Modeling of mitigation and adaptation: competition vs cooperation

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Abstract

We formulate and study a nonlinear game of *n* symmetric countries that produce, pollute, and spend parts of their revenue on pollution mitigation and environmental adaptation actions. Modeling assumptions and obtained analytic outcomes are discussed and compared to other works in this fast-developing area of environmental economics. Both competitive (Nash equilibrium) and cooperative solutions are investigated with a focus on asymptotic analysis of the optimal adaptation and mitigation investments. New financial and policy implications are exposed and debated.

Keywords: Environmental Adaptation; Pollution Mitigation; Nash equilibrium

1. Introduction

Complexity and challenges of climate financing have attracted significant attention in economic-environmental research (Eyckmans et al. 2016, Pittel and Rübbelke 2015). The global climate finance includes a variety of players, most notably, individual countries, for which one of relevant policies is to determine a rational mix of financial investments into mitigation and adaptation. It requires achieving cooperation among countries with diverse interests in managing complex global problems. The climate financing system is

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a part of climate change management that includes technology transfers, investment in clean technologies and renewable energy sources, governance, and adaptation to climate change. Analytic modeling of green climate finance is useful to explore relationships between international and domestic climate policies (Brechet et al, 2016). Integration of domestic policies into global climate financing in our multi-country world is challenging. 2015 Paris Climate Conference emphasized the importance of financial cooperation among countries, highlighting the role of adaptation and need for international transfers.

The present paper highlights challenges in global climate financing and applies a simple game-based analytic framework to analyze environment-related investments in a multi-country world.

Literature Survey

The continuing contamination of the environment is a modern face of the classic *commons dilemma* that has been discussed since 16th century (Agricola, 1556). The commons dilemma, also known as the *tragedy of the commons*, occurs when individuals follow their self-interests that can result in the exhaustion of a common public resource such as land, fish, forest, or the environment (Lloyd 1883, Hardin 1968). As Lloyd (1883) stated, "if all herders made individually rational economic decisions, the commons (land) could be depleted or even destroyed". Hardin (1968) pioneered in the analysis of the negative commons of global environmental pollution and depletion of natural resources (atmosphere and oceans). Ostrom et al. (1999) demonstrated that local solutions can help to avoid the global tragedy of the commons.

Accurate assessment of effective environmental policies and actions has been a subject of intensive research for last forty years, which includes analytic models (Smulders and Gradus 1996, Argawala et al 2011) and computer simulation methods, known as the integrated assessment models, *IAMs* (De Bruin et al 2009, Bahn et al 2019). Analytic models allow for better understanding of observed environmental changes and contribute to the improvement of computer simulation methods.

Major financial avenues to combat climate change on national and international levels include investments in pollution mitigation and environmental adaptation, alongside with related international transfers among countries. The environment, pollution and

mitigation are public goods, while the production output and adaptation are private, i.e., specific to individual countries. The number of related papers has grown fast, but all of them make simplifying assumptions about pollution, mitigation, and adaptation (Benchekroun and Taherthani 2014, Bréchet et al 2013, 2016, Breton et al 2006, Breton and Sbragia 2017, Buob and Stephan 2011, Ebert and Welsch 2012, Eyland and Zaccour 2014, Farnham and Kennedy 2015, , Felgenhauer and Webster 2013, Jørgensen et al 2010, Hritonenko and Yatsenko 2013, Le Kama and Pommeret 2017, Nozawa et al 2018, Zemel 2015, and many others).

A short survey below demonstrates the growing number of related analytic models with scattered underlying assumptions and fragile links among various models and their outcomes. The adaptation-mitigation models can be deterministic or stochastic, static or dynamic, in continuous or discrete time (including two- or three-stage versions). Corresponding optimization problems involve one or several objectives and one or many players (Fankhauser 2017). The optimization models with several players reflect the international context of the environmental protection and lead to static or dynamic games. Multi-country models commonly restrict their analysis to a symmetric case of identical countries (Breton et al 2006, Yatsenko 2015, Bréchet et al 2016, Breton and Sbragia 2017, Farnham and Kennedy 2015).

Two strategies, cooperative and non-cooperative, are commonly considered in a multi-country world, see, e.g., Benchekroun and Taherthani (2014), Breton et al. (2006), Farnham and Kennedy (2015), Felgenhauer and Webster (2013), Eyland and Zaccour (2014), Bréchet et al. (2016). Each country makes its own financial decisions in a case of the *non-cooperative strategy*, while the *cooperative* social planner assumes an international environmental agreement in force. Bréchet et al. (2016) show that the non-cooperative strategy in a *symmetric world* leads to over-pollution, over-production, over-consumption, and over-adaptation. Similar qualitative results have been earlier obtained by Buob and Stephan (2011).

