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Games with Adaptation and Mitigation

Natali Hritonenko [1], **Victoria Hritonenko** [2] and **Yuri Yatsenko** [3,*]

[1] Department of Mathematics, Prairie View A&M University, Prairie View, TX 77446, USA; nahritonenko@pvamu.edu
[2] Department of Sciences, Mathematics and Biotechnology, University of California Extension, Berkeley, CA 94704, USA; hritonenko@berkeley.edu
[3] Dunham College of Business, Houston Baptist University, Houston, TX 77074, USA
* Correspondence: yyatsenko@hbu.edu

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Abstract: We formulate and study a nonlinear game of n symmetric countries that produce, pollute, and spend part of their revenue on pollution mitigation and environmental adaptation. The optimal emission, adaptation, and mitigation investments are analyzed in both Nash equilibrium and cooperative cases. Modeling assumptions and outcomes are compared to other publications in this fast-developing area of environmental economics. In particular, our analysis implies that: (a) mitigation is more effective than adaptation in a crowded multi-country world; (b) mitigation increases the effectiveness of adaptation; (c) the optimal ratio between mitigation and adaptation investments in the competitive case is larger for more productive countries and is smaller when more countries are involved in the game.

Keywords: economic-environmental model; environmental adaptation; pollution mitigation; Nash equilibrium

1. Introduction

Pollution mitigation and adaptation are two major policies commonly used by governments to reduce the environmental damage. Spending on mitigation and adaptation is enormous. Indeed, the total global economic cost of mitigating climate change is estimated to be €200–350 billion per year by 2030 [1]. Accurate assessment of effective environmental policies and actions has been a subject of intensive research for the last forty years. It includes analytic models [2–5] and computer simulation methods, known as the integrated assessment models [6–8]. This paper contributes to analytic modeling of adaptation and mitigation activities in the competitive world. Analytic models lead to better understanding of observed environmental changes and predicting consequences of human impact on the environment. They also stimulate the improvement of computer simulation models. However, a systematic analytic theory of adaptation and mitigation is to be developed.

A short survey below demonstrates a growing number of related analytic models with scattered underlying assumptions and fragile links among various models and their outcomes. The modeling tools often reflect the analytic expertise of their authors. The adaptation–mitigation models can be deterministic or stochastic, static, or dynamic, in continuous or discrete time (including two- or three-stage versions). Because of analytic complexity, all models make simplifying assumptions about production, pollution, mitigation, and adaptation [5,6,9–12]. Corresponding optimization problems can involve one or several objectives, and one or many players [13]. Some adaptation–mitigation models consider one country and neglect the international dimension of environmental protection [5,12,14–17]. The optimization models with several players reflect the international context of the environmental protection and lead to static or dynamic games. Multi-country models usually restrict their analysis to a symmetric case of identical countries [18–24].

Here, we focus on a rigorous analysis of optimal adaptation and mitigation. To reduce modeling complexity, some analytic games with adaptation do not involve a separate mitigation variable and use the emission reduction caused by environmental damage as a proxy for mitigation effort [10,12,16,22,25]. Such concept of mitigation is costless, so, the related models cannot compare adaptation and mitigation investments. Two-stage dynamic game [9] analyzes both adaptation and mitigation but ignores endogenous production. A two-country static game of [10] considers endogenous production, pollution, and adaptation, but oversimplifies mitigation as a reduced emission. The multi-country model of [22] significantly generalizes the game [10] by adding cross-country differences in adaptation costs but it also does not include a separate mitigation cost. Papers [12,16] consider dynamic optimization with uncertain damage, though over-simply mitigation. The models [5,12,15,16,26] rigorously analyze mitigation and adaptation actions in one country ignoring international aspect of the problem. A static game of [27] and a dynamic game of [28] include separate endogenous mitigation variable, nevertheless, do not consider adaptation. Paper [11] analyzes a static game of n countries with pollution and adaptation but does not explicitly include mitigation.

A separate group of studies focuses on the formation and stability of possible coalitions in environmental protection, see [11,18,23,24] and the references therein. The impact of strategic commitment in a model with n symmetric countries, including adaptation and mitigation, is evaluated in [11,18]. Two-stage coalition formation model of [23] employs a general static game of n identical countries with separate endogenous mitigation and adaptation variables. The authors show that adaption can lead to larger stable coalitions and higher global welfare (compared to the only mitigation case), but they do not estimate related adaptation and mitigation investments.

Different modeling assumptions about payoff functions, pollution disutility/damage, and mitigation and adaptation effectiveness are used in [29–38] to explore economic, agricultural, welfare, political, and regional aspects of strategic interactions among pollution, mitigation, and adaptation.

The novelty of the present paper relative to the existing literature is to analyze and compare a country's strategic investments in mitigation and adaptation in the competitive world. Estimating the optimal mix of adaptation and mitigation efforts has tremendous policy implications [5,20]. We introduce a multi–country model with separate mitigation and adaptation investment controls and systematically analyze its competitive and cooperative cases, focusing on analytic solutions for the optimal emission, adaptation, and mitigation. The constructed nonlinear model follows natural economic assumptions and is not restricted to linear-quadratic cases. In general, it is not easy to find analytic solutions to non-quadratic games. For clarity, we employ the static game framework to obtain closed-form solutions, useful for policy analysis. Dynamic models of [20,39] with endogenous production, emission, mitigation, and adaptation are conceptually close to the present paper though they differ in modeling assumptions and are restricted to two regions.

