{\left[1+\delta+n\left(1-\delta\right)\right]^{2}}\right)$$

which is positive when $\alpha_i = 0$ for all i and negative when $\alpha_i = 1$ for all i.

Proof of Proposition 7:

The proof is immediate from Cases 1 and 2 of the analysis of the best-response of a player i.

Proof of Proposition 8:

For the relevant values of the parameters, segment $V_i^{(1)}$ is irrelevant. Since when $\frac{\phi}{1+r} > 1$, $V_i^{(2)}\left(m_i, m_{-i}\right)$ is concave whenever

$$\frac{\phi}{1+r}\in\left(1,\frac{1+2\sqrt{\alpha_{i}\delta}+\alpha_{i}\delta}{1-\alpha_{i}\delta}\right)$$

we have that

$$\lim_{\epsilon\to0}\frac{1+2\sqrt{\left(1-\kappa_{i}\epsilon\right)\left(1-\epsilon\right)}+\left(1-\kappa_{i}\epsilon\right)\left(1-\epsilon\right)}{1-\left(1-\kappa_{i}\epsilon\right)\left(1-\epsilon\right)}=\infty$$

and hence, there exists an $\bar{\epsilon}' > 0$ such that $V_i^{(2)}$ is concave whenever $\epsilon \in (0, \bar{\epsilon}')$.

$V_i^{(3)}$ is concave whenever

$$\frac{\phi}{1+r}\in\left(0,\frac{\left(2-\delta\left(1-\alpha_{i}\right)\right)+\sqrt{2\left(2-\delta\left(1-\alpha_{i}\right)\right)}}{\delta\left(1-\alpha_{i}\right)}\right)$$

and since

$$\lim_{\epsilon\to0}\frac{\left(2-\kappa_{i}\left(1-\epsilon\right)\epsilon\right)+\sqrt{2\left(2-\kappa_{i}\left(1-\epsilon\right)\epsilon\right)}}{\kappa_{i}\left(1-\epsilon\right)\epsilon}=\infty$$

and hence, there exists an $\bar{\epsilon}'' > 0$ such that $V_i^{(3)}$ is concave whenever $\epsilon \in (0, \bar{\epsilon}'')$. Finally, segment $V_i^{(4)}$ is concave for all values of the parameters.

Furthermore, for the segments $V_i^{(2)}$, $V_i^{(3)}$ and $V_i^{(4)}$, it is easy to check that the corresponding unconstrained best-responses as defined in (4), (5) and (6) all converge to:

$$\frac{1}{2}\left(y_{i}-E-\sum_{j\neq i}y_{j}\right)<0$$

when $\epsilon \to 0$. Thus, by continuity, we can choose $\bar{\epsilon} < \min\left\{\bar{\epsilon}', \bar{\epsilon}''\right\}$ such that whenever $\epsilon \in (0, \bar{\epsilon})$, for each player i, $\rho_i\left(m_{-i} = 0\right) = 0$ is optimal whenever all other players choose 0 mitigation. The optimal adaptation is obtained from 2.

Proof of Proposition 9:

Assume indeed that $m_p^* = \frac{y_p - E}{n_p + 1}$ and $m_o^* = 0$. By Case 2, part (iii), we know that for $\alpha_p = 0$, $\delta \in (0, 1)$ and any m_{-i}, the best-response of the pessimist can be chosen to be:

$$m_{p}^{*}=\frac{y_{p}-E-m_{-i}}{2}$$

Thus, for m^*_{-i}, we obtain

$$m^*_p = \frac{y_p - E}{n_p + 1}$$

as desired. At the same time, by Case 2, part (i), we know that for $\alpha_o > 0$, $m^*_o = 0$ is an optimal level of mitigation.

