Interactions between Nutritional and Climate Policies at the International Level

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Abstract

Developed countries and emerging economies face two major challenges, climate change and chronic diseases related to unhealthy diets. These two major challenges are linked since changes in diets impact public health, but also climate change through global greenhouse gas (GHG) emissions. The aim of this paper is to analyze in a global public good game the link between nutritional and climate mitigation policies at the international level. Changes in diets induced by a nutritional policy lead to health benefits at the national level. They can also increase or decrease the GHG emissions of the country, with related externalities to other countries. Our modelling framework thus highlights a novel indirect leakage effect through the nutritional policy, which complicates the public good problem. In this context, we ask whether countries should negotiate an agreement on climate policies only (climate agreement), or an agreement on both climate and nutritional policies (full agreement). In terms of global emissions, our theoretical results show that it is better to cooperate both on climate mitigation and nutritional policies when healthy changes in diets have a large impact on emissions, whatever the direction of this impact. We also investigate whether it is necessarily bad for the environment that countries are not informed about the impacts of nutritional policy on GHG emissions. Our theoretical results on the role of information highlight again the importance of the magnitude of emission changes induced by the nutritional policy. Finally, we assess the welfare implications of two diet recommendations in Denmark, Finland and France.

Keywords: climate mitigation, nutritional policy, healthy diets, cooperation, agreement.

JEL codes: C71, C72, D62, H41, I18.

1 Introduction

In developed countries and emerging economies, governments have to face, on one side, the global climate change issue, which requires mitigation policies negotiated at the international level, and on the other side, the increasing prevalence of obesity and nutrition related chronic diseases, which calls for national public health policies. These two major challenges are linked since changes in diets impact public health but also climate change through global greenhouse gas (GHG) emissions. It is thus important to analyze the interactions at the international level between countries' nutritional and climate mitigation policies. In particular, it is important to investigate whether countries' nutritional policies crowd-in or crowd-out their climate mitigation efforts.

While food production and consumption are vulnerable to the effects of climate change, food systems and diets themselves are also a significant contributor to global GHG emissions. On a worldwide basis, GHG emissions from the agri-food sector account for about 19-29% of global total emissions (UNSCN, 2017).[1] This contribution is similar to that of industry and greater than that of transport. Representing 14.5% of GHG emissions, livestock supply chains are an important contributor to global warming (Gerber et al., 2013).

In this context, in recent years, an increasing number of research has evaluated the effects of changes in diets, in particular reduced consumption of meat and dairy products, on GHG emissions. A review of Aleksandrowicz et al. (2016) which compares the impact of 210 scenarios, show that the change from a typical Western diet to alternative dietary patterns (e.g., Mediterranean, vegetarian, or vegan) provides benefits for the environment in a large majority of cases, but not in all. For instance, in Vieux et al. (2012), meat reduction supplemented isocalorically by fruit and vegetables induces an increase in GHG emissions, since some fruits or vegetables may generate higher GHG emissions per calorie than dairy and non-ruminant meats. Aleksandrowicz et al. (2016) conclude that such scenarios highlight some of the complexity involved in assessing environmental sustainability of diets, and the context- and region-specific nature of such assessments. This review also shows that studies analyzing the health impacts of changes in diets show

[1]Food production and consumption are also responsible of 60% of terrestrial biodiversity loss and 70% of freshwater use (UNSCN, 2017).

modest health gains.

Unhealthy diets are a key risk factor for major chronic, non-communicable diseases (NCDs), including obesity, heart attacks, strokes, diabetes and some types of cancers.[2] In 2015 in Europe, diet-related NCDs are estimated to directly account for 29.3% of NCDs-related deaths and 16.4% of NCDs-related disability-adjusted life years (Melaku et al., 2018).[3] The adverse impacts of unhealthy diets on health and health care budgets[4] lead most high-income countries to set up nutritional prevention policies with information measures (e.g., information campaigns, labeling rules) and market intervention measures (e.g., taxes, subsidies, food standards).