Economic-environmental models usually assume the objective of maximizing a payoff function that equals a country's revenue less environmental damages. Game theory traditionally uses linear or quadratic payoffs and costs. Breton et al. (2006) analyze a static game of n countries with quadratic mitigation cost and linear pollution

damage. The players can invest into adaptation at home and abroad, which can provide lower adaptation costs. The authors demonstrate the advantages of joint implementation of adaptation and mitigation. Benchekroun and Taherthani (2014) study cooperative and Nash cases of a dynamic game of *n* identical countries, which includes adaptation but not mitigation investments. Payoff and adaptation costs are quadratic in emission while the pollution damage function is linear in global emissions. The authors show that adaptation in one country leads to lower mitigation and reduces welfare in the other countries. Eyland and Zaccour (2014) analyze a two-level two-player asymmetric dynamic game (with no mitigation) where one player is non-vulnerable to pollution.

While adaptation was recently criticized, *mitigation* and *adaptation* are recognized as two key instruments to cope with climate change (Mendelsohn 2012). Mathematical descriptions of mitigation and adaptation processes vary significantly in contemporary models (Burke et al 2016). As a result, different modeling assumptions lead to different altered conclusions and recommendations. For instance, Ebert and Welsch (2012) study a two-country static game with endogenous production, pollution emissions, and adaptation, but do not explicitly model mitigation expenditures. They conclude that larger productivity and larger adaptive capacity lead to larger emissions in both cases of non-cooperative behavior and full cooperation. Bréchet et al. (2016) model two symmetric countries in a dynamic infinite-horizon optimization framework with flow mitigation, stock adaptation, and exponential efficiency of adaptation and prove that the global pollution and size of economy are always larger in the competitive scenario than under cooperation. They conclude that the lack of cooperation leads to a too fat global economy where pollution is too high as well as the output, capital and consumption.

This paper focuses on optimal balancing of adaptation and mitigation. To reduce modeling complexity, the majority of analytic games with adaptation do not involve a separate variable for mitigation effort and treat mitigation as a reduction in emission, see (Ebert and Welsch (2012), Felgenhauer and Webster (2013), Zemel (2015) and many others. Two-stage dynamic games of (Buob and Stephan 2011, 2013) analyze both adaptation and mitigation but ignore endogenous production. A two-country static game of (Ebert and Welsch (2012) considers endogenous production, pollution, and adaptation, but oversimplifies mitigation considering it as a reduced emission. Felgenhauer and

Webster (2013) and Zemel (2015) study dynamic optimization with uncertain damage but oversimply mitigation. The models of (Brechet et al 2013), Hritonenko and Yatsenko (2016 ema), Zemel (2015), Felgenhauer and Webster (2013) scrupulously analyze mitigation and adaptation actions in one country ignoring the international aspect of the problem.

Building multi-country models for policy support is an enormously difficult scientific task. Functional specifications of pollution mitigation, environmental adaptation, and international transfers should reflect realistic assumptions, but the models must remain analytically tractable. To meet those demands, researchers have tried a variety of assumptions and functional presentations of involved processes. In fact, in their efforts to reduce modeling complexity, many analytic games with adaptation do not include a separate model for mitigation processes. In particular, mitigation is treated as a reduced emission in Ebert and Welsch (2012), Felgenhauer and Webster (2013), Zemel (2015), and other similar studies.

A static game of (Legras and Zaccour 2011) and a dynamic game of (Benchekroun and Chaudhuri 2014) include separate endogenous mitigation variable, but do not consider adaptation. Benchekroun and Taherkhani (2014) analyzed a static game of *n* countries with pollution and adaptation but does not explicitly model mitigation. Several studies focus on possible coalitions in environmental protection, including adaptation and mitigation, e.g., (Benchekroun and Taherthani 2014, Breton 2017) evaluate the impact of strategic commitment in a model with *n* symmetric countries.

Farnham and Kennedy (2015) consider a static game of several countries with linear adaptation, mitigation, and damage, and quadratic costs. They conclude that the non-cooperative optimal adaptation can be welfare-reducing for small economies. Buob and Stephan (2011) consider a linear relationship between output and mitigation and adaptation, and inverse relationship between adaptation and global mitigation. A restrictive modeling assumption is that the regions' incomes (products) are exogenously given. A nonlinear modification of this model is in (Boub and Stephan 2013). The regions' incomes (outputs) are assumed to be given.

Breton and Sbragia (2017) study strategic commitment scenarios in a stylized model with *n* symmetric countries, each of which uses controlled mitigation and adaptation with

quadratic costs to minimize the environmental damage from total pollution. Two groups of countries, cooperating and individualistic, are distinguished, and various cooperation and leadership scenarios are analyzed. Both mitigation and adaptation linearly decrease the environmental damage as in (Buob and Stephan 2011).

Schumacher (2019) offers a sophisticated dynamic model of two competitive regions (North and South) with endogenous production, mitigation, adaptation, utility, and human capital. The model includes a controlled North-to-South financial transfer to enhance the South adaptation (however, the model does not allow adaptation investment to North itself). It is shown that such transfers may decrease the global pollution in long run. Using this model, the author argues that the adaptation always leads to a significant loss of global welfare and, therefore, is never optimal.