We next check the conjectures for the adaptation policies. For a pessimist,

$$a^*_p\left(m^*_p, m^*_o\right) = \max\left\{y_p - m^*_p - E - n_p m^*_p, 0\right\} = y_p - m^*_p - E - n_p m^*_p = 0$$

Hence, the pessimist finds it optimal not to adapt on the equilibrium path. By monotonicity, we have $a^*_p\left(m^*_p, m_{-i} = \mathbf{0}\right) > 0$.

Consider the adaptation policy of an optimist:

$$a^*_o\left(m^*_p, m^*_o = 0\right) = y_o - E - n_p m^*_p = y_o - E - n_p \frac{y_p - E}{(n_p + 1)} > 0$$

whenever $\frac{y_o - E}{y_p - E} > \frac{n_p}{n_p + 1}$. Furthermore, by monotonicity, $\hat{a}_o\left(m^*_o = 0, m_{-i} = \mathbf{0}\right) > 0$ and

$$a^*_o\left(m^*_o = 0, m_{-i} = y_{-i}\right) = \max\left\{y_o - E - n_p \frac{y_p - E}{(n_p + 1)} - (n_o - 1)\, y_o, 0\right\}.$$

Proof of Proposition 10:

Suppose that only pessimists contribute to mitigation. Then:

$$m^*_p\left(\delta, \alpha_p = 1\right) = \frac{y_p - E}{1 + \delta + n_p\left(1 - \delta\right)}$$

Note that in such an equilibrium, the optimists' optimal mitigation cannot exceed the optimal mitigation they would choose provided they never adapt:

$$\begin{aligned} m^*_o\left(\delta, \alpha_o\right) &\leq \frac{y_o - E - \alpha_o \delta\left[n_p y_p + (n_o - 1)\, y_o\right] - (1 - \delta)\, n_p \frac{y_p - E}{1 + \delta + n_p(1 - \delta)}}{2} \\ &= \frac{y_o\left(1 - (n_o - 1)\,\alpha_o \delta\right)}{2} - \frac{E\left(1 + \delta\right) + \left[(1 - \delta)\left(1 + \alpha_o \delta\right) n_p + \alpha_o \delta\left(1 + \delta\right)\right] n_p y_p}{2\left[1 + \delta + n_p\left(1 - \delta\right)\right]} \end{aligned}$$

Hence, if $\alpha_o \delta > \frac{1}{n_o - 1}$, we obtain that the maximal optimal mitigation for the optimists is $m^*_o = 0$.

Optimal adaptation for the pessimists is given by:

$$a^*_p\left(m_p = \frac{y_p - E}{2}, m^*_o = 0\right) = \max\left\{(1 + r)\left(\frac{\left(\delta + n_p\left(1 - \delta\right)\right) y_p + E}{1 + \delta + n_p\left(1 - \delta\right)}\right) - \phi\left(\frac{E\left(1 + \delta - n_p \delta\right) + n_p y_p}{1 + \delta + n_p\left(1 - \delta\right)}\right), 0\right\}$$

and equals 0 provided that

$$\frac{\phi}{1 + r} > \frac{\left(\delta + n_p\left(1 - \delta\right)\right) y_p + E}{n_p y_p + \left(1 + \delta - n_p \delta\right) E}$$

But since

$$\begin{aligned}\frac{(\delta + n_p(1-\delta))\, y_p + E}{n_p y_p + (1+\delta - n_p\delta)\, E} &< 1 \\ (\delta - n_p\delta)\, y_p &< (\delta - n_p\delta)\, E \\ y_p &> E\end{aligned}$$

this is always satisfied, whenever the optimal mitigation of the pessimists is non-zero.