At the level of public policies, the link between public health and climate policies raises several questions. Public health and mitigation of climate change are two goods of different nature. At the level of a country, public health is a private good while mitigation of climate change is a public good. The benefits of public health policies depend only on national-level policies on non-communicable diseases, while the benefits of climate policies depend on own but also on other countries' policies. This difference between the two goods could explain why governments might be willing to prioritize public health policies over mitigation policies. There are two other arguments in support of this hypothesis. First, consumers seem to be more responsive to nutritional policies aimed at improving their health than climate policies. This could induce governments to set first nutritional policies with a greater potential to be adopted by consumers. By means of stated choice preference experiment, with 529 participants in a consumer survey on organic vegetable consumption, Mondelaers et al. (2009) have shown that health-related characteristics play a greater role in determining consumer preference than environmental characteristics. A 2017 online survey of 2024 British adults quoted by Dangour et al. (2017) indicatesthat while four in five of British adults would be likely to adopt an environmentally sustainable diet if it would improve their health, only 54% said that they would do so to reduce their impact on the climate change.[5]

[2]The rise of NCDs has been driven by primarily four major risk factors: tobacco use, physical inactivity, the harmful use of alcohol and unhealthy diets.

[3]In 2014, NCDs represented the major share of the burden of disease in Europe and were responsible for 86% of all deaths (European Commission, 2014).

[4]The growing burden of NCDs represents a major challenge for health systems: 70 to 80% of health care budgets are spent on NCDs in the European Union (European Commission, 2014).

[5]Global Food Security. Public Attitudes to Climatic Shocks and their interaction with the Food System. 2017.

Second, the effects of climate policies are felt over longer time horizons than those of nutritional and health policies. Governments with a fixed-term mandate may therefore be tempted to prioritize public health policy actions (on meat consumption, for example) over climate policies. In terms of the budgetary constraint of a public power, it appears then a substitutability between public health policies and climate policies. However, there is a potential complementarity in terms of environmental outcomes because nutritional policies can have beneficial environmental effects, particularly in terms of GHG emissions.

In this paper, we analyze in a game-theoretical model the link between nutritional and climate policies at the supranational level in the context of international climate negotiations. Each country implements both a nutritional policy and a climate mitigation policy, with a bias to prioritize the former policy. A nutritional policy could take the form of a standard or a tax aiming at reducing the consumption of animal products (such as red meat) or equivalently at increasing the relative consumption of vegetal products (over animal products). Changes in diets induced by a nutritional policy leads, one the one hand, to health benefits at the national level. On the other hand, these changes in diets increase or decrease the GHG emissions of the country at the origin of these changes. As GHG emissions are a public "bad", these additional or reduced emissions provoke negative or positive externalities to other countries.

This study addresses the following questions: (i) Do countries' nutritional policies crowd-in or crowd-out their climate mitigation effort?, (ii) Should countries negotiate agreements both on mitigation targets and on nutritional objectives?

To address these questions, we develop a global public good game. First, we study the benchmark case which represents the situation without emissions associated with a nutritional policy. Secondly, we investigate the main model which includes the emissions associated with a nutritional policy. In each case, we characterize the non-cooperative situation represented by a Nash equilibrium, a partial cooperation over climate mitigation policy (called "climate agreement"), and the full cooperation over the climate mitigation and the nutritional policies (called "full agree-

(http://www.foodsecurity.ac.uk/ assets/pdfs/public-attitudes-climatic-shocks-interaction-food-system. pdf, accessed 08.01.19).

ment").

The paper is organized as follows. Section 2 discusses the related literature; Section 3 presents the framework of the model; Section 4 characterizes different institutional arrangements, while Section 5 compares the results of these arrangements. Section 6 proposes simulations evaluating their welfare consequences. Finally, Section 7 concludes by summarizing our main results.

2 Related Literature

Our paper is mainly related to two strands of literature. The first one relates to the literature on the environmental and health effects of nutritional policies. Unlike approaches based on ad-hoc change in diets or optimized diets, economic analyses take into account the change in consumer demand induced by nutritional policies by considering substitution effects between food products. While non-economic approaches tend to show that a convergence between health and climate change mitigation objectives is possible in some conditions and that significant decreases in GHG emissions are achievable at the cost of large changes in diets, economic studies provide less optimistic results (Doro and Réquillart, 2018): the convergence is less systematic and the magnitude of the decrease in GHG emissions is much lower. Moreover, when there is a convergence between the two objectives, the health impact is higher in monetary terms as compared to the environmental impact. In a region-specific global study, without consideration of substitution effects, Springmann et al. (2016) estimate that the transition from meat-based diets to plant-based diets could reduce global mortality by 6–10% and food-related GHG emissions by 29–70% with a baseline scenario in 2050, with large differences between regions. In their assessments of the effects of nutritional recommendations on GHG emissions, Irz et al. (2019) show great disparities between France, Denmark and Finland in adjustment to similar nutritional recommendations: imposition of the nutritional constraints results in reductions in GHG emissions, ranging from 0.2% to 5%, with one notable exception in the case of France, where reducing consumption of all animal products would actually raise GHG emissions by 0.9%. Thus, implementation of diet recommendations does not necessarily benefit the environment and differences between countries might be substantial.

