Global warming as an asymmetric public bad

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Abstract

The impacts of anthropogenic global warming are not uniform across latitudes. Cold regions may benefit from, say, lower heating expenditures, while adaptation may lead warm regions to adopt air conditioning, the emissions of which potentially exacerbate warming. In parallel, mitigation capabilities differ across economies: Abatement in India is more expensive than in Russia but cheaper than in the US. We extend the canonical dynamic game model of global warming to accommodate asymmetries in adaptation and mitigation. Within a two-player, linear-state framework, we consider three strategies: myopic, reminiscent of a pre-Kyoto system; forward-looking non-cooperative, mimicking the current pledge system; and cooperative. The trade-offs between global warming and economic efficiency are found to depend upon five public bad regimes. In the most theoretically studied regime where both players suffer damages, free-riding arises and warming is too high under pledges. In more empirically relevant regimes where one player enjoys small benefits, free-riding is counter-balanced by free-driving. If the loser has fewer mitigation capabilities, e.g., India vs. Russia, pledges can lead to even more warming than myopia. Otherwise, e.g., India vs. USA, pledges generate too little warming. Unless players are myopic or face identical damages, they should be imposed differentiated carbon prices.

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1. Introduction

Anthropogenic global warming has brought the problem of public goods to an unprecedented scale. Human activities imply greenhouse-gas (GHG) emissions, which warm the atmosphere. In turn, the atmosphere connects all humans. Therefore, virtually every single individual on the planet is at the same time contributing to and being affected by global warming. Rather than one global externality, global warming generates $\approx (7 \times 10^9)^2$ externalities at current world population.[1]

The economic impacts of global warming, though net negative, are asymmetric at the regional scale (Arent et al., 2014). Recent projections of temperature increase point to a 23% reduction of global income per capita by 2100, with regional gains as high as 50% in Europe and losses as high as 75% in Sub-Saharan Africa (Burke et al., 2015). This asymmetry is primarily due to latitudinal positions and mainly experienced in economic sectors such as agriculture and building energy use, which represent 24% and 6% of global GHG emissions, respectively (Victor et al., 2014).

Asymmetry in global-warming impacts is associated with asymmetry in adaptation technologies, with complex intertemporal retroactions. A moderate increase in temperature is expected to reduce space heating and increase air conditioning, the former effect prevailing in temperate zones and the latter prevailing in tropical zones (Isaac and van Vuuren, 2009). There is growing concern that an increased use of air conditioning will generate GHG emissions, hence exacerbating global warming (Auffhammer and Mansur, 2014; Davis and Gertler, 2015; Barreca et al., 2016). In this context, adaptation is costless and "clean" in temperate zones but costly and potentially "dirty" in tropical ones. Though less documented, a similar divide can be envisioned in agriculture: warming may increase agricultural productivity in previously unsuitable areas but intensify the use of fertilizers in more vulnerable areas, the production of which emits GHGs and thus affects climate.

Besides adaptation, mitigation technologies too are asymmetric, with little correlation between the two. India, for instance, is more vulnerable to global warming than other big GHG emitters such as the US and Russia(Samson et al., 2011). Yet while its GHG abatement costs are cheaper than the former's, they are also more expensive than Russia's (Nordhaus, 2015).

[1] Let N be the size of a population. In a static perspective, every contributor is affected by all others. The number of externalities is $N(N-1)$. In a dynamic perspective, this number scales up to N^2, since, in addition, every contributor is affected in the future by his or her present actions. This number would be even larger if one considered multiple generations.

These different sources of asymmetry change the conceptual nature of global warming and mitigation thereof. Specifically, they add free-driving to the classical free-riding problem. Global warming has traditionally been modeled as imposing uniform damages on all countries. In this view, mitigation is a public good subject to free-riding: because any contributor can reap benefits from another's effort without bearing its cost, all mitigate too little in equilibrium. This results in too much global warming. Now consider that the contributors integrate the above-mentioned cold/warm asymmetries into their mitigation decisions. Mitigation by cold regions prevents GHG emissions (e.g., from air conditioning) from increasing in warm regions, hence exerting a positive externality on the latter. As a result, the former under-mitigate, which is but another form of free-riding. Yet in turn, mitigation by the warm regions prevents GHG emissions (e.g., from space heating) from decreasing in cold regions. This negative externality leads the former to over-mitigate, thereby becoming free-drivers. The net effect on global warming and social welfare depends on the relative magnitude of those conflicting externalities.

In this paper, we consider global warming as an asymmetric public bad and examine how this conceptual shift from a uniform perspective changes predictions about temperature increase, economic efficiency and optimal policy. We extend the canonical model of global warming mitigation to accommodate asymmetries in impacts, adaptation and mitigation. We consider two players, a warm region and a cold one. Perfect adaptation to global warming increases the former player's GHG emissions and decreases the latter's. Both players can mitigate GHG emissions by investing in energy or carbon efficiency. As mitigation is each player's sole control variable, subject to perfect adaptation, we refer to player's actions as "adaptive mitigation." We characterize cooperative and non-cooperative optimization subject to temperature increase. We also consider myopic optimization, which occurs when the players ignore the future consequences of their and their competitor's present actions.

The structure of the model is parsimonious enough to allow us to derive closed-form solutions for steady-state temperature, intertemporal efficiency and optimal incentive policy. This is made possible by important simplifications. Perhaps the most sensible one is the assumption of linear impacts, instead of the quadratic one made in related models. This specification is best-suited to short-term, moderate impacts, a context quite pertinent to current negotiations. Another strong simplification is our focus on smooth global warming, which abstracts from climate change impacts other than warming (e.g., sea-level rise, ocean acidification) and, perhaps more importantly, from catastrophic events, which is a major concern with global climate change (Weitzman, 2009). Lastly, the retroactions considered here may be relevant to some economic sectors, but not all.

Notwithstanding these limitations, the efficiency-warming trade-offs are found to depend on five public-bad regimes, which differ through the distribution of damages and benefits.

In the most theoretically studied regime where both players suffer damages, free-riding arises and warming is too high under pledges. In more empirically relevant regimes where one player enjoys small benefits, free-riding is counterbalanced by free-driving. If the loser has fewer mitigation capabilities, e.g., India vs. Russia, pledges can lead to even more warming than myopia. Otherwise, e.g., India vs. USA, pledges generate too little warming. Unless players are myopic or face identical damages, they should be imposed differentiated carbon prices, namely a large tax on emissions on the gaining player and a small subsidy for (emitting) adaptation on the losing player.

Our main contribution is to address the question of gainers and losers, an issue early pointed out as crucial to global warming (Schelling, 1992). Most of the discussion has focused on how equity weights should be used when one aggregates impacts (Azar, 1999; Anthoff et al., 2009). We show that prior to requiring correction by equity weights, asymmetries matter for overall (unweighted) efficiency. In particular, taking into account strategic interactions can amend the textbook argument of a uniform Pigouvian incentive to internalize the global externality.

More generally, we contribute to developing new economic concepts to address global warming. The problem has primarily been studied as a *uniform* public bad generating a global negative externality, the internalization of which hinges upon the unlikely existence of a supranational authority. Some authors have started to incorporate real-world frictions into this model. Kotchen (2005) uses the concept of *impure* public good to take into account the possibility that mitigation measures yield private benefits (e.g., alleviation of local pollution in China) in addition to collective ones. This is another type of free driver. More recently, Nordhaus (2015) proposes to form climate *clubs* to overcome free-riding. Beside these new directions, our *asymmetric* conceptualization concurs to stress that private forces can, under certain conditions, offer partial, welfare-improving solutions to the global warming problem.