In a one-country dynamic optimization model with uncertainty of (Zemel 2015), the uncertain damage is reduced by the stock adaptation. Felgenhauer and Webster (2013) study a one-country optimization problem with uncertainty that employs a nonlinear adaptation efficiency. Le Kama and Pommeret (2017) analyze a one-country dynamic model with a linear payoff and mitigation and adaptation as stock variables. To capture the global aspect of pollution and mitigation, their last model includes ad hoc emissions from the rest of the world and a separate mitigation investment abroad.

Recent papers (Roco et al 2014, Watkiss et al 2015, Eyckmans et al 2016, Bonen et al 2016, Duan et al 2018, Vardar and Zaccour 2018, Weiler et al 2018, Catalano et al 2020, Mavi 2020) use different modeling assumptions about payoff functions, pollution disutility/damage, and the effectiveness of mitigation and/or adaptation to analyze various economic, agricultural, political, and regional aspects of interactions among pollution, mitigation and adaptation. The survey (Hritonenko and Yatsenko 2022) emphasizes the importance of multi-disciplinary modeling of urban adaptation and mitigation in interaction with other areas of city planning and management.

International transfers refer to dedicated investment flows from one group of countries to the other, usually from developed countries to developing ones, to support their economic infrastructure and implement mitigation and adaptation in order to improve the global environment quality. Traditional North-South transfers to increase welfare and reduce poverty have been used for decades. Following IPCC (2014), the so-

called *conditional* transfers generate financial flows to reduce greenhouse gas emissions (mitigation transfers) and/or become climate-resilient (adaptation transfers). Conditional transfers have financial support from the Adaptation Fund established by the Kyoto Protocol.

Buob and Stephan (2013) significantly generalize their two-stage dynamic game model (Buob and Stephan 2011) with mitigation and adaptation adding a separate endogenous "North-to-South adaptation funding" control. The restrictive modeling assumption is that the regions' incomes (products) are exogenously given. They conclude that North-to-South financial transfers are economically feasible only when the adaptation and mitigation are complementary policy instruments, otherwise, North-to-South transfers could turn out to be ineffective.

Pittel and Rübbelke (2015) consider a static game with mitigation, adaptation, and international transfers in two, developing and industrialized, countries. The income (production output) of both countries is assumed to be given, and their utilities depend on consumption and global mitigation only. The industrialized country provides conditional financial transfers to match the adaptation effort in the developing country. The adaptation increases the consumption and affects the mitigation level in both countries. Their major outcome is that the profitability of adaptation transfers depends mostly on the strengths of substitution effects generated through the transfers. However, for simplicity, consumption and mitigation are both assumed to linearly depend on adaptation effort, which together with the assumption about given exogenous incomes make the model not quite realistic.

Eyckmans et al. (2016) discuss climate change related transfers from rich countries to poor countries and find that isolated transfers may reduce the actual adaptation effort because the South reallocates its own resources to achieve the adaptation/consumption balance it prefers. Only in the case of least-developed countries, which are unable to adapt fully due to financial constraints, the adaptation support leads to better climate resilience.

Hritonenko et al (2020) introduce a multi–country model with pollution mitigation and adaptation and provide its theoretic analysis. The model uses separate mitigation and adaptation investment controls. It focuses on asymptotic solutions for the optimal

emission, adaptation and mitigation investments. The static game framework is employed to obtain closed-form solutions, useful for policy analysis. Dynamic models of (Bréchet el al 2016) and (Sakamoto et al 2020) with endogenous production, mitigation, and adaptation are conceptually close but are restricted to two countries.

The paper is organized as follows. Section 2 describes modeling assumptions and compares them to other known models. Section 3 provides comparative analysis of the competitive (Nash equilibrium) and cooperative solutions, focusing on their asymptotic analysis. Section 4 discusses obtained outcomes and their policy implications.

2. Modeling Framework

We consider n countries, each of which produces an economic output q_i, emits pollution x_i and reduces the related damages using mitigation (y_i) and adaptation (z_i) investments. The model is based on the following assumptions.

2.1 Production, pollution, and mitigation

Industrial production generates pollution emissions that contaminate the environment. Many environmental games (Benchekroun and Ray Chaudhuri (2014), Breton and Sbragia (2016), and others) assume the pollution emission x_i to be proportional to the industrial output q_i as $q_i = A_i\, x_i\, f(y_i)$, where parameter A_i describes production cleanness and $f(y)$ is the effectiveness of mitigation investment y. This specification assumes that pollution can be reduced by mitigation efforts y, which reflect a wide spectrum of economic activities that decrease pollution intensity and, alternatively, allow producing more per one unit of pollution emission. The function $f(y)$ is increasing and concave, that is, $f(y) > 0,\ f(0) \geq 0,\ f' > 0,\ f'' < 0.$

Choosing the power function $f(y)$, Hritonenko and Yatsenko (2021) express the output q_i in terms of pollution x_i as

$$q_i = A_i x_i y_i^k, \tag{1}$$

where k, $0 < k < 1$, represents the marginal efficiency of the mitigation investment y_i. The variables q_i, x_i, and y_i are per capita. The mitigation actions are more effective at a larger k (and are not available at $k = 0$).