At the same optimal adaptation satisfies

$$a_p^*\left(m_i = \frac{y_p - E}{2}, m_{-i} = 0\right) = 0,$$

or

$$\begin{aligned}&(1+r)\left(y_p - \frac{y_p - E}{1+\delta + n_p(1-\delta)}\right) - \phi\left(E + \frac{y_p - E}{1+\delta + n_p(1-\delta)}\right) \\ = \;& (1+r)\left(\frac{[\delta + n_p(1-\delta)]\, y_p + E}{1+\delta + n_p(1-\delta)}\right) - \phi\left(\frac{[\delta + n_p(1-\delta)]\, E + y_p}{1+\delta + n_p(1-\delta)}\right) < 0\end{aligned}$$

which is equivalent to

$$\frac{\phi}{1+r} > \frac{[\delta + n_p(1-\delta)]\, y_p + E}{[\delta + n_p(1-\delta)]\, E + y_p} \tag{11}$$

Finally, we need that on the equilibrium path, optimists choose strictly positive adaptation:

$$\begin{aligned}a_o^*\left(m_o^* = 0, m_p = \frac{y_p - E}{2}\right) &= (1+r)\, y_o - \phi\left(E + n_p \frac{y_p - E}{1+\delta + n_p(1-\delta)}\right) \\ &= y_o - \frac{\phi}{1+r}\left(\frac{E(1+\delta - n_p\delta) + n_p y_p}{1+\delta + n_p(1-\delta)}\right) > 0\end{aligned}$$

or

$$\frac{\phi}{1+r} < \frac{E(1+\delta - n_p\delta) + n_p y_p}{(1+\delta + n_p(1-\delta))\, y_o}.$$

For this to be consistent with condition (11), we need:

$$\frac{E(1+\delta - n_p\delta) + n_p y_p}{(1+\delta + n_p(1-\delta))\, y_o} > \frac{[\delta + n_p(1-\delta)]\, y_p + E}{[\delta + n_p(1-\delta)]\, E + y_p}$$

or

$$y_o < \frac{E(1+\delta - n_p\delta) + n_p y_p}{(1+\delta + n_p(1-\delta))} \frac{[\delta + n_p(1-\delta)]\, E + y_p}{[\delta + n_p(1-\delta)]\, y_p + E}$$

Note that, by monotonicity, we have:

$$a_o^*(m_i^* = 0, m_{-i} = 0) = (1+r)\, y_o - \phi E > a_o^*\left(m_o^* = 0, m_p = \frac{y_p - E}{2}\right) > 0$$

and that

$$a_o^*(m_i^* = 0, m_{-i} = n_p y_p + (n_o - 1)\, y_o) = \max\left\{(1+r)\, y_o - \phi\left[n_p y_p + (n_o - 1)\, y_o\right], 0\right\}$$

Proof of Proposition 11:

(i) Differentiating $V_i^{(4)}(m_i, m_{-i}, \tau)$ w.r.t. m_i, we obtain that in an interior optimum player i's strategy m_i satisfies:

$$m_i = \frac{y_i + t_i - E - (1-\delta) m_{-i} - \alpha_i \delta \sum_{j \neq i} (y_j + t_j)}{2}$$

Summing both sides over i and solving for M, we obtain:

$$M(\delta, (\alpha_i)_{i=1}^n, \tau) = \frac{y\left(1 + \tau\left[1 - \alpha\delta(1+\gamma)\frac{(n-1)}{n} + \frac{\gamma\delta}{y}\sum_i \alpha_i \sum_{j\neq i} y_j\right]\right) - nE - \sum_i \alpha_i \delta \sum_{j\neq i} y_j}{\left[2 + (1-\delta)(n-1) + \tau\left[1 - \alpha\delta(1+\gamma)\frac{(n-1)}{n} + \frac{\gamma\delta}{y}\sum_i \alpha_i \sum_{j\neq i} y_j\right]\right]}$$

Finally, using $\sum_i \alpha_i \sum_{j\neq i} y_j = \sum_i \alpha_i (y - y_i)$ gives:

$$M(\delta, (\alpha_i)_{i=1}^n, \tau) = \frac{y\left(1 - \alpha\delta + \tau\left[1 - \frac{\alpha\delta}{n}(n-1-\gamma) - \frac{\gamma\delta}{y}\sum_i \alpha_i y_i\right]\right) - nE + \delta\sum_i \alpha_i y_i}{\left[2 + (1-\delta)(n-1) + \tau\left[1 - \frac{\alpha\delta}{n}(n-1-\gamma) - \frac{\gamma\delta}{y}\sum_i \alpha_i y_i\right]\right]}$$

as stated.