The second strand of the literature studies transboundary pollution problems and international environmental cooperation with game-theoretic modeling (Barrett, 2003; Finus, 2008). The incentives of countries to participate to an agreement on the reduction of GHG emissions have been analyzed with a cartel formation game, which originates from the literature in industrial organization (d'Aspremont et al., 1983) and has been widely applied in the literature on International Environmental Agreements (IEAs) (Barrett, 1994, Carraro and Siniscalco, 1993, and Hoel, 1992). The latter literature points out to a pessimistic result: either climate coalitions are small and gains from cooperation are large, or coalitions are large but gains to cooperation are small. Recent papers analyze the impact of additional strategies to mitigation on the success of coalition formation, like R&D investment to reduce mitigation costs (El-Sayed and Rubio, 2014; Battaglini and Harstad, 2016), breakthrough technologies with zero emissions (Barrett, 2006; Hoel and de Zeeuw, 2010), or adaptation to climate change (Bayramoglu, Finus and Jacques, 2018; Li and Rus, 2019). All these papers focus on the effects of climate-related strategies on climate coalition formation. In this paper, we do not study the coalition formation. We develop an original theoretical model with n similar countries to investigate the effects of nutritional policies on international climate cooperation.

Our paper contributes to the literature in several dimensions. We are the first to provide a theoretical framework that helps highlighting the role played by nutritional policies on the incentives of the countries to provide climate mitigation and to cooperate over the climate with other countries. This game-theoretical framework allows us to investigate the total mitigation achieved under different institutional arrangements. We also investigate whether total mitigation is larger when countries are not informed about the impacts of nutritional policy on GHG emissions, i.e., when they are myopic about the environmental impacts of their nutritional policy. Finally, we assess the welfare implications of two diet recommendations in Denmark, Finland and France.

3 Model

We develop a simple game theory model with n countries. Each country i chooses its mitigation policy inducing a level of direct emissions e_i and its nutritional policy leading to changes in diets f_i which induce indirect emissions $\widetilde{e_i}$. We consider that the nutritional policy is well chosen and well implemented in order to increase the relative consumption of vegetal products (over animal products) and then improve national public health. However, the nutritional policy could decrease or increase GHG emissions of a country through changes in overall diets with international spillovers to other countries.

Total GHG emissions E_i emitted by country i could be written as:

$$E_i = e_i + \widetilde{e_i} \qquad \text{where} \quad \widetilde{e_i} = \alpha_i f_i, \text{ with } \alpha_i >< 0$$

where e_i represents the level of emissions generated by country i after the implementation of climate policy, and $\widetilde{e_i} = \alpha_i f_i$ additional (or reduced) emissions generated by country i coming from the changes in diets triggered by its nutritional policy, f_i. The emissions of country i generated in the business as usual (BAU) case (at the absence of any national climate policy) are denoted $\bar{e}_i$. A climate policy induces a reduction of emissions compared to the BAU, i.e., $\bar{e}_i - e_i > 0$. We assume that $E_i > 0$, thus we discard cases where total emissions generated by country i are zero or negative.

GHG emissions of the country i could be increased or decreased by the GHG emissions associated to a nutritional policy. We focus on two cases:

- Case 1: $-1 < \alpha_i < 0$

- Case 2: $0 < \alpha_i < 1$

Case 1 (*resp.* Case 2) highlights the situation in which a nutritional policy aiming at increasing the relative consumption of vegetal products decreases (*resp.* increases) GHG emissions generated by country i. As the impact of a nutritional policy on emissions is additional, we assume that $|\alpha_i| < 1$. The case $\alpha_i = 0$ corresponds to the standard model without emissions induced by the nutritional policy.