The paper is organized as follows. Section 2 formulates optimization problems for competitive and cooperative scenarios. Section 3 provides a comparative analysis of the competitive (Nash equilibrium) and cooperative solutions, focusing on their dependence on the number of countries and country's productivity. Section 4 discusses obtained outcomes and their policy implications and concludes.

2. Models and Methods: Games with Mitigation and Adaptation

This section provides formal statements and interpretation of mathematical problems under study.

2.1. Modeling Framework

Let us consider n countries, each of which produces an economic output q_i, emits pollution x_i and reduces it using a mitigation investment y_i. Following other environmental games [18,25,27,28], we express the output q_i in terms of the pollution x_i as

$$q_i = A_i x_i {y_i}^k, \qquad i = 1, \dots, n, \tag{1}$$

where the parameter A_i describes the country's productivity (more exactly, environmental cleanness of production), while 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 less effective at a smaller k and completely useless at $k = 0$.

The total pollution $X = \sum_{i=1}^{n} x_i$ from all countries causes the environmental damage $\Omega_i = B_i X^2$ to the country i [2,6,40], which can be reduced by the country's adaptation spending z_i as

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

The parameter $B_i > 0$ 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 of mitigation y_i in Equation (1) and adaptation z_i in Equation (2) is in line with the majority of related studies [3–6,19,20,25,41].

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 a 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:

$$F(q_i, x_i, y_i, z_i) = (q_i - y_i - z_i)^{1-\eta} - B_i\left(\frac{1}{1 + a_i z_i} + D_i\right)\left(\sum_{j=1}^{n} x_j\right)^2, 0 < \eta < 1. \quad (3)$$

The objective function (3) uses the standard *isoelastic* (also known as *CRRA*) utility function ${C_i}^{1-\eta}$ with the *risk aversion parameter* $0 < \eta < 1$ [2,24] rather than a quadratic payoff. In doing so, we keep our model in line with the mainstream economic theory. The choice of the benefit function should be theoretically and empirically grounded. Quadratic payoff functions are favorite in the game theory because they allow for finding analytic solutions in many cases [11,18,27,36]. However, the quadratic utility leads to increasing absolute risk aversion (which never happens in reality) and has never been seriously considered by economists. The isoelastic utility possess a tremendous potential to increase the quality of many economic-environmental models, including games. An empiric justification of the isoelastic utility for the multi-country world was recently provided in [24] on a dataset about 264 countries, where ${C_i}^{1-\eta}$ with $\eta \approx 0.875$ appears to be statistically significant. Because $0 < \eta < 1$, we use ${C_i}^{1-\eta}$ in Equation (3) rather than its more general version ${C_i}^{1-\eta}/(1-\eta)$.

The model (1)–(3) provides a simple framework for the current policy debate about environmental policies. Its three control variables describe output/pollution intensity, mitigation effort, and adaptation effort. For convenience, Table 1 contains descriptions of all variables and parameters of the model.

2.2. Competitive and Cooperative Games

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

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

A solution (x_i, y_i, z_i), $x_i \ge 0$, $y_i \ge 0$, and $z_i \ge 0$, $i = 1, \ldots, n$, of the nonlinear static game (4), if it exists, represents the *Nash equilibrium* [13,19,20,25,27].

Table 1. The list of used parameters and variables.

Notation	Description
$n, n \geq 1$	the number of countries
$x_i, I = 1, 2, \ldots, n$	pollution intensity of the country i
c_i	the consumption in the country i
q_i	the production output of the country i
A_i	a productivity factor
$y_i, I = 1, 2, \ldots, n$	mitigation investment in the country i
$k, 0 < k < 1$	the efficiency of mitigation investment
$z_i, I = 1, 2, \ldots, n$	adaptation investment in the country i
$a_i, a_i > 0$	the efficiency of adaptation investment
$\eta, 0 < \eta < 1$	the risk aversion parameter of utility function
F	the payoff function
$B_i, B_i > 0$	vulnerability to environmental damage
$D_i, D_i > 0$	the non-avoidable damage in the country
(x_N, y_N, z_N)	the Nash equilibrium solution of the game (4)
(x_C, y_C, z_C)	the solution of the cooperative problem (5)
σ	an auxiliary parameter defined by Equation (27)
v	an auxiliary variable (in Theorems 3 and 5)

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:

$$\begin{aligned} \max_{x_i, y_i, z_i, i=1,\ldots n} F_c &= \sum_{i=1}^{n} F_i(x_i, y_i, z_i) \\ &= \sum_{i=1}^{n} \left[\left(A_i x_i y_i^{\,k} - y_i - z_i \right)^{1-\eta} - B_i \left(\tfrac{1}{1+a_i z_i} + D_i \right) \left(\sum_{j=1}^{n} x_j \right)^2 \right] \end{aligned} \tag{5}$$

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

Following standard assumptions of environmental games [18–24,27,28], we restrict ourselves to the symmetric case of n identical countries:

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

Similar models with several asymmetric countries have been analyzed in [25].

Under condition (6), the optimal pollution x_i, mitigation y_i, and adaptation z_i in 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). A simple link between those solutions is presented below.

Theorem 1. *Let the nonlinear game (4) have a solution $x_N(n, B)$, $y_N(n, B)$, $z_N(n, B)$ for any $n = 1,2,3, \ldots$ and any $B > 0$. Then, the solution of the cooperative problem (5) is:*

$$x_C = x_N(1, B_w), \qquad y_C = y_N(1, B_w), \qquad z_C = z_N(1, B_w), \tag{7}$$

where $B_w = Bn^2$.