2.2 Environmental damage and adaptation

Pollution emissions are specific to a country. Still, each country's pollution accumulates in the global atmosphere and contributes to global warming. Pollution does not respect national borders and impacts all regions, but each region has its own pollution vulnerability. Consequently, the environmental damage of a specific region (country) depends on the aggregate emissions $X = \sum_{i=1}^{n} x_i$, where n is the number of countries.

The monetary damage from this global pollution is usually described by the function $\Omega_i = B_i X^{\mu}$, where $\mu > 0$, the *vulnerability parameter* B_j is region-specific and depends on a country's geography, stage of development, infrastructures, and so on.. Such an approach has been considered in many models with adaptation, e.g., in Smulders and Gradus (1996), Benchekroun and Taherthani (2014), Bréchet et al. (2016). For clarity, we will assume the quadratic environmental damage with $\mu = 2$, which is a typical case in the literature and possesses properties similar to the more general $\mu > 1$ case.

In reality, the vulnerability factor B can be reduced by adaptation activities z_i: $B_i = B_i(z_i)$ with $B_i' < 0, B_i'' > 0$. Thus, adaptation-related integrated assessment models (Bosello et al. 2010) empirically estimate and implement the nonlinear adaptation efficiency function $B(z) = 1/(1 + az)$, where $a>0$ is the marginal efficiency of adaptation z. Hritonenko and Yatsenko (2015) generalize this function to $1/(1 + az) + d$ with adding the *unavoidable environmental damage* $d > 0$. It means that, even after implementing all adaptation measures, there still exist some damages that cannot be avoided. Utilizing this approach, the environmental damage $\Omega_i = B_i X^2$ to the country i can be reduced by the country's adaptation spending z_i (in financial units) as

$$\Omega_i = B_i \left(\frac{1}{1+a_i z_i} + D_i\right)\left(\sum_{i=1}^{n} x_i\right)^2, \tag{2}$$

In (2), $B_i > 0$ describes the country vulnerability to environmental damage (in monetary units), $a_i > 0$ is the efficiency of adaptation, and $D_i > 0$ is the residual non-avoidable damage in the country. The adaptation is not possible at $a_i = 0$. Concave effectiveness functions of mitigation y_i in (1) and adaptation z_i in (2) are in line with the most of related studies (Vellinga 1999, Jones and Manuelli 2001, Agrawala et al. 2011, Hall et al. 2012, Hritonenko & Yatsenko 2013, 2016, 2019).

2.3 Individual consumption, utility, and welfare

The individual consumption is the difference $c_i = q_i - y_i - z_i$ between the output and mitigation and adaptation investments. The objective of country i is to maximize the individual welfare, measured by the difference between the consumption utility ${c_i}^{1-\eta}$ and the monetarized disutility (2) of environmental damages:

$$F(q_i, x_i, y_i, z_i) = (q_i - y_i - z_i)^{1-\eta} - B_i \left(\frac{1}{1+a_i z_i} + D_i\right)\left(\sum_{j=1}^{n} x_j\right)^2 . \qquad (3)$$

The objective function (3) uses the standard economic CRRA utility function ${c_i}^{1-\eta}$ with the *risk aversion parameter* $0 < \eta < 1$ (Smulders and Gradus 1996) rather than quadratic payoff functions of game theory (Breton 2016, Legras and Zaccour (2011), Benchekroun and Taherkhani (2014)),

The model (1)-(3) provides a simple framework for the ongoing policy debate about rational mix of financial investments into pollution mitigation and environmental adaptation. Its three control variables x_i, y_i, and z_i describe output/pollution intensity, mitigation effort, and adaptation effort of each country.

2.4 Competition and cooperation

In accordance with other research, we analyze two cases, competitive and cooperative. In the competitive case, all countries compete and each country i, $1 \leq i \leq n$, maximizes its own payoff by taking strategies of other countries as given. The *competitive game* with the payoff (3) is described as

$$\max_{x_i, y_i, z_i} \quad F_N(x_i, y_i, z_i) = (A_i x_i {y_i}^k - y_i - z_i)^{1-\eta} - B_i \left(\frac{1}{1+a_i z_i} + D_i\right)\left(\sum_{j=1}^{n} x_j\right)^2, \qquad (4)$$

for each $i = 1,\ldots,n$. A solution $x_i \geq 0$, $y_i \geq 0$, and $z_i \geq 0$, $i = 1,\ldots, n$, of the static game (4), if it exists, represents the *Nash equilibrium* (Fankhauser 2017).

The *cooperative case* maximizes the total payoff of all countries in the ideal case of a global environmental agreement and is described by the following optimization problem:

$$\max_{x_i, y_i, z_i, i=1,\ldots,n} F_c = \sum_{i=1}^{n} \left[(A_i x_i {y_i}^k - y_i - z_i)^{1-\eta} - B_i \left(\frac{1}{1+a_i z_i} + D_i\right)\left(\sum_{j=1}^{n} x_j\right)^2\right]. \qquad (5)$$

This problem also has $3n$ unknown variables: $x_i \geq 0$, $y_i \geq 0$, and $z_i \geq 0$, for $i = 1,\ldots, n$.