The paper is organized as follows. Section 2 provides theoretical and empirical background. Section 3 introduces the model. Section 4 characterizes steady-state equilibria. Section 5 discusses the trade-offs between steady-state temperature and intertemporal efficiency. Section 6 formulates policy recommendations. Section 7 concludes.

2. Background

2.1. Related economic models of global warming

Fundamentally, global warming is a dynamic and strategic problem. The two dimensions have been integrated in dynamic games, with most applications to mitigation.[2] In contrast, research on adaptation is still in its infancy and borrows from a broader set of frameworks.

Dynamic games of mitigation. Research on dynamic games of global warming is broadly reviewed in Missfeldt (1999), Jørgensen et al. (2010) and Calvo and Rubio (2013). Most studies have been concerned with how players set their emission levels, or, equivalently, their mitigation level. Indeed, if global warming is regarded as a public bad, then mitigation is the mirror picture of a public good.

The canonical model has multiple identical players who derive utility from GHG emissions and suffer damages from GHG concentration, that is, cumulative emissions. The resulting value function increases in a linear-quadratic manner in emissions and decreases quadratically in cumulative emissions. The game consists of players maximizing their value function with respect to emissions (or mitigation thereof), subject to emissions accumulation, net of a natural sink. It is usually set up in continuous time, hence as a differential game.

The social optimum, characterized as the cooperative solution, is generally contrasted with two non-cooperative solutions: the open-loop Nash equilibrium, which emerges when players simultaneously commit to an inter-temporal schedule of emissions (or mitigation) at the outset of the game, and the feedback Nash equilibrium, which emerges when players simultaneously react to the state of the system at each stage. Both equilibria are time-consistent: if players start on the equilibrium path, it is optimal for them to stick to it. But unlike its open-loop counterpart, the feedback equilibrium has the additional property of subgame perfectness: if one player deviates from his or her equilibrium strategy at some stage, others will still react optimally to the state of the system, so that further playing feedback strategies will still be a Nash equilibrium. With open-loop strategies, the players remain off equilibrium path once one has deviated. Generally speaking, feedback strategies are intellectually more palatable, as they capture the essence of dynamic interactions. In contrast, open-loop strategies are akin to non-cooperative strategies in a static version of the game (Figuières, 2009).

[2] The two dimensions remain mostly studied separately, following the seminal works of Nordhaus (1993) in dynamic optimization and Barrett (1994) and Carraro and Siniscalco (1998) in static game theory.

The differential-game approach to global warming was pioneered by Ploeg and Zeeuw (1992). The authors found that linear feedback strategies magnify the incentives to free-ride, hence lead to a higher equilibrium concentration of GHGs than open-loop strategies. Hoel (1993) complemented this analysis by examining optimal emission taxes needed to reach the social optimum. Assuming that the tax receipts are rebated to countries in proportion to the damages they suffer, the author found that the same tax rate should be implemented in open-loop and feedback equilibria.

Subsequent analyses of the canonical model have focused on feedback information. Dockner and Van Long (1993) found that if the players' discount rate is low enough, non-linear strategies can establish the socially optimal level of warming.[3] Rubio and Casino (2002) found that this result required that the initial stock of pollution be above socially optimal. Wirl (2007) placed further restrictions on the result by requiring the elasticity of marginal utility to be increasing. Altogether, these models find that there is a unique feedback Nash equilibrium when strategies are linear and multiple equilibria when they are non-linear.

All the above-mentioned analyses assume identical players. To our knowledge, only Martin et al. (1993) have considered asymmetric players in the sense that some are harmed by global warming while others benefit. The paper consists of numerical computation of feedback Nash equilibria, which limits its comparison with analytical counterparts. More recently, Zagonari (1998) has considered heterogeneity in damages and other dimensions of players' payoff (e.g., technology).[4] The author finds that linear feedback strategies can lead to more mitigation, thus less warming, than socially optimal. The result is similar to that of Dockner and Van Long (1993), with some differences: it is less restrictive in a way, for it only relies on linear strategies, but more restrictive in another way, since it requires heterogeneity across players.

To sum up, the properties of feedback strategies are better known than those of open-loop strategies. The latter have been somehow disregarded for their lack of realism, based on the premise that transient, short-sighted governments cannot credibly honor decades-long commitments. Yet open-loop strategies have some relevance to actual negotiations. For instance, Canada – a country expected to gain in the short-run – exiting the Kyoto Protocol

[3]The novelty of the result at the time was that trigger strategies were not needed for the cooperative outcome to emerge non-cooperatively.

[4] Other authors have considered heterogeneity across players in the extent of damages they face (Tahvonen, 1994; Fankhauser and Kverndokk, 1996). Long (1992) has considered heterogeneity as regards the leader or follower status of the players.

in 2011 can be interpreted as a pledge to free-ride; in turn, activism from Pacific islands – a more vulnerable region – can be interpreted as free-driving.

Models of adaptation. Adaptation does not have as clear-cut an understanding as mitigation. In the simplest sense, mitigation is a publicly-driven intervention motivated by the existence of a market failure – the free-riding problem – while adaptation is a private, efficient response to the consequences of the market failure – global warming. In this view, mitigation is the first-order problem, only seconded by adaptation.

Some complications however motivate a closer look at adaptation. First, adaptation can have a public-good dimension. As discussed by Mendelsohn (2000), adaptation in water control may require joint efforts from countries sharing an aquifer. The problem can become first-order for global warming if, as we touched in the introduction, some adaptation measures emit GHGs. Second, some authors make a distinction between proactive (or anticipatory, or *ex ante*) and reactive (or *ex post*) adaptation (Lecocq and Shalizi, 2007). While the former is equivalent to efficient adaptation, the latter suggests that some market failures might bias expectations in relation to adaptation.

Adaptation is overwhelmingly modeled jointly with mitigation. The modeling frameworks vary from dynamic optimization (Bréchet et al., 2012) to static game theory (Ebert and Welsch, 2011; Farnham and Kennedy, 2014). To our knowledge, only Buob and Stephan (2011) and Ingham et al. (2013) have integrated the two dimensions in two-period games. In those two models, mitigation is chosen first and adaptation second; adaptation yields private benefits and does not feed back to the climate system.

The question receiving most attention in these papers is whether mitigation and adaptation (both specified as control variables) are complements or substitutes (Kane and Shogren, 2000). So far, the substitute view is dominant. Another frequently addressed question is that of asymmetries, which are mostly viewed as differences in countries' wealth or size conditioning the availability of adaptation measures.

Against this background, we are interested in fully integrating mitigation and adaptation within a dynamic game framework and taking into account asymmetries in adaptation technologies.

2.2. **Prospects of asymmetric impacts of global warming**

Global warming is expected to have a net negative impact, with important asymmetries. Integrated assessments have consistently concluded that global impacts would be relatively small, e.g., 2% of gross domestic product (GDP) losses for a 2.5 degree Celcius (°C) increase in global temperature, with income gains as high as 4% in Eastern Europe and losses as high as 8% in Africa (Tol, 2009). Recently, empirical works exploiting variations over time and across space have refined estimates of the effect of temperature on a variety of economic outputs (Dell et al., 2014). Integrating these more accurate estimates into economic projections leads to substantially larger impacts than previously thought. Burke et al. (2015) project a 23% reduction of global income per capita by 2100, with regional gains as high as 50% in Europe and losses as high as 75% in Sub-Saharan Africa. Lemoine and Kapnick (2015), interacting similar estimates with physical climate models find that 1°C of warming within ten years would increase global growth by 1 to 3 percentage points (pp), with negative impacts up to -5 pp and positive impacts up to 7 pp. Figure 1 displays the distribution of impacts found in Tol (2009) and Burke et al. (2015).