Proof. Let us consider the cooperative optimization problem (5). Substituting Equation (6) and $x_i = x_C$, $y_i = y_C$, $z_i = z_C$, $i = 1, \ldots, n$ to Equation (5), we obtain

$$\max_{x_i, y_i, z_i, i=1,\ldots n} F_c = n \cdot \max_{x_C, y_C, z_C}\left[\left(Ax_C {y_C}^k - y_C - z_C\right)^{1-\eta} - Bn^2 x_c^2\left(\frac{1}{1+az_c} + D\right)\right]$$

i.e., the solution (x_C, y_C, z_C) coincides with the solution of the *one-country model*

$$\max_{x_1, y_1, z_1} F_1 = \max_{x_1, y_1, z_1}\left[\left(Ax_1 {y_1}^k - y_1 - z_1\right)^{1-\eta} - Bn^2 x_1^2\left(\frac{1}{1+az_1} + D\right)\right] \tag{8}$$

with the modified parameter $B = B_w = Bn^2$. On the other side, the one-country model (8) is a special case of the game (4) at $n = 1$. Therefore, the solution (x_N, y_N, z_N) to Equation (4) coincides with the solution (x_1, y_1, z_1) to Equation (8). It justifies the formulas (7).

The Theorem is proven. □

Theorem 1 reduces a technical complexity of the forthcoming analysis and allows us to compare competitive and cooperative strategies with less effort.

3. Results: Comparative Analysis

In this section, we investigate and compare analytic properties of the competitive game (4) and cooperative problem (5). In our analysis, we emphasize the dynamics of competitive and cooperative strategies when the number of countries is large. To demonstrate our technique, let us start with the simplest case.

Special case ***k = 0, a = 0*** *(no adaptation and no mitigation).* Then, the game (4) becomes

$$\max_{x_i} F_N(x_i) = (Ax_i)^{1-\eta} - B(1+D)\left(\sum_{i=1}^{n} x_i\right)^2 \text{ for all i} = 1, \ldots, n, \ldots \tag{9}$$

and does not include mitigation and adaptation controls y_i and z_i. The only control in Equation (9) is the pollution level x_i that also defines the economic output (1). Differentiating (9) in x_i, setting the derivative to zero, and using the symmetry assumption (6), we obtain the Nash equilibrium solution of the game (4) as

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

$$F_N = \left(1 - \frac{n}{2}(1-\eta)\right)A^{1-\eta}x_N^{1-\eta} = \left(1 - \frac{n}{2}(1-\eta)\right)\left[\frac{(1-\eta)A^2}{2Bn(1+D)}\right]^{(1-\eta)/(1+\eta)} \tag{11}$$

By Theorem 1, the cooperative solution is

$$x_C = \left[\frac{(1-\eta)A^{1-\eta}}{2B(1+D)n^2}\right]^{1/(1+\eta)}, \tag{12}$$

$$F_c = \frac{1-\eta}{2}A^{1-\eta}{x_C}^{(1-\eta)} = \frac{1-\eta}{2}\left[\frac{(1-\eta)A^{2/(1-\eta)}}{2B(1+D)n^2}\right]^{(1-\eta)/(1+\eta)} \tag{13}$$

It is easy to see that the pollution is higher: $x_N = n^{1/(1+\eta)} \cdot x_C$, and the payoff is smaller in the competitive game (4) than in the cooperative case:

$$F_N = \frac{2 - n(1-\eta)}{1+\eta} n^{(1-\eta)/(1+\eta)} F_C. \tag{14}$$

By Equations (11) and (14), the cooperative payoff F_C is always positive, but the competitive payoff $F_N > 0$ only when $n(1-\eta) < 2$. Thus, the concave utility $\eta > 0$ is required for a positive Nash payoff at $n > 1$. A similar condition on model parameters appears in [18] to guarantee that each player's decision is interior in equilibrium.

Next, we explore the properties of competitive and cooperative strategies in models with mitigation, adaptation, and both controls. We compare competitive and cooperation strategies in the terms of pollution, adaptation, and mitigation. We also analyze how those strategies depend on the key model parameters, the number n of countries and their stage of development, represented by the production cleanness factor A.

3.1. Model with Mitigation

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

$$\max_{x_i,y_i} F_N(x_i,y_i) = \left(Ax_i{y_i}^k - y_i\right)^{1-\eta} - B(1+D)\left(\sum_{i=1}^{n} x_i\right)^2, \ldots \text{for all i} = 1,\ldots,n. \tag{15}$$

Differentiating Equation (15) in y_i and x_i and setting derivatives to zero, we obtain the explicit formulas for Nash equilibrium solution:

$$y_N = \left(\frac{A^2(1-\eta)k^{1+\eta}}{2B(1+D)n(1-k)^\eta}\right)^{1/(1+\eta-2k)}, \tag{16}$$

$$x_N = \frac{{y_N}^{1-k}}{kA} \tag{17}$$

and the related payoff

$$F_N = {y_N}^{1-k}\frac{k^{\eta-1}}{2(1-k)^\eta}(2-2k-n(1-\eta)). \tag{18}$$

By Theorem 1, the solution of the related cooperative problem (5) is

$$y_C = \left(\frac{A^2(1-\eta)k^{1+\eta}}{2B(1+D)n^2(1+k)^\eta}\right)^{1/(1+\eta-2k)}, \tag{19}$$

$$x_C = \frac{{y_C}^{1-k}}{kA}, \tag{20}$$

$$F_C = {y_C}^{1-\eta}\frac{k^{\eta-1}}{2(1-k)^\eta}(1+\eta-2k). \tag{21}$$

Here and thereafter, the notation $z(v) \sim f(v)$ describes asymptotic behavior of the function $z(v)$ when v is large and means that $\lim\limits_{v\to\infty}\frac{z(v)}{f(v)} = const \neq 0$.