(ii) Denote by

$$Z := \left[1 - \frac{\alpha\delta}{n}(n-1-\gamma) - \frac{\gamma\delta}{y}\sum_i \alpha_i y_i\right]$$

Then

$$\frac{\partial M(\delta, (\alpha_i)_{i=1}^n, \tau)}{\partial \tau} = \left(\frac{yZ[1 + \alpha\delta + (1-\delta)(n-1)] + ZnE + Z\delta[\alpha y - \sum_i \alpha_i y_i]}{[2 + (1-\delta)(n-1) + \tau Z]^2}\right) > 0$$

as stated.

(iii) Write

$$\frac{\partial M^*(\delta, (\alpha_i)_{i=1}^n, \tau)}{\partial\left(\sum_i \alpha_i \frac{y_i}{y}\right)}$$

$$= \delta \frac{[2 + (1-\delta)(n-1)] + \tau\left[1 - \frac{\alpha\delta}{n}(n-1)\right]}{\left[2 + (1-\delta)(n-1) + \tau\left[1 - \frac{\alpha\delta}{n}(n-1-\gamma) - \frac{\gamma\delta}{y}\sum_i \alpha_i y_i\right]\right]^2}$$
$$+\delta \frac{\gamma\tau\left[\delta\left[\frac{\alpha}{n} - \sum_i \alpha_i \frac{y_i}{y}\right] + y(1-\alpha\delta) - nE + \delta\sum_i \alpha_i y_i - [2 + (1-\delta)(n-1)]\right]}{\left[2 + (1-\delta)(n-1) + \tau\left[1 - \frac{\alpha\delta}{n}(n-1-\gamma) - \frac{\gamma\delta}{y}\sum_i \alpha_i y_i\right]\right]^2}$$

Clearly, the first two terms of the numerator are always positive, thus, if the third term is also positive, i.e.,

$$\left[\delta\left[\frac{\alpha}{n} - \sum_i \alpha_i \frac{y_i}{y}\right] + y(1-\alpha\delta) - nE + \delta\sum_i \alpha_i y_i - [2 + (1-\delta)(n-1)]\right] > 0 \qquad (12)$$

we can set $\bar{\gamma}=\infty$ and conclude that $\frac{\partial M^*\left(\delta,(\alpha_i)_{i=1}^n,\tau\right)}{\partial\left(\sum_i \alpha_i \frac{y_i}{y}\right)}>0$ for all $\gamma<\infty$. In contrast, if the inequality in (12) is reversed, we can set

$$\bar{\gamma}=\frac{\left[2+(1-\delta)(n-1)\right]+\tau\left[1-\frac{\alpha\delta}{n}(n-1)\right]}{\tau\left[\alpha\delta\left(y-\frac{1}{n}\right)+\delta\left(\frac{1}{y}-1\right)\sum_i \alpha_i y_i+2+(1-\delta)(n-1)-(y-nE)\right]}$$

and conclude that $\frac{\partial M^*\left(\delta,(\alpha_i)_{i=1}^n,\tau\right)}{\partial\left(\sum_i \alpha_i \frac{y_i}{y}\right)}>0$ for all $\gamma<\bar{\gamma}$.