Impacts are expected to be most asymmetric in economic sectors such as building energy use, agriculture, water supply and tourism (Arent et al., 2014). In particular, warming is expected to increase agricultural productivity in some places while deterring it in other places (Reilly et al., 1994; Auffhammer and Schlenker, 2014). In the building sector, higher temperatures are expected to decrease energy use for heating in cold climates and increase energy use for air conditioning in warm climates (Isaac and van Vuuren, 2009). Higher temperature and heat waves are empirically found to damage health (Deschenes, 2014) and stimulate adoption of air conditioning systems (Davis and Gertler, 2015). This adaptation strategy effectively reduces mortality due to heat waves (Barreca et al., 2016). A downside is that it increases energy use, hence potentially global warming (Cian et al., 2013; Auffhammer and Mansur, 2014).

Importantly, global wealth inequalities are found to be caused by spatial heterogeneity (Hsiang and Meng, 2015). As wealth inequalities strongly correlate with vulnerabilities to impacts, they are most likely to be amplified by global warming (Mendelsohn et al., 2006).

Figure 2 fig shows, for the four biggest emitting countries, that asymmetries in exposure to climate change little correlates with heterogeneity in GHG abatement cost.

3. Model

We build a differential-game model of global warming integrating asymmetries in impacts, adaptation and mitigation. We take energy use for space heating and air conditioning in buildings as an example.[5]

3.1. Setup

We consider an economy partitioned into two players: A cold region, noted c, and a warm region, noted w. Region c mainly experiences benefits from global warming, noted b, while Region w mainly experiences damages, noted d. To keep the model as parsimonious as possible, impacts are the only source of heterogeneity considered. The model is summarized in Figure 3.

Adaptive mitigation. The cold region predominantly uses energy for space heating and the warm region predominantly uses energy for air conditioning. Energy use e^i to region $i \in \{c, w\}$ reads:

$$\begin{cases} e^c(q,T) \equiv \epsilon - \alpha^c q - bT \\ e^w(q,T) \equiv \epsilon - \alpha^w q + dT \end{cases} \tag{1}$$

Regions perfectly adapt to global warming: temperature T alleviates net energy use in the cold region at a marginal rate b and increases net energy use in the warm one at a marginal rate d.

Under such perfect adaptation, each region i controls its mitigation effort q^i by investing in energy efficiency (e.g., insulation, efficient heating and cooling systems). Mitigation decreases energy use at a marginal rate equal to α^i and is purchased at a quadratic cost:

$$m^i(q) \equiv \gamma^i q^2/2 \tag{2}$$

[5] As we argued in the introduction, at least conceptually, similar retroactions can be envisioned in agriculture. Indeed, as geographical location is the prime determinant of gains and losses, positive impacts in building energy use and agriculture might correlate. There may also be a spatial correlation between exposure to positive impacts and fossil fuel endowments (think of Russia or Canada, for instance), which impose an opportunity cost on global warming mitigation. Such a correlation can sharpen the contrast between gainers and losers.

Both regions face the same irreducible energy use ϵ, assumed to be high enough for steady-state temperature to be interior.

The objective function of region i is the total cost $\Gamma^i(q, T) \equiv e^i(q, T) + m(q)$, that is, the sum of energy expenditures (with the price of energy normalized to 1) and mitigation costs. Efficiency is measured as the opposite of total cost.

Global warming. We focus on CO_2 as the main GHG. Energy use in both regions generates CO_2 emissions which accumulate in the atmosphere, with some amount captured by a natural sink (e.g. forests, oceans) at a marginal rate s. The resulting increase in atmospheric temperature T from its initial level T^0 reads (the dot refers to the temporal derivative)[6]:

$$
\begin{aligned}
\dot{T} &= e^c(q^c, T) + e^w(q^w, T) - sT \\
&= 2\epsilon - (\alpha^c q^c + \alpha^w q^w) - (s + b - d)T
\end{aligned}
\tag{3}
$$

The state variable T identifies (up to two multiplicative constants) cumulative energy use, the atmospheric CO_2 concentration and the global-mean surface temperature. Implicitly, we hold the carbon intensity of energy constant. Therefore, mitigation in our example is better interpreted as energy efficiency than carbon efficiency (e.g., substitution of renewable energy sources for fossil fuels). Moreover, we assume a linear response of the atmospheric temperature to the CO_2 concentration, a reasonable approximation of physical processes (Matthews et al., 2009).

Stability condition. Convergence of the system to a stable steady state requires $(\mathrm{d}\dot{T}/\mathrm{d}T)_{T_\infty} < 0$. This imposes that what we shall refer to as the physico-economic absorption capacity be positive:

$$
s + b - d > 0 \tag{4}
$$

In other words, the natural sink s needs to absorb more warming than the net economically harmful fraction $d - b$. Note that the stability condition is always satisfied if warming is a global public good ($b > d$, see definition below).

[6]Note that the state variable appears in the right-hand side at several places, not only in the natural sink as is the case in related models. Still, our linear specification of impacts prevents from complications that would occur if the state equation were quadratic in the state variable.

3.2. **Public-good regimes: Taxonomy**

Our model is general enough to address a variety of public-good regimes.[7] Depending on the sense and magnitude of local damages d and benefits b, we propose the following taxonomy:

- $d > b$: warming is a global public *bad*.
- $d < b$: warming is a global public *good*.
- $bd > 0$: players and the global public good/bad are *non-uniform*;
  - if $d = b$, they are *symmetric*,
  - otherwise, they are *asymmetric*.
- $bd < 0$: players and the global public good/bad are *uniform*;
  - if $d = -b$, they are *homogeneous*,
  - otherwise, they are *heterogeneous*.

Altogether, this taxonomy defines seven types of goods, which are illustrated in Figure **??**. In what follows, we will focus on the global public bad semi-plane (weakly defined as $d \geq b$), most relevant to global warming. Moreover, since $d = -b$ is a symmetry axis, we will further confine our attention to $d \geq -b$. We will therefore focus on the Northern corner of Figure 4, where $d \geq\mid b \mid$. This covers the vast majority of the projections displayed in Figure 1.

3.3. **Model specificities**

We summarize here how our model relates to the mitigation and adaptation models reviewed in Section 2.1. Its structure is similar to that of the canonical mitigation model (Ploeg and Zeeuw, 1992; Dockner and Van Long, 1993), with a set of differences. A straightforward yet unessential one is that we minimize costs instead of maximizing utility. More important differences include:

(i) *Generalized impacts:* Related analytical models have focused on uniform public bads. Our model can address a broader set of goods, in particular asymmetric ones, which, according to Figure 1, are empirically most relevant.[8]

[7] Public goods are generally defined by the properties of non-rivalry and non-excludability (Sandmo, 2008).

[8] An even more general specification would feature a bell-shaped curve with temperature increasing player's payoff until a certain threshold and deterring it afterward (Burke et al., 2015; Mendelsohn et al., 2006). This would however require a non-linear specification of temperature in energy use, say $(T - T^{critical})^2$, which would introduce complications in the state equation.

(ii) *Linear-state specification:* We depart from the quadratic specification of impacts assumed in related models. Our linear specification is not unique in dynamic games of global warming (e.g., Beccherle and Tirole (2011)), nor is it empirically irrelevant (Dell et al., 2014; Burke et al., 2015)[9]. It seems well-suited to a time frame of a few decades, which is the typical horizon of climate negotiations. From a technical perspective, it allows us to derive closed-form solutions for efficiency.

(iii) *Perfect adaptation:* We integrate mitigation and adaptation and model the latter in quite a specific way. Rather than being a control variable like in related models, it is a perfect adjustment.[10] This is equivalent to ignoring any market failure potentially associated with adaptation. With respect to the terminology reviewed in Section 2.1, adaptation in our model is proactive when players are forward-looking and reactive when they are myopic. Moreover, adaptation is conducted at the private level, but, since it affects the state of the system, also has a public dimension. Therefore, it is neither a pure public nor private good/bad, but rather a blend of the two, which some authors refer to as an impure public good/bad (Kotchen, 2005).