Theorem 2. *Let $k < (\eta + 1)/2$. Then, in both competitive game (15) and its cooperative case, the optimal emission x, mitigation y, and payoff F increase when A and/or η increase, but decrease when n and/or B increase. The mitigation /pollution ratio increases and is convex when A increases:*

$$\frac{y}{x} \sim A^{\frac{1+\eta}{1+\eta-2k}}. \tag{22}$$

The global emission in the competitive case $X = nx \sim n^{(\eta-k)/(1+\eta)}$ decreases in n at $k < \eta$and increases at $\eta < k < (\eta + 1)/2$. At $k \to (\eta + 1)/2$, the optimal $x\to\infty$ and $y\to\infty$.

Proof. Follows from formulas (16)–(21). □

The game (13) and related cooperative problem have no finite solution at $k \geq (\eta + 1)/2$.

By Equations (16) and (19), the optimal mitigation y is positive in both competitive and cooperative scenarios, but it is small and much smaller than emission, $x << y$, for weak economies with $A << 1$. The optimal emission (17) of an individual country is always larger in the presence of mitigation than with no mitigation in both competitive and social optimum scenarios. However, it is not so for the competitive optimal payoff (18). By Theorem 2, the relation between the mitigation effectiveness parameter k and risk aversion η essentially affects both optimal competitive and cooperative strategies. The sign of $k - \eta$ determines whether the global pollution increases or decreases when the number n of countries becomes larger. The optimal emission, mitigation, and payoffs are finite at $0 < k < (\eta + 1)/2$, but they increase indefinitely when $k \rightarrow (\eta + 1)/2$. At $k \geq (\eta + 1)/2$, mitigation is so effective that the optimal output $Ax_iy_i^k$ in Equation (1) grows faster than the mitigation cost y_i, which leads to the infinite output and pollution.

3.2. Model with Adaptation

With adaptation, the competitive and cooperative strategies become richer, but the analytic complexity increases. For clarity, let us first consider the problems (4) and (5), with adaptation but without mitigation. Then, the competitive game (4) becomes

$$\max_{x_i, z_i} F_N(x_i, z_i) = (Ax_i - z_i)^{1-\eta} - B\left(\frac{1}{1 + az_i} + D\right)\left(\sum_{i=1}^{n} x_i\right)^2, \ldots \text{for all i} = 1, \ldots, n. \tag{23}$$

Theorem 3. *Let*

$$a > a_{cr} = \left[\frac{2^{2+\eta}(1 + D)^{2+\eta}}{(1 - \eta)A^2 N^\eta}\right]^{1/(1+\eta)}, \tag{24}$$

then the Nash equilibrium solution of the competitive game (23) is:

$$x_N = \frac{2\left(v + Dv^2\right)}{Aan} > 0, z_N = \frac{v - 1}{a} > 0, \tag{25}$$

where v, $1 \leq v < \infty$, is the unique solution of the nonlinear equation

$$\left(\frac{2D}{n}v^2 - v\left(1 - \frac{2}{n}\right) + 1\right)^\eta (1 + Dv)^2 = \sigma, \tag{26}$$

with

$$\sigma = \frac{(1 - \eta)A^2 a^{1+\eta}}{4B}. \tag{27}$$

If $a < a_{cr}$, then the optimal adaptation $Z_N = 0$ and x_N is determined by Equation (10).

The payoff is

$$F_N = (Ax_N - z_N)^{-\eta}\left[Ax_N\left(1 - \frac{n(1 - \eta)}{2}\right) - x_N\right] \tag{28}$$

Proof. Setting the partial derivatives of $F_N(x_i, z_i)$ in Equation (23) with respect to x_i and z_i to zero, we obtain the following system of two nonlinear equations in x_i and z_i:

$$\frac{\partial F_N(x_i, z_i)}{\partial e_i} = A(1 - \eta)(Ax_i - z_i)^{-\eta} - 2B\left(\frac{1}{1 + az_i} + D\right)\left(\sum_{i=1}^{n} e_i\right) = 0, \tag{29}$$

$$\frac{\partial F_N(x_i,z_i)}{\partial e_i} = -(1-\eta)(Ax_i - z_i)^{-\eta} + \frac{aB}{(1+az_i)^2}\left(\sum_{i=1}^{n} x_i\right)^2 = 0 \tag{30}$$

Since the countries are identical, their competitive strategy is the same: $x_i = x$, $z_i = z$, $I = 1, \ldots, n$, and the system of Equations (29) and (30) becomes

$$A(1-\eta)(Ax-z)^{-\eta} = 2Bnx\left(\frac{1}{1+az} + D\right), \tag{31}$$

$$(1-\eta)(Ax-z)^{-\eta} = \frac{aB}{(1+az_i)^2}(nx)^2. \tag{32}$$

Formulas (25) follow from Equations (31) and (32) after expressing them via the new auxiliary variable $v = 1 + az$. Excluding x from the system of Equations (31) and (32), we obtain one nonlinear Equation (26) in v. To analyze the existence and uniqueness of its solution, let us rewrite Equation (26) as

$$f(v) = \sigma, \tag{33}$$

where $f(v) = \left(2Dv^2/n - v\left(1 - \frac{2}{n}\right) + 1\right)^{\eta}(1 + Dv)^2$ and σ is defined by (27).