We restrict ourselves to the symmetric case of n identical countries:

$$A_i = A,\ a_i = a,\ D_i = D,\ B_i = B, \quad i = 1, \ldots, n. \tag{6}$$

which is a common assumption in environmental games (Legras and Zaccour 2011, Benchekroun and Chaudhuri 2014, Breton 2016, and others). Under conditions (6), the optimal pollution x_i, mitigation y_i, and adaptation z_i in both problems (4) and (5) are the same for all countries. We denote the solution of the competitive game (4) as (x_N, y_N, z_N) and the solution of the cooperative problem (5) as (x_C, y_C, z_C).

3. Results: Comparative Analysis of Competition and Cooperation

In this section, we investigate and compare analytic properties of the competitive game (4) and cooperative problem (5). In our analysis, we emphasize the asymptotic of competitive and cooperative strategies when the number of countries is large. To get the first glance on optimal investment strategies in the nonlinear optimization problems (4) and (5), we start qualitative analysis with a business-*as-usual* case that does not involve adaptation, mitigation, or international transfer. The only policy instrument in this case is rational balancing between economic effectiveness and environmental damage to achieve a feasible strategy.

3.1 Competition vs Cooperation: business-as-usual case

Let ***k* = 0, *a* = 0 (***no adaptation*** and ***no mitigation*****).** Then, the competitive game (4)

$$\max_{x_i} \quad \tilde{\tilde{F}}_N(x_i) = (Ax_i)^{1-\eta} - B(1+D)\left(\sum_{i=1}^{n} x_i\right)^2 \text{ for all } i = 1,\ldots, n\,. \tag{7}$$

does not include the mitigation and adaptation controls y_i and z_i. The only control in (7) is the pollution level x_i, which also defines the economic output (1). Differentiating (7) in x_i, setting the derivative to zero, and using the symmetry assumption (6), we obtain the Nash equilibrium solution as

$$\tilde{\tilde{e}}_N = \left[\frac{(1-\eta)A^{1-\eta}}{2B(1+D)n}\right]^{1/(1+\eta)}, \tag{8}$$

$$\tilde{\tilde{F}}_N = \left(1 - \frac{n}{2}(1-\eta)\right) A^{1-\eta} \tilde{\tilde{x}}_N{}^{1-\eta} = \left(1 - \frac{n}{2}(1-\eta)\right)\left[\frac{(1-\eta)A^2}{2Bn(1+D)}\right]^{(1-\eta)/(1+\eta)}. \tag{9}$$

The solution of the cooperative problem (5) is

$$\tilde{\tilde{x}}_C = \left[\frac{(1-\eta)A^{1-\eta}}{2B(1+D)n^2}\right]^{1/(1+\eta)}, \tag{10}$$

$$\tilde{\tilde{F}}_C = \frac{1+\eta}{2} A^{1-\eta} \tilde{\tilde{x}}_C{}^{(1-\eta)} = \frac{1+\eta}{2}\left[\frac{(1-\eta)A^{2/(1-\eta)}}{2B(1+D)n^2}\right]^{(1-\eta)/(1+\eta)}. \tag{11}$$

The pollution is always higher, $\tilde{\tilde{x}}_N = n^{1/(1+\eta)} \cdot \tilde{\tilde{x}}_C$, and the payoff is smaller in the competitive game (4) than in the cooperative case:

$$\tilde{\tilde{F}}_N = \frac{2-n(1-\eta)}{1+\eta} n^{(1-\eta)/(1+\eta)} \tilde{\tilde{F}}_C. \tag{12}$$

Moreover, by (9) and (12), the cooperative payoff $\tilde{\tilde{F}}_C$ is always positive, but the competitive payoff $\tilde{\tilde{F}}_N > 0$ only when $n(1-\eta) < 2$. So, the concave utility $\eta > 0$ is required to have a positive Nash payoff at $n > 1$. A similar condition on model parameters appears in (Breton and Sbragia 2016) to guarantee that each player's decisions are interior in equilibrium.

Next, we explore the properties of Nash and cooperative strategies in models with mitigation, adaptation, and both controls. Our focus is on comparison of competitive and cooperation strategies in terms of pollution, adaptation and mitigation. We also analyze how those strategies depend on key model parameters, in particular, on the number n of countries and their stage of development, represented by productivity A.