4. Steady-state equilibria

Throughout, we focus on global warming as an asymmetric public bad, for which $d \geq \mid b \mid$.

4.1. Information structures

In order to formalize the deadweight loss due to the dynamic public bad problem, one would like to compare the social optimum with a *laissez-faire* equilibrium. The difficulty in the context studied here is that two information structures can be used to define the non-cooperative equilibrium considered as *laissez faire*.

Myopic players. Players act myopically when they ignore the intertemporal effects of their and their competitor's actions on the system. This is reminiscent of a Pre-Kyoto regime, when countries were not taking action against global warming. It might still be relevant to the few countries which, for a variety of reasons (e.g., civil war), do not take part in climate

[9]To clear up any misunderstanding, we remind that although Burke et al. (2015) emphasize non-linear responses to local temperatures in the title of their paper, they conclude that ”expected global losses are approximately linear in global mean temperature.”

[10]Because mitigation and adaptation are separable and the latter is not a control variable, the question of substitutability vs. complementarity which receives most attention in related papers does not apply here.

negotiations yet. Note that according to the terminology reviewed in Section 2.1, myopia in our model mimics reactive adaptation.

Forward-looking players. Within our linear-state model, open-loop and feedback strategies are known to coincide (Fershtman, 1987). That is, the solution of commitments by forward-looking players is subgame perfect here.

Open loop is perhaps the information structure that best describes actual countries' behavior. The mere notion of a country being involved in international negotiations suggests a forward-looking perspective. It seems relevant, for instance, to the positions of Canada and the Pacific islands mentioned in the Introduction. In practice, countries typically make commitments to horizons such as 2020, 2030 or 2050.

The recent Paris Agreement[11] has hallowed Nationally-Determined Contributions (NDCs) as a central instrument for collective action. Such pledges, despite their open-loop flavor,[12] are built on the principle of ”common but differentiated responsabilities and respective capabilities,” which is not considered in our model. We rather see NDCs as self-imposed constraints bringing the economy somewhere halfway between the open-loop equilibrium and the social optimum.

4.2. **Myopic equilibrium (M)**

At each time, each region i minimizes its private instantaneous cost $\Gamma^i(q^i, E)$ with respect to own mitigation effort q^i. The resulting mitigation effort equalizes the marginal cost of mitigation to its marginal benefit in terms of reduced energy expenditures:

$$q^i_M = \alpha^i / \gamma^i \tag{5}$$

The steady-state temperature is equal to:

$$\dot{T} = 0 \Leftrightarrow T^\infty_M = \frac{2\epsilon - (\alpha^c q^c_M + \alpha^w q^w_M)}{b - d + s} \tag{6}$$

[11] `https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf`

[12] In particular, while their binding nature is legally unclear, one may argue that it is economically safeguarded by the Nash equilibrium concept.

Solving the differential equation (3) with the stability condition (4), the system converges to a stable steady state along the following trajectory:

$$T_M(t) = T_M^\infty - (T_M^\infty - T^0)\mathrm{e}^{-(b-d+s)t} \tag{7}$$

The present-value social cost along the trajectory is:

$$\begin{aligned} \Gamma_M &= \textstyle\int_0^{+\infty} \sum_{i\in\{c,w\}} \Gamma^i(q^i, T)\mathrm{e}^{-rt}\mathrm{d}t \\ &= \frac{\alpha^c q_M^c + \alpha^w q_M^w}{2r} + \frac{(r+s)(b-d+s)}{r(r+b-d+s)} T_M^\infty + \frac{d-b}{r+b-d+s} T^0 \end{aligned} \tag{8}$$

4.3. **Social optimum (S)**

The social optimum is modeled as a social planner minimizing the joint stream of cost borne by each player, discounted at some rate $r > 0$, and subject to temperature increase:

$$\begin{gathered} \underset{q^c, q^w}{\text{Minimize}} \int_0^{+\infty} \sum_{i\in\{c,w\}} \Gamma^i(q^i, T)\mathrm{e}^{-rt}\mathrm{d}t \\ \text{subject to } (3), q^c \geq 0, q^w \geq 0, T^0 \text{ given} \end{gathered} \tag{9}$$

The current-value Hamiltonian to be minimized is:

$$\mathcal{H}_S(T, q^c, q^w, \lambda_S) \equiv \sum_{i\in\{c,w\}} \Gamma^i(q^i, T) - \lambda \left[e^c(q^c, T) + e^w(q^w, T) - sT \right] \tag{10}$$

with λ the co-state variable associated with the atmospheric stock of CO_2. Put differently, λ is the social value of global temperature.

The first-order necessary condition for optimality leads to the same mitigation effort q_S in both regions:

$$\forall i \in \{c, w\} \frac{\partial \mathcal{H}_S}{\partial q^i} = 0 \Rightarrow q_S^i = q_M^i(1-\lambda) \tag{11}$$

The co-state equation is:

$$\dot{\lambda} - r\lambda = \frac{\partial \mathcal{H}_S}{\partial T} \Rightarrow \dot{\lambda} = (r + b - d + s)\lambda - b + d \tag{12}$$

and the transversality condition is:

$$\lim_{t \to \infty} \mathrm{e}^{-rt} \lambda(t) T_S(t) = 0 \tag{13}$$

The co-state variable at steady state, defined by $\dot{\lambda} = 0$, is:

$$\lambda = \frac{b - d}{r + b - d + s} \tag{14}$$

In our public-bad regime ($d >\mid b \mid$), global warming has a negative social value at steady state ($\lambda < 0$). (Note that it would be positive in a public-good regime.) Plugging Expression (14) in Equation (11), we derive socially optimal mitigation:

$$q_S^i = q_M^i \left(\frac{r + s}{r + b - d + s} \right) \tag{15}$$

Using Equations (3), (15) and setting $\dot{T} = 0$, the steady-state temperature is:

$$T_S^\infty = \frac{2\epsilon - (1 - \lambda)(\alpha^c q_M^c + \alpha^w q_M^w)}{b - d + s} \tag{16}$$

The state and co-state trajectories are given by the differential system formed by Equations (3) and (12), the solution of which have the following forms (with U, V unknown):

$$\begin{cases} \lambda(t) = U\mathrm{e}^{(r+b-d+s)t} + \lambda \\ T_S(t) = T_S^\infty + \frac{2}{r+2(b-d+s)} U\mathrm{e}^{(r+b-d+s)t} + V\mathrm{e}^{-(b-d+s)t} \end{cases} \tag{17}$$

The stability condition (4) and the transversality condition (13) impose $U = 0$. The co-state variable is stationary in current value ($\forall t \ \lambda(t) = \lambda$), hence so are mitigation efforts ($\forall t \ q_S(t) = q_S$). It follows that $V = T^0 - T_S^\infty$ and:

$$T_S(t) = T_S^\infty - (T_S^\infty - T^0)\mathrm{e}^{-(b-d+s)t} \tag{18}$$

Finally, the present-value social cost is:

$$\Gamma_S = \frac{(\alpha^c q_M^c + \alpha^w q_M^w)(1-\lambda)^2}{2r} + \frac{(r+s)(b-d+s)}{r(r+b-d+s)} T_S^\infty + \frac{d-b}{r+b-d+s} T^0 \tag{19}$$

4.4. **Forward-looking Nash equilibrium (L)**

The players minimize their discounted private cost subject to (3). Each one now faces a specific co-state variable λ^i. The current-value Hamiltonian to player i is ($-i$ denotes the competitor):

$$\mathcal{H}_L^i(T, q^i, q^{-i}, \lambda^i) \equiv \Gamma^i(q^i, T) - \lambda^i \left[e^i(q^i, T) + e^{-i}(q^{-i}, T) - sT\right] \tag{20}$$