A typical shape of the function $f(v)$ is shown with the solid line in Figure 1. Because of the constraint $z_i \geq 0$ in Equation (23), we are interested in the solution v of the Equation (33) only in the interval $[1, \infty)$. It is easy to see that there is no solution $v \geq 1$ if the right-hand side σ of Equation (33) is small. Let a_{cr} denote the smallest critical value of the parameter a when a solution $v \geq 1$ exists.

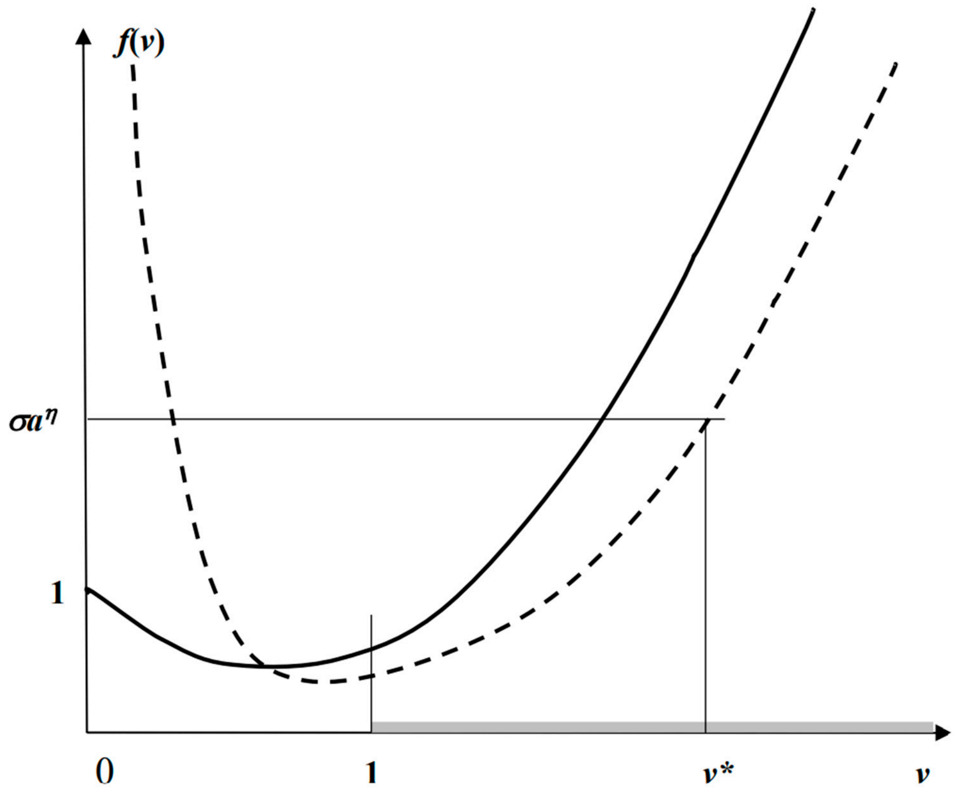

Figure 1. The function $f(v)$ in the nonlinear Equations (26) (solid curve) and (47) (dashed curve). The acceptable interval $(1, \infty)$ of the solution v^* is indicated in bold gray.

To find a_{cr}, let $z = \frac{v-1}{a} = 0$, then $v = 1$ and $x_N = \frac{2(1+D)}{Aan}$ in Equation (25). Therefore, a_{cr} is determined from Equations (26) and (27) as Equation (24).

The payoff (28) is obtained combining Equations (23) and (29). Next, we find the derivative $f'(v)$ and obtain that $f'(v) > 0$ at $v \geq 1$ at natural conditions. Therefore, the solution v to the nonlinear Equation (33) is unique in the interval [1, ∞).

If $0 < a < a_{crN}$, then the optimal $z_N = 0$ is a corner solution in [0, ∞), while x_N coincides with Equation (10). As expected, the resulting payoff (28) in this case is the same as (11).

The Theorem is proven. □

By Theorem 3, the economy must be productive enough to engage into adaptation activities. The critical value a_{cr} positively depends on the climate vulnerability B and residual damage D. Thus, the larger B and D are, the more economically powerful a country should be to profitably engage in adaptation.

Using Theorems 1 and 3, the cooperative solution is

$$x_C = \frac{2\left(v_C + Dv_C{}^2\right)}{Aa} > 0,\ z_C = \frac{v_C - 1}{a}, \tag{34}$$

At

$$a > a_C = \left[\frac{2^{2+\eta}(1+D)^{2+\eta}Bn^2}{(1-\eta)A^2}\right]^{1/(1+\eta)}. \tag{35}$$

where v_c is the unique solution of the nonlinear equation over [1,∞):

$$\left(2Dv_C{}^2 + v_C + 1\right)^{\eta}(1 + Dv_C)^2 = \sigma/n^2 \tag{36}$$

while $z_C = 0$ and x_c is given by Equation (12) at $0 < a \leq a_C$. The cooperative payoff is:

$$F_C = (Ax_C - z_C)^{-\eta}\left[Ax_C\frac{1+\eta}{2} - z_C\right]. \tag{37}$$

The adaptation threshold a_C is larger in the cooperative scenario: $a_C > a_{cr}$.

The behavior of optimal solutions (25)–(27) and (34)–(37) at large values of parameters n and A is summarized in the below statement.