3.2 Model with mitigation (no adaptation)

The competitive game (4) with mitigation is as follows:

$$\max_{x_i, y_i} \ \tilde{F}_N(x_i, y_i) = (Ax_i y_i{}^k - y_i)^{1-\eta} - B(1+D)\left(\sum_{i=1}^n x_i\right)^2, \quad i = 1,\ldots, n \tag{13}$$

It has the explicit *Nash equilibrium solution* [2]

$$\tilde{y}_N = \left(\frac{A^2(1-\eta)k^{1+\eta}}{2B(1+D)n(1-k)^\eta}\right)^{1/(1+\eta-2k)}, \tag{14}$$

$$\tilde{x}_N = \frac{\tilde{y}_N{}^{1-k}}{kA}, \tag{15}$$

and the related payoff is

[2] The proof of all subsequent formulas and statements can be found in the mathematical complement (Hritonenko and Yatsenko 2021) to this paper

$$\tilde{F}_N = \tilde{y}_N{}^{1-\eta} \frac{k^{\eta-1}}{2(1-k)^{\eta}} (2 - 2k - n(1-\eta)). \tag{16}$$

The solution of the related cooperative problem (5) is

$$\tilde{y}_C = \left(\frac{A^2(1-\eta)k^{1+\eta}}{2B(1+D)n^2(1-k)^{\eta}} \right)^{1/(1+\eta-2k)}, \tag{17}$$

$$\tilde{x}_C = \frac{\tilde{y}_C{}^{1-k}}{kA},$$

$$(20)\tilde{F}_C = \tilde{y}_C{}^{1-\eta} \frac{k^{\eta-1}}{2(1-k)^{\eta}} (1 + \eta - 2k). \tag{18}$$

Next, we use the common notation $z(v) \sim f(v)$ that means $\lim_{v\to\infty} \frac{z(v)}{f(v)} = \text{const} > 0$. It describes asymptotic behavior of the function $z(v)$ when $v >> 1$ is large.

Statement 1. Let $k < (\eta + 1)/2$. Then, in both competitive and cooperative cases, the optimal emission e, mitigation y and payoff F increase when A and/or η increase but decrease when n and/or B increase. The mitigation /pollution ratio y/x is increasing and convex with respect to A:

$$\frac{y}{x} \sim A^{\frac{1+\eta}{1+\eta-2k}}. \tag{19}$$

The global emission in the competitive case $E = nx \sim n^{(\eta-k)/(1+\eta)}$ decreases in n at $k < \eta$ and increases at $\eta < k < (\eta + 1)/2$. At $k \to (\eta + 1)/2$, the optimal emission $x \to \infty$. The cooperative game has no finite solution at $k \geq (\eta + 1)/2$.

By Statement 1, the relation between the mitigation effectiveness parameter k and risk aversion η essentially affects both optimal competitive and cooperative strategies. The optimal emission, mitigation, and payoffs are finite at $0 < k < (\eta + 1)/2$ and they increase indefinitely when $k \to (\eta + 1)/2$. At $k \geq (\eta + 1)/2$, mitigation is so effective that the optimal output $Ax_iy_i^k$ in (1) grows faster than the mitigation cost y_i, which leads to the infinite output and pollution increase. At $0 < k < (\eta + 1)/2$, the sign of $k-\eta$ determines whether the global pollution increases or decreases when the number N of countries becomes larger.

3.3 Model with adaptation (no mitigation)

With adaptation, the competitive and cooperative strategies become richer, but the analytic complexity increases. Let us consider the problems (4) and (5) with adaptation but no mitigation. The competitive game (4) becomes

$$\max_{x_i, z_i} \hat{F}_N(x_i, z_i) = (Ax_i - z_i)^{1-\eta} - B\left(\frac{1}{1+az_i} + D\right)\left(\sum_{i=1}^{n} x_i\right)^2, \; i = 1,\ldots, n. \tag{20}$$

Statement 2. If

$$a > a_{Na} = \left[\frac{2^{2+\eta}(1+D)^{2+\eta}B}{(1-\eta)A^2 n^{\eta}}\right]^{1/(1+\eta)}, \tag{21}$$

then the game (20) has a unique positive Nash equilibrium solution $\hat{x}_N > 0, \hat{z}_N > 0$. If $a \leq a_{Na}$, then the optimal adaptation $\hat{z}_N = 0$ and $\hat{x}_N = \tilde{\tilde{x}}_N$. The payoff is

$$\hat{F}_N = (A\hat{x}_N - \hat{z}_N)^{-\eta}\left[A\hat{x}_N\left(1 - \frac{n(1-\eta)}{2}\right) - \hat{z}_N\right]. \tag{22}$$

By Statement 2, the economy must be productive enough to engage into adaptation activities. The critical value a_N positively depends on the climate vulnerability B and residual damage D. The larger B and D are, the more economically powerful a country should be to profitably engage in adaptation.

The corresponding cooperative problem has a unique positive solution $\hat{x}_C > 0, \hat{z}_C > 0$

$$\text{at } a > a_C = \left[\frac{2^{2+\eta}(1+D)^{2+\eta}Bn^2}{(1-\eta)A^2}\right]^{1/(1+\eta)}. \tag{23}$$

and $\hat{z}_C = 0$, $\hat{x}_C = \tilde{\tilde{x}}_C$ at $0 < a \leq a_C$. The cooperative payoff is:

$$\hat{F}_C = (A\hat{x}_C - \hat{z}_C)^{-\eta}\left[A\hat{x}_C\frac{1+\eta}{2} - \hat{z}_C\right]. \tag{24}$$

The adaptation threshold a_C is larger in the cooperative scenario: $a_C > a_N$.