As in the socially optimal path, the mitigation investment is set so that $q_L^i = q_M^i(1-\lambda^i)$. Players i's co-state equation is:

$$\dot{\lambda}^i - r\lambda^i = \frac{\partial \mathcal{H}_L^i}{\partial T} \Rightarrow \begin{cases} \dot{\lambda}^c = (r+b-d+s)\lambda^c - b \\ \dot{\lambda}^w = (r+b-d+s)\lambda^w + d \end{cases} \tag{21}$$

and the transversality condition is $\lim_{t\to\infty} \mathrm{e}^{-rt}\lambda^i(t)T_L(t) = 0$. Setting $\dot{\lambda}^i = 0$ in Equation (21), we find

$$\begin{cases} \lambda^c = \frac{b}{r+b-d+s} > 0 \\ \lambda^w = \frac{-d}{r+b-d+s} < 0 \end{cases} \tag{22}$$

The players only consider their own private value: Global warming is good for the cold region and bad for the warm region. Reciprocally, mitigation by the cold region exerts a positive externality on the warm region, where mitigation exerts a negative externality on the former. The social value of the stock is the sum of private values: $\lambda^c + \lambda^w = \lambda$. This leads to the following mitigation efforts:

$$\begin{cases} q_L^c = q_M^c \left(\frac{r-d+s}{r+b-d+s}\right) \\ q_L^w = q_M^w \left(\frac{r+b+s}{r+b-d+s}\right) \end{cases} \tag{23}$$

Unlike q_L^w, q_L^c is not necessarily interior. This is the case if and only if $d < r + s$. In other words, if the damages to the warm region are larger than the discounted value of natural absorption, then the cold region will expect so much mitigation from the warm one that mitigation will be set at minimum in the cold region. Given the stability condition, $r > b$ is a sufficient condition for q_L^c to be interior.

Setting $\dot{T} = 0$, the steady-state temperature is:

$$T_L^{\infty} = \frac{2\epsilon - (\alpha^c(1-\lambda^c)q_M^c + \alpha^w(1-\lambda^w)q_M^w)}{b-d+s} \tag{24}$$

By a reasoning similar to that of the social optimum, the co-state variables and mitigation efforts are stationary. The warming trajectory is $T_L(t) = T_L^{\infty} - (T_L^{\infty} - T^0)\mathrm{e}^{-(b-d+s)t}$ and the present-value social cost is:

$$\Gamma_L = \frac{\alpha^c q_M^c (1-\lambda^c)^2 + \alpha^w q_M^w (1-\lambda^w)^2}{2r} + \frac{(r+s)(b-d+s)}{r(r+b-d+s)} T_L^{\infty} + \frac{d-b}{r+b-d+s} T^0 \tag{25}$$

5. Comparative analysis of equilibria

We derive a set of propositions that shed light on the trade-offs between global warming and economic efficiency under different information structures and different regimes of public bads. We assume that all conditions for interior solutions are satisfied.

5.1. Mitigation

First off, note that the relative magnitude of q_M^i depends on on the impacts faced by the players.

$$\text{If } d > b \text{ then } \begin{cases} q_L^c < q_M^c < q_S^c \\ q_M^w < q_S^w < q_L^w \end{cases} \tag{26}$$

$$\text{If } d = b \text{ then } \begin{cases} q_L^c < & q_M^c = q_S^c \\ & q_M^w = q_S^w < q_L^w \end{cases} \tag{27}$$

Both regions under-mitigate when they are myopic. In addition, mitigation is smaller than socially optimal in the cold region – which we refer to as free-riding – and larger than socially optimal in the warm region – which we refer to as free-driving.

5.2. **Global warming**

It is clear from Equations (6) and (16) that:

$$\begin{cases} T_M^\infty > T_S^\infty \text{ if } d > b \\ T_M^\infty = T_S^\infty \text{ if } d = b \end{cases} \tag{28}$$

Defining μ such that

$$\mu \equiv \frac{\alpha^c q_M^c}{\alpha^w q_M^w} = \frac{\gamma^w}{\gamma^c}\left(\frac{\alpha^c}{\alpha^w}\right)^2 \tag{29}$$

we have from Equations (16) and (24):

$$\begin{cases} T_L^\infty > T_S^\infty \text{ if } d < b/\mu \\ T_L^\infty = T_S^\infty \text{ if } d = b/\mu \\ T_L^\infty < T_S^\infty \text{ if } d > b/\mu \end{cases} \tag{30}$$

Comparing Equations (6) and (16), we have

$$\begin{cases} T_L^\infty > T_M^\infty \text{ if } d < b\mu \\ T_L^\infty = T_M^\infty \text{ if } d = b\mu \\ T_L^\infty < T_M^\infty \text{ if } d > b\mu \end{cases} \tag{31}$$

5.3. **Economic efficiency**

To display the results in an intuitive way, we consider efficiency – the opposite of cost Γ – which we rank using ordinal preference relations such that $A \succsim B$ is equivalent to $\Gamma_A \leq \Gamma_B$.

Comparing Equations 19), (25) and (8) allows us to verify that by construction, the social optimum is better than non-cooperative equilibria:

$$S \succ M \text{ and } S \succ L \tag{32}$$

Moreover, working out Equations (25) and (8), the comparison between equilibria L and M again depends on μ:

$$\begin{cases} L \succ M \text{ if } b \leq d < b(1+\mu+\sqrt{1+\mu+\mu^2}) \\ L \sim M \text{ if } d = b(1+\mu+\sqrt{1+\mu+\mu^2}) \\ L \prec M \text{ if } d > b(1+\mu+\sqrt{1+\mu+\mu^2}) \end{cases} \tag{33}$$

6. **Policy**

We now turn to policies that could be used to correct the economic distortions associated with the global public bad. The occurrence of externalities naturally calls for Pigouvian incentives, the design of which is specific to the non-cooperative equilibrium considered as *laissez faire*.

Forward-looking non-cooperative strategies can be seen as bilateral agreements or pledges, which, if political or institutional constraints prevent introduction of optimal incentives, can still be seen as a second-best, non-market approach like those promoted in the Paris Agreement (Article 6, paragraph 8).

6.1. **Bilateral agreements**

The economic efficiency and environmental effectiveness of pledges or bilateral agreements depends on the public-bad regime considered, that is, the relative heterogeneity of impacts vs. mitigation capabilities. As illustrated in Figures **??** and **??**, five domains arise from the previous Section.

When damages are relatively high (Domain i), the warming level and economic efficiency of the forward-looking equilibrium L_i is intermediate. When mitigation costs are, in addition, lower in the losing region, free-driving is exacerbated, leading to too much aggregate mitigation, hence too little warming (Domains ii and iii, L_{ii} and L_{iii}). When mitigation turns out cheaper in the gaining region, free-driving is reduced, which leads to too little mitigation, hence too much warming (Domains iv and v, L_{iv} and L_v)

6.2. **First-best intervention: Pigouvian incentives**

We suppose that the externalities generated by energy use or GHG emissions are internalized through Pigouvian incentives τ^i imposed on each player i in proportion to the GHG-intensity of their energy use. The incentives are assumed to be funded (for subsidies $\tau^i < 0$) or rebated (for taxes $\tau^i > 0$) in a lump-sum manner. Optimal values of the τs would be set by the social planner by backward induction in a two-stage game: In the second stage, the players respond optimally to a given τ; in the first stage, the planner seeks the values of the τs that maximize social welfare (that is, minimize total cost).