Corollary 1. *Let* $(1-\eta)A^2a^{1+\eta} \gg B$ *in the competitive game (23). Then, the following relations hold for optimal adaptation and emission controls:*

$$z_N \sim a^{\frac{1}{2}}\left(\frac{n^{\eta}(1-\eta)A^2}{2^{\eta+2}BD^{\eta+2}}\right)^{\frac{1}{2(1+\eta)}} \text{and } x_N \sim \left(\frac{(1-\eta)A^{1-\eta}}{BDn}\right)^{\frac{1}{1+\eta}}. \tag{38}$$

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

$$z_C \sim a^{\frac{1}{2}}\left(\frac{(1-\eta)A^2}{2^{\eta+2}BD^{\eta+2}n^2}\right)^{\frac{1}{2(1+\eta)}} \text{and } x_C \sim \left(\frac{(1-\eta)A^{1-\eta}}{BDn^2}\right)^{\frac{1}{1+\eta}}. \tag{39}$$

Proof. The proof is based on the analysis of the nonlinear Equation (33). The condition $(1+\eta)A^2a^{1+\eta} \gg B$ means $\sigma >> 1$. In Equation (33), if $f(v)$ is large, then v is also large: $v >> 1$, because of specific form of the function f. Next,

$$f(v) = v^{2(1+\eta)}(D + 1/v)^2\left(2D/n - (1-2/n)/v + 1/v^2\right)^{\eta} \approx v^{2(1+\eta)}D^{2+\eta}2^{\eta}n^{-\eta}$$

when $v >> 1$.

Therefore,

$$v \approx \left(\frac{\sigma}{D^{2+\eta}2^{\eta}n^{-\eta}}\right)^{1/2(1+\eta)} = \left(\frac{(1-\eta)A^2a^{1+\eta}n^{\eta}}{B2^{2+\eta}D^{2+\eta}}\right)^{1/2(1+\eta)} \tag{40}$$

Substituting Equation (40) to the formulas (25), we obtain (38). The asymptotic estimate (39) for the cooperative case is obtained analogously. The Corollary is proven. □

Corollary 1 implies that the optimal adaptation in a competitive case is asymptotically greater for a larger $n >> 1$. Theorem 4 extends this result for any number $n > 1$.

Theorem 4. *Let $\sigma > 1$ in the competitive game (23). Then, the adaptation z_N increases and pollution x_N decreases when n increases. For $n >> 1$,*

$$z_N \sim n^{\frac{\eta}{2(1+\eta)}}, x_N \sim n^{\frac{-1}{1+\eta}}, \text{ and } E \sim n^{\frac{\eta}{1+\eta}}. \tag{41}$$

Both emission x_N and adaptation z_N increase when A increases, in both competitive and cooperative cases. For $A >> 1$,

$$z_N \sim z_C \sim A^{\frac{1}{1+\eta}} \text{ and } x_N \sim x_C \sim E \sim A^{\frac{1-\eta}{1+\eta}}. \tag{42}$$

Proof. We consider the case of an increasing n first. Let us assume that $f(v)$ in the Equation (33) is a function of two variables v and n:

$$f(v,n) = \sigma, \text{ where } f(v,n) = \left(2Dv^2/n - v(1-2/n) + 1\right)^{\eta}(1+Dv)^2. \tag{43}$$

Let us give some increments Δv and Δn to v and n. Then, by the Implicit Function theorem,

$$\frac{\Delta v}{\Delta n} \approx \frac{dv}{dn} = -\frac{\frac{\partial f(v,n)}{\partial n}/f(v,n)}{\partial v}, \tag{44}$$

and by Equation (43),

$$\frac{\partial f(v,n)}{\partial n} = -2\left(Dv^2 + v\right)^3/n^2 < 0.$$

Next, as shown in the proof of Theorem 3, $\frac{f(v,n)}{\partial v} > 0$ because $\sigma > 1$ and $v > 1$. So, $\Delta v > 0$ at $\Delta n > 0$ by Equation (44), and, therefore, both v and $z_N = \frac{v-1}{a}$ are larger when n is larger.

At $\sigma >> 1$, the solution v of Equation (43) is also large: $v >> 1$. Next, the asymptotic estimates (41) and (42) for z_N, x_N, and E follow directly from Equations (38) and (39).

The proof of the case of increasing A is analogous. The Theorem is proven. □

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

3.3. Model with Mitigation and Adaptation

Now, we explore the games (4) and (5) with both adaptation and mitigation controls and analyze how the number of countries affects environmental policies, in particular, the optimal ratio between mitigation and adaptation. In the case of two countries, this issue is studied in [20].

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

$$a_{cr} = \left[\frac{2^{2+\eta-2k}(1+D)^{2+\eta-2k}(1-k)^{\eta}B}{n^{\eta-2k}(1-\eta)A^2k^{2k}}\right]^{1/(1+\eta-2k)}, \tag{45}$$

then the Nash equilibrium solution of the competitive game (4) is:

$$x_N = \frac{{y_N}^{1-k}}{kA},\ y_N = \frac{2k\left(v + Dv^2\right)}{an} > 0,\ z_N = \frac{v-1}{a} > 0, \tag{46}$$

where v, 1 ≤ v < ∞, is the unique solution to the nonlinear equation

$$v^{-2k}\left(\frac{2(1-k)}{n}Dv^2 - v\left(1 - \frac{2(1-k)}{n}\right) + 1\right)^{\eta}(1+Dv)^{2(1-k)} = \sigma\left(\frac{2k}{na}\right)^{2k}, \tag{47}$$

and σ is given by Equation (27).