Proof of Proposition 12:

Setting $M\left(\delta,(\alpha_i)_{i=1}^n,\tau\right)=M^S$ gives

$$\frac{y\left(1+\tau\left(1-\sum_{i=1}^n \alpha_i\delta\left(\frac{(n-1)}{n}(1+\gamma)-\gamma\frac{\sum_{j\neq i}y_j}{y}\right)\right)\right)-nE-\sum_{i=1}^n \alpha_i\delta\sum_{j\neq i}y_j}{\left[n+1+(n-1)\delta+\tau\left(1-\sum_{i=1}^n \alpha_i\delta\left(\frac{(n-1)}{n}(1+\gamma)-\gamma\frac{\sum_{j\neq i}y_j}{y}\right)\right)\right]}=\frac{y-E}{2}$$

$$\begin{aligned}
&\tau(y+E)\left(1-\sum_{i=1}^n \alpha_i\delta\left(\frac{(n-1)}{n}(1+\gamma)-\gamma\frac{\sum_{j\neq i}y_j}{y}\right)\right)-2\sum_{i=1}^n \alpha_i\delta\sum_{j\neq i}y_j\\
=\;& y\left[n-1+(n-1)\delta\right]-E\left[-n+1+(n-1)\delta\right]\\
&\tau=\frac{(n-1)\left[y(1-\delta)+E(1+\delta)\right]+2\sum_{i=1}^n \alpha_i\delta\sum_{j\neq i}y_j}{(y+E)\left(1-\delta\sum_{i=1}^n \alpha_i\left(\frac{(n-1)}{n}(1+\gamma)-\gamma\frac{\sum_{j\neq i}y_j}{y}\right)\right)} \qquad (13)
\end{aligned}$$

or

$$\tau^S\left(\delta,(\alpha_i)_{i=1}^n\right)=\frac{(n-1)\left[y(1-\delta)+E(1+\delta)\right]+2\alpha\delta y-2\delta\sum_i \alpha_i y_i}{\left[1-\frac{\alpha\delta}{n}\left[n-1-\gamma\right]-\frac{\gamma\delta}{y}\sum_i \alpha_i y_i\right]}$$

(i) Note that the numerator of (13) is increasing in α_i. In contrast, the denominator is decreasing in α_i, since:

$$\begin{aligned}
&-\alpha_i\delta(1+\gamma)\frac{(n-1)}{n}+\frac{\gamma\delta}{y}\alpha_i\sum_{j\neq i}y_j\\
=\;& -\alpha_i\delta\frac{1}{ny}\left[(n-1)y(1+\gamma)-\gamma n(y-y_i)\right]\\
=\;& -\alpha_i\delta\frac{1}{ny}\left[(n-1+\gamma)y+\gamma n y_i\right]<0
\end{aligned}$$

Thus, for any $i\in\{1...n\}$, $\frac{\partial\tau}{\partial\alpha_i}>0$.

(ii) Using the expression in (13), we obtain:

$$\begin{aligned}
&\frac{\partial\tau^S\left(\delta,(\alpha_i)_{i=1}^n\right)}{\partial\delta}\\
=\;& \frac{(n-1)\underbrace{(E-y)}_{<0}+2\sum_i \alpha_i\sum_{j\neq i}y_j+(n-1)(y+E)\underbrace{\left[\alpha(1+\gamma)\frac{(n-1)}{n}-\frac{\gamma}{y}\sum_i \alpha_i\sum_{j\neq i}y_j\right]}_{>0}}{\left[1-\alpha\delta(1+\gamma)\frac{(n-1)}{n}+\frac{\gamma\delta}{y}\sum_i \alpha_i\sum_{j\neq i}y_j\right]^2}
\end{aligned}$$

Note that in an interior mitigation equilibrium, the first term in the numerator is negative, whereas the second and the third one are positive. Substituting $\alpha_i = 0$ for all $i \in \{1...n\}$, we have $\frac{\partial \tau^S\left(\delta,(\alpha_i=0)_{i=1}^n\right)}{\partial \delta} < 0$. If $\alpha_i = 1$ for all $i = 1...n$,

$$\frac{\partial \tau^S\left(\delta,(\alpha_i=1)_{i=1}^n\right)}{\partial \delta} = \frac{(n-1)(y+E)}{\left[1-\delta(n-1)\right]^2} > 0.$$

Assuming that $\alpha_i = \bar{\alpha}$ for all i, we have that

$$\frac{\partial \tau^S\left(\delta,(\alpha_i=\bar{\alpha})_{i=1}^n\right)}{\partial \delta} = 0$$

iff

$$(n-1)(E-y) + 2\bar{\alpha}(n-1)y + (n-1)(y+E)\bar{\alpha}(n-1) = 0, \tag{14a}$$

or

$$\bar{\alpha} = \frac{(y-E)}{2y + (y+E)(n-1)} \in (0,1)$$

and the rest of the statement follows from the fact that the l.h.s. of (14a) is increasing in $\bar{\alpha}$.