The second stage is equivalent to solving the same private optimization programs as in Section 4, only with the objective functions modified as follows: $e^i(q^i, T)(1 + \tau^i) + m(q^i)$. Let ρ^i_k be the new co-state variable to player i associated with each equilibrium concept $k \in \{M, L\}$. The new first-order condition for privately optimal mitigation is:

$$(q^i_k)_{\text{after incentive}} = 1 + \tau^i_k - \rho^i_k \tag{34}$$

and the steady-state value of the co-state variables (with the λs defined in Section 4):

$$\rho^i_k = (1 + \tau^i_k)\lambda^i_k \tag{35}$$

In the first stage, the planner minimizes the sum of the modified cost functions, subject to temperature increase. This leads to socially optimal mitigation efforts $q = 1 - \lambda_S$. Matching this with the $(q^i_k)_{\text{after incentive}}$ defined in Equation (34) provides optimal incentive rates:

$$\tau^i_k = \frac{\lambda^i_k - \lambda}{1 - \lambda^i_k} \tag{36}$$

Myopic players. Since $\lambda_M^i = 0$, the optimal incentive is the same to both players: $\tau = -\lambda > 0$. Since the players neither internalize their nor their competitor's actions, it is as if there were one global negative externality equal to the aggregate damage which should be internalized through a uniform tax on GHG emissions.

Forward-looking players. The players internalize the consequence of their actions on themselves, but not that on the other player. If the players are asymmetric, energy use in the cold region exerts a negative externality on the warm region. The resulting incentives are:

$$\begin{cases} \tau^c = \frac{d}{r-d+s} > 0 \\ \tau^w = \frac{-b}{r+b+s} < 0 \end{cases} \tag{37}$$

Note that $| \tau^c | > | \tau^w |$. The gaining region should be imposed a relatively large tax on emissions while the losing region should receive a relatively small subsidy.

Our results are at odds with the textbook recommendation of a uniform tax to internalize the global negative externality. This is simply because unless players are myopic, we have in fact several externalities. Rather, our model emphasizes that as soon as the impacts of global warming differ across strategic, forward-looking countries, a rationale exists for differentiating incentives.

7. Conclusion

We propose an extension of the concept of dynamic public goods. In the canonical model, impacts on the well-being of contributors are assumed to be uniform, which gives rise to free-riding, that is, under-provision. Accounting for asymmetry in impacts, adaptation and mitigation, we argue that free-riding is in fact counterbalanced by free-driving, which brings trade-offs between aggregate contribution and economic efficiency. The trade-offs depend on the relative heterogeneity of adaptation and mitigation technologies across players.

Together with other refinements of public-good concepts, such as Kotchen (2005)'s *impure* public goods and Nordhaus (2015)'s climate *clubs*, our *asymmetric* conceptualization contributes to a richer understanding of global warming due to anthropogenic GHG emissions. We address this dynamic, globally harmful but spatially-differentiated problem in a differential-game model. A central element of the model is the notion of adaptive mitigation, that is, mitigation of GHG emissions under perfect adaptation to global warming.

This refers to the idea that at least in some economic sectors such as building energy use or agriculture, there can be spatial asymmetries in the GHG-intensity of adaptation. For instance, warming may decrease GHG emissions in temperate zones (e.g., due to reduced space heating) but increase them in tropical ones (e.g., due to increased air conditioning). We consider two players, a setting relevant to large and asymmetrically vulnerable regions, for instance Russia and India.

We compare Pigouvian incentives to internalize free-riding and free-driving under different information structures. We consider myopic, reminiscent of a Pre-Kyoto regime, and forward-looking players, interpreted as the prevailing pledge system. We find the comparison to depend on the public-bad regime considered. Unless players are myopic, the occurrence of multiple externalities justifies differentiated incentives, namely large taxes to internalize free-riding and small subsidies to internalize free-driving.

Our model trades off simplicity against complexity. Its structure is general enough to encompass the prevailing *uniform* model. It is parsimonious enough to enable us to derive closed-form solutions of mitigation, global warming and intertemporal efficiency. Such easing comes at the cost of strong assumptions – not the least being a deterministic and linear specification of impacts – which matter all the more that differential games are known to be highly sensitive to specifications. Nonetheless, our goal is to focus on basic features which remain unexplored in the global warming context, namely asymmetries in players' characteristics.

Our contribution to global-warming policy is two-fold. First, climatic asymmetries are known to largely explain global wealth inequalities (Mendelsohn et al., 2006; Hsiang and Meng, 2015), which in turn justify the use of equity weights in economic assessments (Azar, 1999; Anthoff et al., 2009). We stress that even prior to raising equity concerns, climatic asymmetries affect overall efficiency. Second, against the textbook argument of a uniform Pigouvian incentive we note that partial internalization of the global externality by large strategic players provides a rationale for differentiating incentives.

We see several interesting extensions to our model. From a technical perspective, incorporating accumulation of mitigation capital would provide richer insights into the dynamic aspects of mitigation and adaptation. From a public policy perspective, it would also be worth studying how the asymmetric public bad problem may interact with other market failures associated with mitigation (e.g., the co-benefits discussed by (Parry et al., 2015)) and adaptation. , or the development of the climate monitoring platform.

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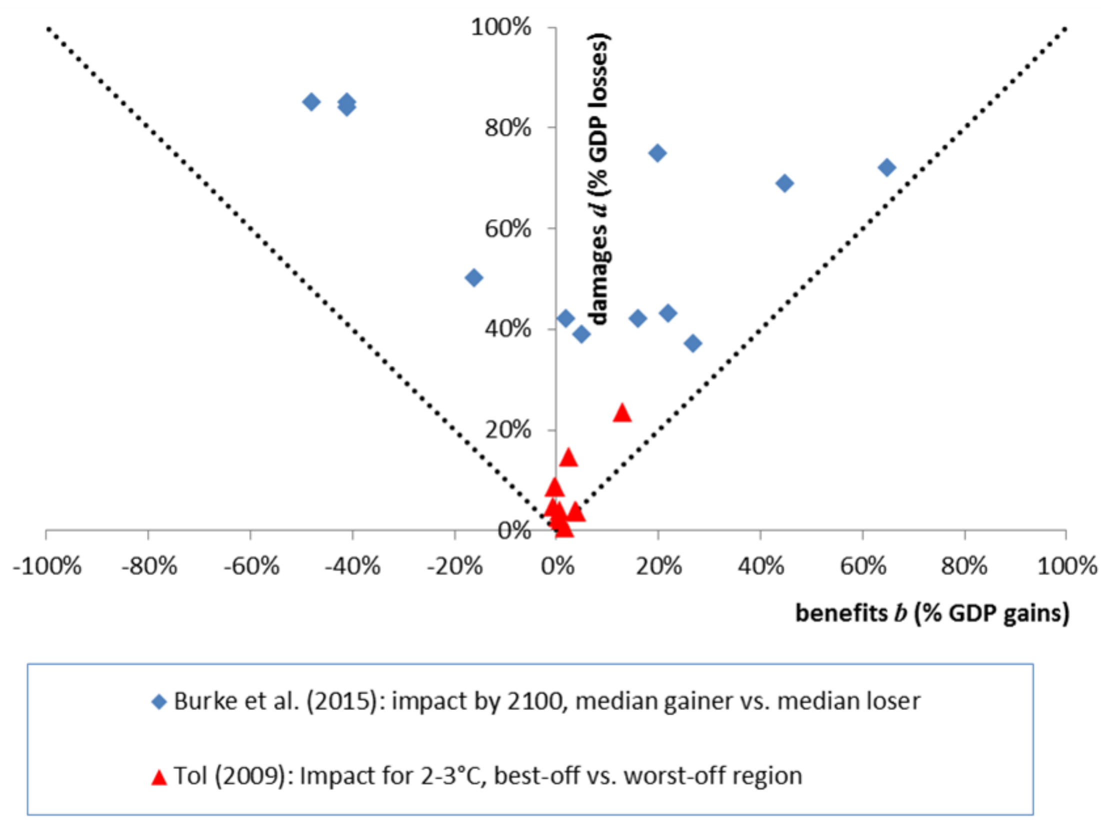

FIGURE 1. **Projections of global warming impacts.** Each dot is a pair of impact estimate to a representative 'gainer' and a representative 'loser,' from two datasets. The red-triangle data come from Tol (2009), Table 1, p.31. Estimates come from 13 integrated assessments performed between 1993 and 2006. Impacts are calculated in % of GDP, for levels of warming ranging from 1.0 to 3.0°C. The gainer and loser considered here are the best-off and worst-off region of each assessment. The blue-diamond data come from Burke et al. (2015), Extended Data Table 3. The 12 estimates result from simulations using four different models and three different scenarios based on RCP8.5. Impacts are calculated in % of GDP by 2100. The gainer and loser considered here are respectively the 75th and 25th percentiles of the impact distribution.