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

If $0 < a < a_{cr}$, then the optimal adaptation $z_N = 0$, while pollution x_N and mitigation y_N are given by Equations (16) and (17). The payoff is

$$F_N = \left(\frac{1-k}{k}y_N - z_N\right)^{-\eta}\left[\frac{y_N}{k}\left(1 - k - \frac{n(1-\eta)}{2}\right) - z_N\right] \tag{48}$$

Proof. Setting the partial derivatives of $F_N(x_i, y_i, z_i)$ in Equation (4) with respect to x_i, y_i, and z_i equal to zero and taking the symmetry condition (6) into consideration, we obtain the following system of three nonlinear equations

$$(1-\eta)\left(kAxy^{k-1} - 1\right)\left(Axy^k - y - z\right)^{-\eta} = 0, \tag{49}$$

$$Ay^k(1-\eta)\left(Axy^k - y - z\right)^{-\eta} - 2Bne\left(\frac{1}{1+az} + D\right) = 0, \tag{50}$$

$$-(1-\eta)\left(Axy^k - y - z\right)^{-\eta} + \frac{aB}{(1+az)^2}(nx)^2 = 0, \tag{51}$$

with respect to three unknowns $x_i = x$, $y_i = y$, $z_i = z$, $I = 1, \ldots, n$. In the new variable $v = 1 + az$, this system is reduced to one nonlinear Equation (47) in v. Let us rewrite Equation (47) as

$$f(v) = \sigma\left(\frac{2k}{na}\right)^{2k}, \tag{52}$$

where

$$f(v) = v^{-2k}\left(\frac{2(1-k)}{n}Dv^2 - v\left(1 - \frac{2(1-k)}{n}\right) + 1\right)^{\eta}(1+Dk)^{2(1-k)}. \tag{53}$$

The nonlinear function $f(v)$ is shown in Figure 1 with a dashed line. Its behavior differs from the function (33) from Theorem 1 at small v but is qualitatively similar over the interval $v \in [1, \infty)$. As before, we are interested in solutions $v > 1$ because of the constraint $z \geq 0$. Again, it is easy to see that no solution $v > 1$ exists if the RHS of Equation (52) is small enough. Let a_{cr} denote the smallest critical value of the parameter of a when the solution $v \geq 1$ exists. To find a_{cr}, let $Z_N = 0$, then $v = 1$, $Z_N = 0$ by Equation (46), and $y_N = \frac{2k(1+D)}{an}$. Substituting those values to (47), we obtain the formula (45) for a_{cr}.

Next, let us analyze the asymptotic of $f(v)$ at large v. By Equation (53), $f(v) \sim v^{1-2k+\eta}$, so $\lim_{v\to\infty} f(v) = \infty$ at $k < (\eta + 1)/2$, and $\lim_{v\to\infty} f(v) = 0$ at $k > (\eta + 1)/2$. Therefore, the Equation (52) is guaranteed to have a solution $1 \leq v < \infty$ only at $k < (\eta + 1)/2$. Similarly to Equation (33), the first derivative $f'(v)$ is positive at $v \geq 1$ at natural conditions. Hence, the solution to the Equation (52) is unique if it exists. The payoff (48) is obtained from Equations (3) and (46).

If $0 < a < a_{cr}$, then the optimal $z^N = 0$ is a corner solution in $[0, \infty)$, while the optimal x^N and y^N coincide with (19) and (20). The payoff (48) is the same as (18).

The theorem is proven. □

Again, a solution to the cooperative problem (5) is obtained using Theorem 1. Namely, if $a > a_{cr}$, where

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

Then

$$x_C = \frac{{y_C}^{1-k}}{kA},\ y_C = \frac{2k\left(v_C + D{v_C}^2\right)}{a} > 0,\ z_C = \frac{v_C - 1}{a} > 0, \tag{54}$$

where v_C, $1 \le v_C < \infty$, is a unique solution of the nonlinear equation

$${v_C}^{-2k}\left(2(1-k)D{v_C}^2 + (1-2k)v_C + 1\right)^{\eta}(1+Dv_C)^{2(1-k)} = \frac{\sigma}{n^2}\left(\frac{2k}{a}\right)^{2k}. \tag{55}$$

If $a < a_{cr}$, then $z_C = 0$, while x_C and y_C are found in Equations (19) and (20).
The cooperative payoff is

$$F_C = \left(\frac{1-k}{k}y_C - z_C\right)^{-\eta}\left[\frac{1+\eta-2k}{2}\frac{y_C}{k} - z_C\right]. \tag{56}$$

The solutions (46) and (47) and (54) and (55) depend on six given model parameters: risk aversion η, mitigation efficiency k, adaptation efficiency a, productivity A, climate change vulnerability B, and the number of countries n. Analysis of these dependencies leads to interesting outcomes with relevant policy implications. Analogously to Theorem 4 and Corollary 1, we establish the following result.