The asymptotic of optimal solutions at large values of parameters n and A is summarized in the below statement.

Statement 3. Let $(1-\eta)A^2a^{1+\eta} >> B$ in the game (20). Then, the following asymptotic relations hold for optimal adaptation and emission controls:

$$z_N \sim a^{-\frac{1}{2}}\left(\frac{n^{\eta}(1-\eta)A^2}{2^{\eta+2}BD^{\eta+2}}\right)^{\frac{1}{2(1+\eta)}} \text{ and } \quad x_N \sim \left(\frac{(1-\eta)A^{1-\eta}}{BDn}\right)^{\frac{1}{1+\eta}}. \tag{25}$$

In the cooperative case, if $(1-\eta)A^2a^{1+\eta} \gg Bn^2$, then:

$$z_C \sim a^{-\frac{1}{2}}\left(\frac{(1-\eta)A^2}{2^{\eta+2}BD^{\eta+2}n^2}\right)^{\frac{1}{2(1+\eta)}} \text{ and } \quad x_C \sim \left(\frac{(1-\eta)A^{1-\eta}}{BDn^2}\right)^{\frac{1}{1+\eta}}. \tag{26}$$

This statement implies that the optimal adaptation in competitive case is asymptotically greater for a larger n >>1. The next statement extends this result for any number $n > 1$.

Statement 4. Let $\sigma > 1$ in the competitive game (20), where

$$s = \frac{(1-h)A^2a^{1+h}}{4B} \tag{27}$$

Then, the adaptation z_N increases and pollution x_N decreases when n increases. For n >>1,

$$z_N \sim n^{\frac{\eta}{2(1+\eta)}}, x_N \sim n^{\frac{-1}{1+\eta}}, \text{ and } \quad E \sim n^{\frac{\eta}{1+\eta}}. \tag{28}$$

Both pollution e_N and adaptation z_N increase when A increases, in both Nash and cooperative cases. For A >>1,

$$z_N \sim z_C \sim A^{\frac{1}{1+\eta}} \text{ and } x_N \sim x_C \sim E \sim A^{\frac{1-\eta}{1+\eta}}. \tag{29}$$

By Statement 4, the presence of adaptation does not affect the asymptotic growth of pollution. In particular, the global pollution always increases when the number of competing countries becomes larger in the absence of mitigation.

3.4 Model with Mitigation and Adaptation

Now, we explore the game (4) and problem (5) with both adaptation and mitigation controls. We would like to analyze how the number of countries affects domestic climate policies, in particular, the optimal ratio between mitigation and adaptation. In the case of two countries, this issue was studied by (Brechet et al (2016).

Statement 5. Let $k < (\eta + 1)/2$. If $a > a_{cr}$,

$$a_{cr} = \left[\frac{2^{2+\eta-2k}(1+D)^{2+\eta-2k}(1-k)^{\eta}B}{n^{\eta-2k}(1-\eta)A^2k^{2k}}\right]^{1/(1+\eta-2k)}, \tag{30}$$

then the unique Nash equilibrium solution of the competitive game (4) is positive: $x_N > 0, y_N > 0, z_N > 0$. If $0 < a < a_{cr}$, then the optimal adaptation $z_N = 0$, while

pollution $x_N = \tilde{x}_N > 0$ and mitigation $y_N = \tilde{y}_N > 0$ are defined in Statement 3. The payoff is:

$$F_N = \left(\frac{1-k}{k} y_N - z_N\right)^{-\eta} \left[\frac{y_N}{k}\left(1 - k - \frac{n(1-\eta)}{2}\right) - z_N\right]. \tag{31}$$

At $k \to (\eta + 1)/2$, the optimal emission $x_N \to \infty$. The game (4) has no finite solution at $k \geq (\eta + 1)/2$.

The unique solution to the cooperative problem (5) is positive: $x_C > 0$, $y_C > 0$, $z_C > 0$, if $a > a_{cr}$, where

$$a_{cr} = \left[\frac{2^{2+\eta-2k}(1+D)^{2+\eta-2k}(1-k)^{\eta} B n^2}{(1-\eta)A^2 k^{2k}}\right]^{1/(1+\eta-2k)}.$$

If $a < a_{cr}$, then $z_C = 0$, $x_C = \tilde{x}_C$ and $y_C = \tilde{y}_C$.