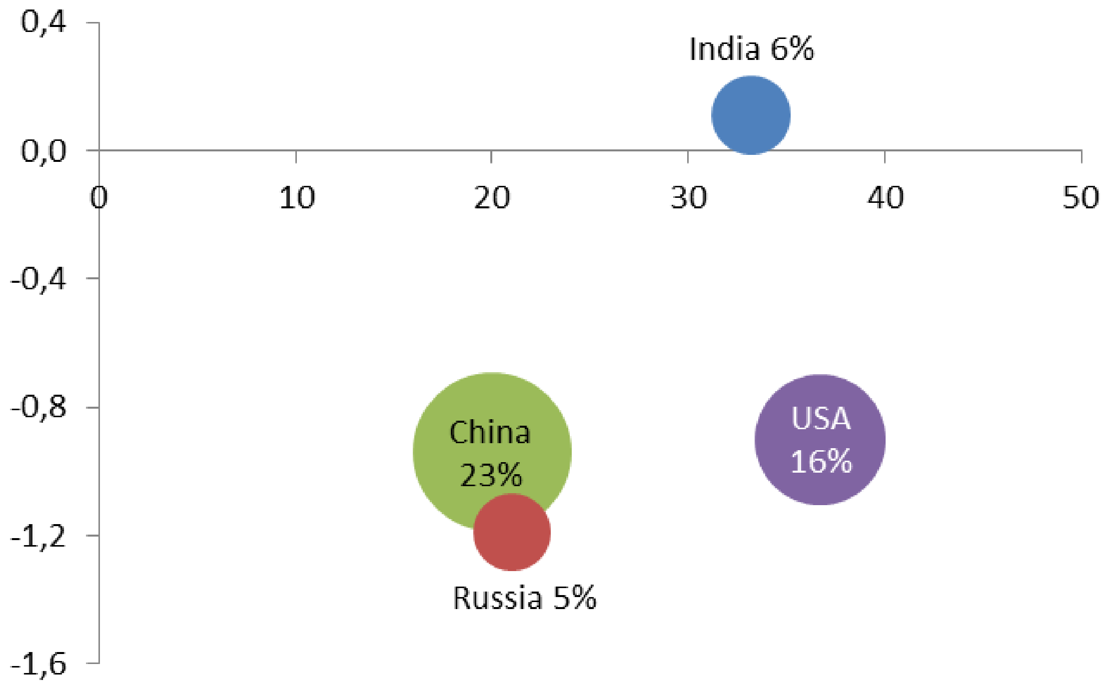

Figure 2. **Adaptation and mitigation capabilities of the four biggest GHG emitters.** Vulnerability data on the y-axis comes from Samson et al. (2011). Abatement cost parameters come from Nordhaus (2015). The size of the circle, representing the share of countries' GHG emissions come from **?**.

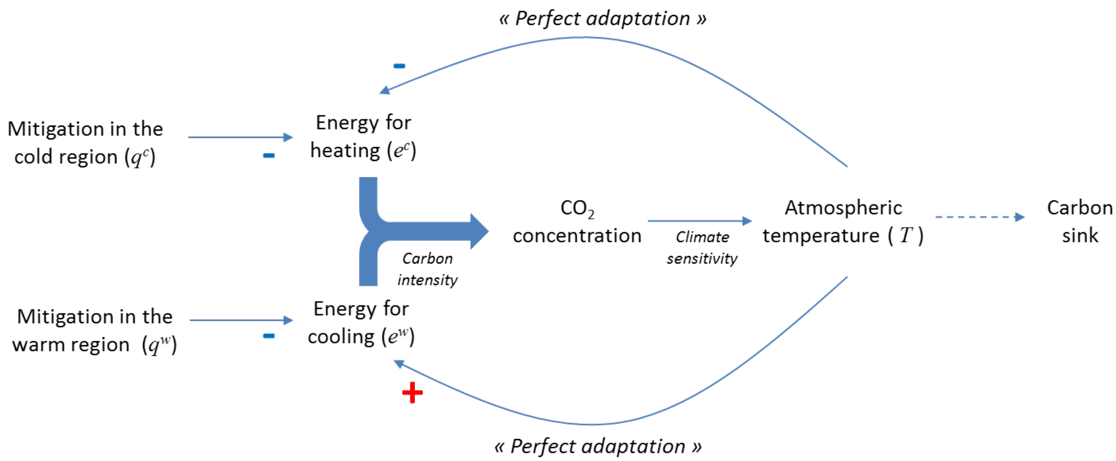

FIGURE 3. **Schematic view of the model.** The (−) and (+) signs represent negative and positive retroactions, respectively. Thick arrows denote accumulation. The dashed arrow denotes system outflow.