(*iii*) Differentiating, we obtain:

$$\frac{\partial \tau^S\left(\delta,(\alpha_i)_{i=1}^n\right)}{\partial\left(\sum_i \alpha_i y_i\right)} = \frac{\gamma\delta\left[(n-1)\left[(1-\delta)+\frac{E}{y}(1+\delta)\right]+2\alpha\delta\left(1-\frac{1}{n}\right)\right]-2\delta\left[1-\frac{\alpha\delta}{n}(n-1)\right]}{\left[1-\frac{\alpha\delta}{n}[n-1-\gamma]-\frac{\gamma\delta}{y}\sum_i \alpha_i y_i\right]^2}$$

which (given $\delta > 0$) is strictly positive iff

$$\gamma < \frac{2\left[1-\frac{\alpha\delta}{n}(n-1)\right]}{\left[(n-1)\left[(1-\delta)+\frac{E}{y}(1+\delta)\right]+2\alpha\delta\left(1-\frac{1}{n}\right)\right]}.$$

Proof of Proposition 13:

Checking that the specified strategies represent an equilibrium is straightforward given that the best-responses of the players are given by (8). We note that all the denominators in the expressions are positive. In particular,

$$[(1+\delta)(3-\delta) - \delta[2\alpha_o - \alpha_p(1-\delta) - (1+\delta)]] > 0$$

because

$$3(1+\delta) - \delta[2\alpha_o - \alpha_p(1-\delta)] \geq 3(1+\delta) - 2\delta > 0$$

The first cut-off point for m_s is also positive, because:

$$\begin{aligned} (1+\delta)(\tilde{y}-E) - \delta[2\alpha_o - \alpha_p(1-\delta)]\tilde{y} &> 0 \\ [1+\delta-2\delta\alpha_o + \delta\alpha_p(1-\delta)]\tilde{y} - (1+\delta)E &> 0 \end{aligned}$$

Furthermore, for $\delta > 0$,

$$\frac{\tilde{y}(1-\delta\alpha_p) - E}{3-\delta\alpha_p} > \frac{(1+\delta-2\delta\alpha_o + \delta(1-\delta)\alpha_p)\tilde{y} - (1+\delta)E}{[(1+\delta)(3-\delta) - \delta[2\alpha_o - \alpha_p(1-\delta) - (1+\delta)]]}$$

is equivalent to

$$\tilde{y}\left[2\left(\alpha_o-\alpha_p\right)-\delta\left(1-\delta\alpha_p\right)\right]+\left(\alpha_o-\alpha_p\right)E>0$$

which is satisfied given our assumption.

Finally, we have that in an interior equilibrium, the pessimist contributes more than the optimist, since

$$\begin{aligned}&\frac{\left[(1+\delta)-2\delta\alpha_p+\delta\left(1-\delta\right)\alpha_o\right]\tilde{y}-\left(1+\delta\right)E-\delta\left[\alpha_o\left(1-\delta\right)+(1+\delta)-2\alpha_p\right]m_s}{\left(1+\delta\right)\left(3-\delta\right)}\\ >\ &\frac{\left(1+\delta-2\delta\alpha_o+\delta\left(1-\delta\right)\alpha_p\right)\tilde{y}-\left(1+\delta\right)E+\delta\left[2\alpha_o-\alpha_p\left(1-\delta\right)-(1+\delta)\right]m_s}{\left(1+\delta\right)\left(3-\delta\right)}\end{aligned}$$