The cooperative payoff is

$$F_C = \left(\frac{1-k}{k} y_C - z_C\right)^{-\eta} \left[\frac{1+\eta-2k}{2}\frac{y_C}{k} - z_C\right]. \tag{32}$$

Statement 6. Let $k < (\eta + 1)/2$ in the competitive game (4) . Then, the optimal emission e_{Na} is smaller and mitigation y_N is larger for a larger n. For n >>1:

$$x_N \sim n^{-\frac{1-k}{1+\eta-2k}}, \; y_N \sim n^{-\frac{1}{1+\eta-2k}}, \quad \text{and} \quad z_N \sim n^{\frac{\eta-2k}{2(1+\eta-2k)}}. \tag{33}$$

i.e., adaptation z_N increases if $k < \eta/2$ and decreases otherwise. The optimal ratio between adaptation and mitigation is:

$$\frac{z_N}{y_N} \sim n^{\frac{1}{2}+\frac{1}{2(1+\eta-2k)}}. \tag{34}$$

The global emission $E = N x_N \sim n^{\frac{\eta-k}{1+\eta-2k}}$ is smaller for larger n at $k > \eta$ and larger at $k < \eta$. The optimal emission, adaptation and mitigation efforts are larger in both competitive (4) and cooperative (5) games for a larger A. At A >>1:

$$x_N \sim x_C \sim A^{\frac{1-\eta}{1+\eta-2k}}, \; y_N \sim y_C \sim A^{\frac{2}{1+\eta-2k}}, \quad \text{and} \quad z_N \sim z_C \sim A^{\frac{1}{1+\eta-2k}}, \tag{35}$$

and the optimal ratio between adaptation and mitigation decreases with A as:

$$\frac{z_N}{y_N} \sim \frac{z_C}{y_C} \sim A^{-\frac{1}{1+\eta-2k}}. \tag{36}$$

The solutions to problems (4) and (5) depend on six given parameters: risk aversion η, mitigation efficiency k, adaptation efficiency a, productivity A, climate change vulnerability B, and the number of players n. Analysis of their dependencies on those parameters leads to interesting outcomes with relevant policy implications.

The above results demonstrate that the global emission in the competitive case is smaller for a larger number n when the mitigation technology is efficient (at $k > \eta$) and is larger at $k < \eta$. Second, the adaptation in both competitive (4) and cooperative games (5) is positive only above a certain adaptation efficiency threshold. This threshold depends on the country's ratio between its vulnerability B, non-avoided damage D, and the productivity A of the economy. This result was earlier obtained for a dynamic two-country model in (Brechet et al 2016). Statement 6 extends this result to multi-country case. Now, one can see how this result depends on the number n of symmetric countries. In particular, by (34), the optimal ratio y_N / z_N between mitigation and adaptation in competitive strategy asymptotically increases when more countries are involved in the game and decreases when the country's productivity is larger.

Another new outcome is that the adaptation investment z_N in competitive strategy is larger in absolute units for a bigger number n if the mitigation effectiveness is weak: at $k < \eta/2$. At more effective mitigation: $\frac{\eta}{2} < k < \frac{1+\eta}{2}$, the investment in adaptation becomes less relevant and decreases with n. If mitigation appears to be even more effective, $k \geq (\eta + 1)/2$, then the optimal output grows faster than the mitigation cost and leads to infinite output as it was in the model (11) with mitigation only.

4. Discussion

The theoretic debate about rational investments in mitigation versus adaptation will continue, while management practice will use both instruments. The answer still is not clear. Most related research tend to favor mitigation versus adaptation for some obvious relevant (and not-so-obvious) reasons. Thus, Schumacher (2019) argues that adaptation always represents a significant loss of global welfare and, as such, should be zero. The present paper confirms the secondary role of adaptation compared to mitigation in a very crowded (with a large n) and/or highly efficient (large A) symmetric world. By Statement

6, the adaptation efficiency a (in contrast to the mitigation efficiency parameter k) does not appear in the growth rates of optimal emission and output in competitive and cooperative strategies.

At the same time, we prove that the pollution/output, adaptation and mitigation efforts in both competitive and cooperation strategies increase with the country's productivity, and this increase is asymptotically faster with a more effective mitigation. Therefore, the *presence of mitigation increases the effectiveness of adaptation*. This conclusion analytically confirms a simulation outcome from the integrated assessment model AD-MERGE (Bahn et al 2019) that applying both adaptation and mitigation is more effective than using just one.

We shall notice that major properties of the optimal emission, mitigation and adaptation in our model are determined by the relation between mitigation efficiency k and consumer utility aversion η. The global emission in competitive world is larger for a larger number of competing countries when the mitigation technology is not efficient ($k < \eta$) but smaller at $k > \eta$. The adaptation in competition is larger in absolute units for a bigger number n when the mitigation is weak: $k < \eta/2$. If the mitigation is effective, $k > \eta/2$, then the adaptation decreases with n. On the other side, when the mitigation is too effective in our model, then the production output can grow faster than the pollution disutility and, as result, both competitive and cooperative strategies lead to infinite production increase. Adaptation is always smaller in the cooperative case. Here we have considered an environmental economic model of a symmetric world. The model can be extended to asymmetric world to describe developed and developing countries and include the possibility of an international transfer (Hritonenko et al 2019).

In conclusion, we would like to highlight the recent global lesson from COVID-19 pandemic and related lockdowns. As Elliott et al (2022) reveal, the emission reductions from the COVID-related lockdowns in 2020 appear to be rather small, which suggests that even large-scale reductions of economic activity do not necessary cause the desired global mitigation effect. This fact farther increases the importance of adaptation as a more reliable policy choice.

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