Corollary 2. *Let $k < (\eta + 1)/2$ in the competitive game (4). Then, the optimal emission x_N is smaller and mitigation y_N is larger for a larger n. For $n >> 1$,*

$$x_N \sim n^{\frac{1-k}{1+\eta-2k}},\ y_N \sim n^{\frac{1}{1+\eta-2k}},\ \textit{and}\ z_N \sim n^{\frac{\eta-2k}{2(1+\eta-2k)}}. \tag{57}$$

i.e., the adaptation z_N increases in n at $k < \eta/2$ and decreases otherwise. The optimal ratio between adaptation and mitigation

$$\frac{z_N}{y_N} \sim n^{\frac{1}{2}+\frac{1}{2(1+\eta-2k)}}. \tag{58}$$

The global emission $E = N_{x_N}\ n^{\frac{\eta-k}{1+\eta-2k}}$ 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 $A >> 1$,

$$x_N \sim x_C \sim A^{\frac{1-\eta}{1+\eta-2k}},\ y_N \sim y_C \sim A^{\frac{2}{1+\eta-2k}},\ \textit{and}\ z_N \sim z_C \sim A^{\frac{1}{1+\eta-2k}}, \tag{59}$$

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

$$\frac{z_N}{y_N} \sim \frac{z_C}{y_C} \sim A^{\frac{-1}{1+\eta-2k}}. \tag{60}$$

Proof. The first step is to obtain an asymptotic estimate (for large n) for the solution v of nonlinear Equation (47). Using the same technique as in Corollary 1, we obtain the estimate

$$v \approx \left(\frac{(1-\eta)k^{2k}A^2a^{1-2k+\eta}n^{-\eta}}{2^{4-2k-\eta}(1-k)^kBD^{2-2k+\eta}}\right)^{1/2(1-2k+\eta)} \gg 1 \tag{61}$$

for the solution v of Equation (47) when $f(v)$ is large. The formula (61) is similar to (52) but includes the additional parameter k. Nevertheless, fixing all parameters in Equation (61) except for n, we obtain the asymptotic estimate $v \sim n^{-\eta/2(1-2k+\eta)}$. Next, substituting this estimate to Equation (46), we obtain the asymptotic estimates (57) for x_N, y_N, z_N and, subsequently, (58).

The asymptotic estimates (59) and (60) for the case of large and increasing A are obtained analogously.

The Corollary is proven. □

Theorem 5 and Corollary 2 generalizes outcomes of Sections 3.1 and 3.2. First of all, the global emission E in the competitive case is smaller for a larger number n of countries 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. A similar result was obtained for one country case in [5,26] and for a dynamic two-country model in [20]. Theorem 5 extends this result to the multi-country case. Now, one can see how this result depends on the number n of symmetric countries. In particular, by Equations (58) and (60), the optimal ratio y_N/z_N between mitigation and adaptation in the competitive strategy is smaller when more countries are involved in the game, and is larger when the country's productivity becomes larger.

A new outcome is that the adaptation investment z_N in competitive strategy is larger in absolute units for a larger number n if the mitigation effectiveness k is weak: $k < \eta/2$. At more effective mitigation: $\frac{\eta}{2} < k < \frac{1+\eta}{2}$, the adaptation becomes less relevant and decreases with n. If mitigation becomes 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 (13) with mitigation only).

4. Discussion and Conclusions

Many recent publications [29–38,42–46] explore various economic, political, financial, welfare, and regional aspects of strategic interplay between mitigation and adaptation. The majority of related papers tend to favor mitigation versus adaptation for various relevant (and not-so-relevant) reasons. The most convincing pitch of [38] states that adaptation always represents a significant loss of global welfare and, as such, should be zero. The present paper adds a new argument to this discussion. Namely, as opposed to the mitigation efficiency parameter k, the adaptation efficiency a does not appear in the growth rates for the optimal emission and output in both competitive and cooperative strategies. This implies that mitigation leads to a higher payoff than adaptation and, therefore, adaptation *plays a secondary role compared to mitigation* in a crowded (large n) and/or highly efficient (large A) symmetric world. Indeed, mitigation addresses the causes of environmental contamination, while adaptation reduces related damages, but does not decrease the contamination itself.

At the same time, our analysis reveals that the *presence of mitigation increases the effectiveness of adaptation*. Indeed, the output, emission, adaptation, and mitigation efforts (in both competition and cooperation) increase with the country's productivity, and this increase is *faster* with a more effective mitigation. This outcome analytically confirms the recent simulation result of the integrated assessment model AD-MERGE [8] that using both adaptation and mitigation is more effective than using just one. In other words, there is a synergy between adaptation and mitigation, even in the one-country case.

The optimal pollution and output of an individual country are always larger in the presence of mitigation than with no mitigation in both competitive and social optimum scenarios. However, the competitive optimal welfare (payoff) evolution depends on the efficiency of mitigation. All of those levels can only increase further when the adaptation is added.

As the primary strategy, the mitigation determines whether the collective action dilemma worsen when the number n of players (countries) increases. Namely, the answer depends on the relation between mitigation efficiency k and the utility function parameter η (consumer risk aversion). The global emission in the competitive world is larger for a larger number of countries when $k < \eta$ and smaller at $k > \eta$.

Despite being a public good, mitigation is the only strategy that can alleviate the environmental pollution problem. The optimal adaptation activity is also subjected to the mitigation efficiency. If the mitigation is effective, then the adaptation effort decreases with n. When the mitigation is weak, then adaptation investment in competition is larger in absolute units for a bigger n. The optimal ratio between mitigation and adaptation investments in the competitive case decreases when the country's productivity is larger and increases when more countries are involved in the game.

In both competitive and cooperative cases, the adaptation is positive starting at a certain critical level of a country's productivity/harmfulness ratio. Adaptation in the cooperative case starts later and is smaller than in competition. As shown above, the optimal environmental policy for weak economies (with small productivity A) involves a minimal mitigation effort and no adaptation. In reality, poorer countries are more affected by global environmental problems, but they simply cannot pay for those efforts. A nonlinear game of two asymmetric regions, north and south, developed in [22], addresses this inequality issue. Incorporating such asymmetries in a multi-country environmental game is an important direction for further research.

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