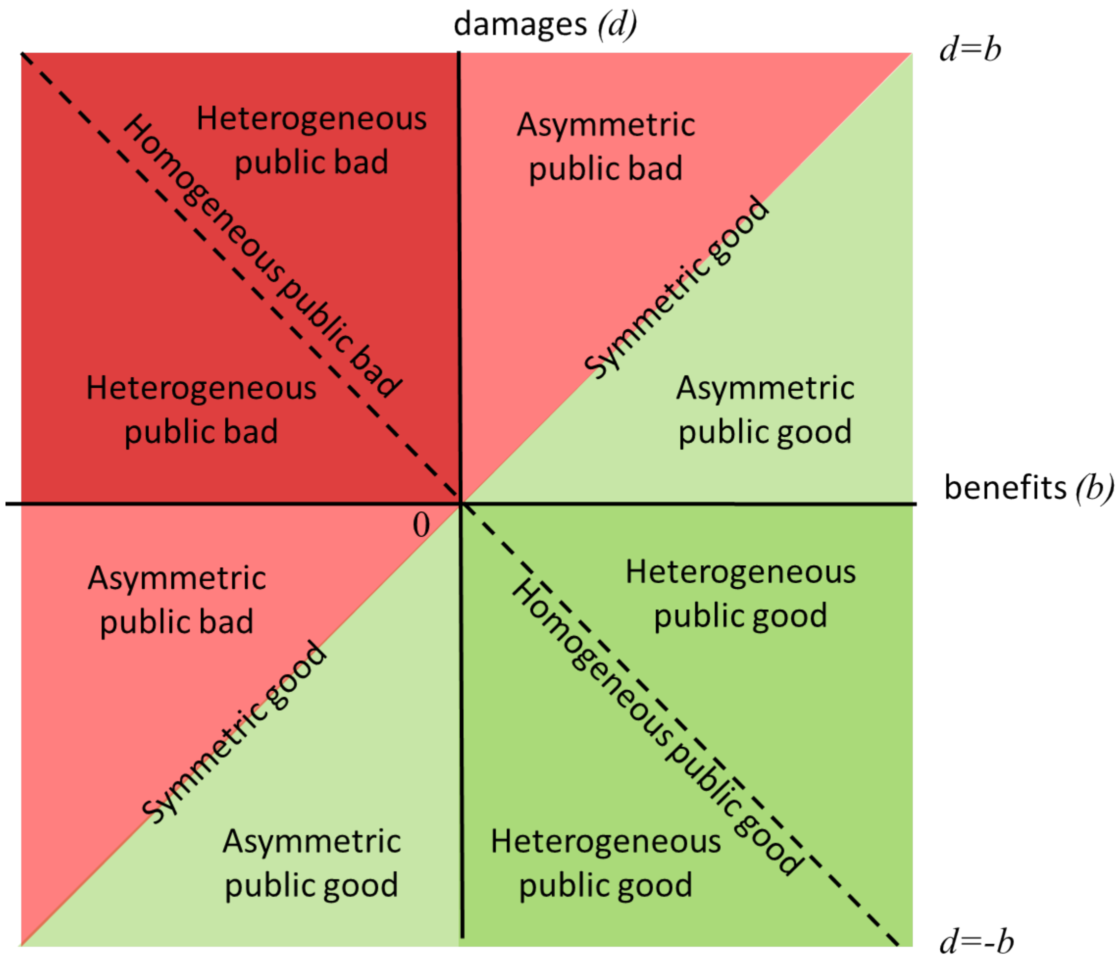

Figure 4. **Taxonomy of public-good regimes.** This depicts the regimes defined in Section 3.2. In the paper, we focus on public bads, hence the red semi-plane. Moreover, since $d = -b$ is a symmetry axis, we further focus on the Northern corner, where $d \geq | b |$. This corner covers most of the projection estimates displayed in Figure 1. Note that existing differential-game models of global warming tend to focus on the dark red region (uniform, i.e., homogeneous and heterogeneous, public bads).

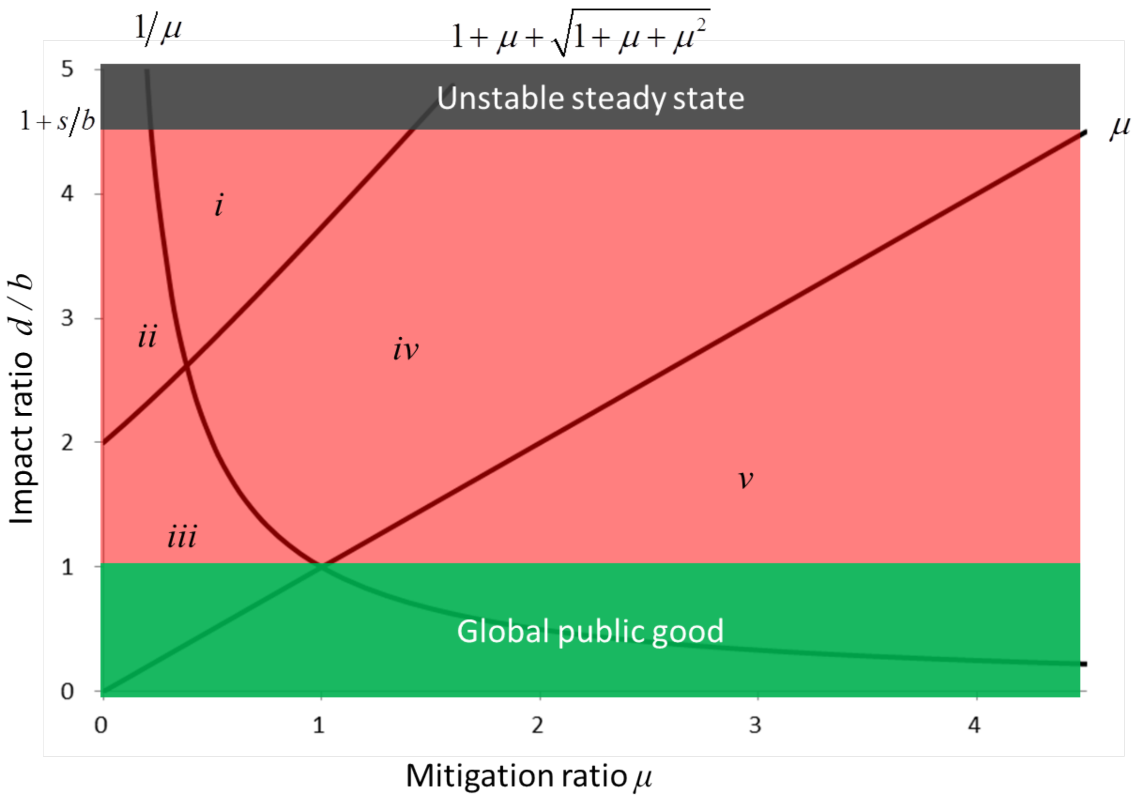

Figure 5. **Public-bad regimes.**

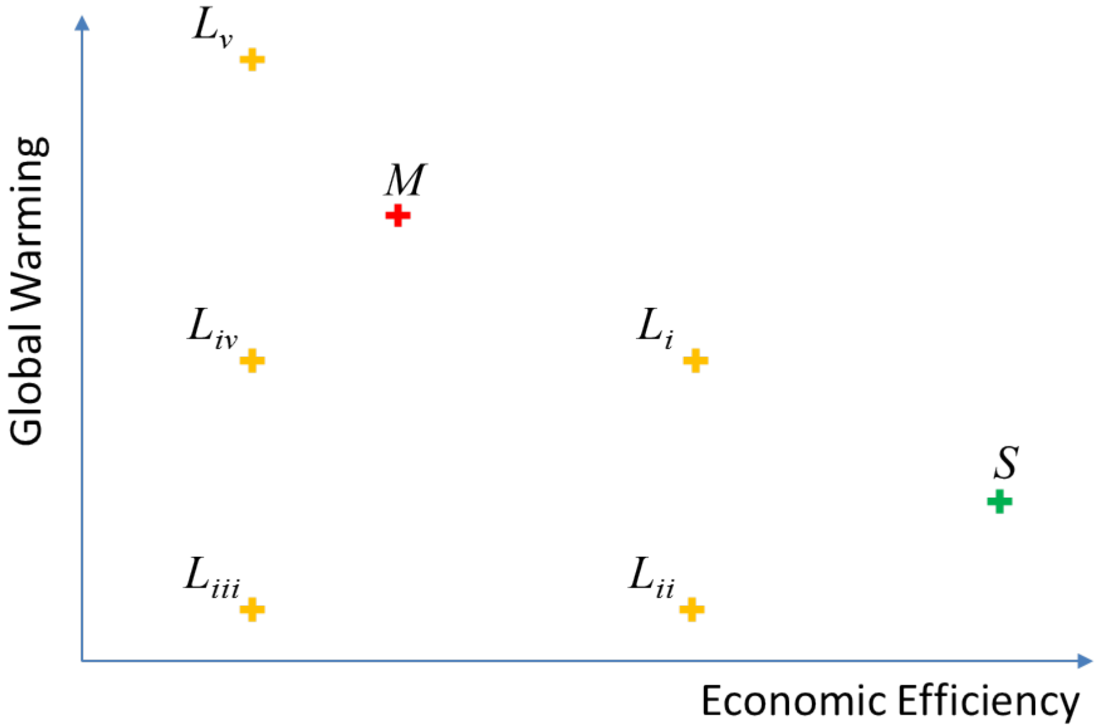

FIGURE 6. **Trade-offs between global warming and economic efficiency under the different public-bad regimes.**