is equivalent to

$$\delta\left(3-\delta\right)\left(\alpha_o-\alpha_p\right)\left(\tilde{y}-m_s\right)>0$$

whereas for $m_s\leq\frac{(1+\delta)(\tilde{y}-E)-\delta[2\alpha_o-\alpha_p(1-\delta)]\tilde{y}}{[(1+\delta)(3-\delta)-\delta[2\alpha_o-\alpha_p(1-\delta)-(1+\delta)]]}$, we have $m_s<\tilde{y}$ because

$$\frac{\left(1+\delta-2\delta\alpha_o+\delta\left(1-\delta\right)\alpha_p\right)\tilde{y}-\left(1+\delta\right)E}{\left[\left(1+\delta\right)\left(3-\delta\right)-\delta\left[2\alpha_o-\alpha_p\left(1-\delta\right)-(1+\delta)\right]\right]}<\tilde{y}$$

is equivalent to $2\tilde{y}+E>0$, which is always true.

To show (i), note that for $m_s<\frac{(1+\delta-2\delta\alpha_o+\delta(1-\delta)\alpha_p)\tilde{y}-(1+\delta)E}{[(1+\delta)(3-\delta)-\delta[2\alpha_o-\alpha_p(1-\delta)-(1+\delta)]]}$,

$$\frac{\partial M\left(\delta,\alpha_o,\alpha_p,m_s\right)}{\partial m_s}=\frac{\partial m_o^*\left(\delta,\alpha_o,m_s\right)}{\partial m_s}+\frac{\partial m_p^*\left(\delta,\alpha_o,m_s\right)}{\partial m_s}=-\frac{\delta\left(2-\alpha_o-\alpha_p\right)}{\left(3-\delta\right)}<0.$$

(ii) follows since for $m_s>\frac{(1+\delta-2\delta\alpha_o+\delta(1-\delta)\alpha_p)\tilde{y}-(1+\delta)E}{[(1+\delta)(3-\delta)-\delta[2\alpha_o-\alpha_p(1-\delta)-(1+\delta)]]}$,

$$\frac{\partial M\left(\delta,\alpha_o,\alpha_p,m_s\right)}{\partial m_s}=\frac{\partial m_o^*\left(\delta,\alpha_o,m_s\right)}{\partial m_s}+\frac{\partial m_p^*\left(\delta,\alpha_o,m_s\right)}{\partial m_s}=\frac{1+\delta\alpha_p}{2}>0.$$

Finally, to show (iii), note that $M\left(\delta,\alpha_o,\alpha_p,0\right)=\frac{[2-\delta(\alpha_o+\alpha_p)]\tilde{y}-2E}{(3-\delta)}$ and since $M\left(\delta,\alpha_o,\alpha_p,m_s\right)$ is decreasing for $m_s<\frac{(1+\delta-2\delta\alpha_o+\delta(1-\delta)\alpha_p)\tilde{y}-(1+\delta)E}{[(1+\delta)(3-\delta)-\delta[2\alpha_o-\alpha_p(1-\delta)-(1+\delta)]]}$, we have that $M\left(\delta,\alpha_o,\alpha_p,m_s\right)>M\left(\delta,\alpha_o,\alpha_p,0\right)$ obtains iff

$$\frac{\tilde{y}\left(1-\delta\alpha_p\right)-E-\left(1-\delta\alpha_p\right)m_s}{2}+m_s>\frac{\left[2-\delta\left(\alpha_o+\alpha_p\right)\right]\tilde{y}-2E}{\left(3-\delta\right)}$$

or

$$m_s>\frac{\left(1+\delta+\delta\alpha_p-\delta^2\alpha_p-2\delta\alpha_o\right)\tilde{y}-\left(1+\delta\right)E}{\left(1+\delta\alpha_p\right)\left(3-\delta\right)}.$$

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