Global GHG emissions $E = \sum_{i=1}^{n} E_i$ induce damages to n countries with $i = 1, 2, \ldots, n$. The payoff function of country i is given by:

$$U_i(e_i, f_i) = \gamma_i A(f_i) + B(e_i) - D\left(E\right). \tag{1}$$

Country i's payoff comprises benefits and costs from changes in diets induced by the nutritional policy f_i, that is, a net benefit $A(f_i)$, benefits $B(e_i)$ from individual (direct) emissions e_i, and also damage costs $D(E)$ which depend on global emissions $E = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n} (e_i + \alpha_i f_i)$.

Throughout of the paper, we assume that countries have identical benefit and cost functions. Here, we study the case of symmetric countries with similar bias for nutritional policies $\gamma_i = \gamma_j = \gamma > 1$ and similar effects of nutritional policies on GHG emissions $\alpha_i = \alpha_j = \alpha$, with $\alpha > 0$ or $\alpha < 0$.

Changes in diets induced by a nutritional policy could lead to net health benefits for country i represented here by the function $A(f_i)$. Benefits represent savings in social security expenditures related to reduction in diets-related diseases and savings related to reduced mortality. Implementation costs include costs of public policy intervention (information campaigns, subsidies for consumers, etc.) and costs for consumers (taxes, utility loss due to changes in taste, increasing cooking time of meals, etc.). We assume that the regulator has a bias towards implementing the nutritional policy instead of the climate policy. Hence, we assume that $\gamma_i > 1$ meaning that the regulator puts a higher weight on net health benefits than on net benefits from mitigation of emissions in its objective function.

Note that all functions, including their first and second derivatives, are continuous in their variable(s). We also make the following assumptions regarding the components of the payoff functions where subscripts denote derivatives, $A_f = \frac{\partial A}{\partial f}$ and $A_{ff} = \frac{\partial^2 A}{\partial f^2}$.

Assumptions

a) $B_e > 0$, $B_{ee} \leq 0$, $D_E > 0$, $D_{EE} > 0$.

b) $A_f \gtreqless 0$, $A_{ff} < 0$.

Assumptions $a)$ and $b)$ are the standard assumptions of concave benefit and convex damage functions. Assumption $a)$ indicates that emission is a pure public "bad", i.e. the marginal damage from emissions depends on the sum of all (and not on individual) emission levels. In contrast, Assumption $b)$ indicates that change in diets is a private good, i.e. the marginal net benefit depends on the individual change in diets of a country (and not on those of others). While change in diet is a private good, it becomes a public good via its effect on global GHG emissions.

4 Institutional Arrangements

We focus on three institutional arrangements: the non-cooperative situation represented by a Nash equilibrium, a climate agreement, and a full agreement (the full cooperative solution). The climate agreement corresponds to partial cooperation on direct emissions only. In contrast, in the full agreement, the regulator takes into account not only negative externalities from direct emissions, but also externalities from indirect emissions due to nutritional policies.

For each institutional arrangement, we first investigate the main case which includes the emissions associated with a nutritional policy in addition to direct emissions. Then, we study the benchmark case which represents the situation without emissions associated with a nutritional policy. This corresponds to the standard model in the literature of international environmental agreements.

4.1 Non-cooperation: Nash equilibrium

We first investigate the non-cooperative solution given by a Nash equilibrium, marked by "NS" for the main case and by "NB" for the benchmark case.

4.1.1 Main case

Country i maximizes its payoff with respect to e_i and f_i taking the total emissions of the other countries $E_{-i} = E - E_i = \sum_{j \neq i} E_j$ as given and with $E_i = e_i + \alpha f_i$:

$$\max_{e_i, f_i} U_i(e_i, f_i) = \gamma A(f_i) + B(e_i) - D(E_i + E_{-i}) \tag{2}$$

The first-order condition (FOC) with respect to e_i is:

$$\frac{\partial U_i}{\partial e_i} = 0 \Leftrightarrow B_e(e_i) - D_E(E)\frac{\partial E}{\partial e_i} = 0 \Leftrightarrow B_e(e_i) = D_E\left(\sum_{i=1}^{n}(e_i + \alpha f_i)\right) \tag{3}$$

This condition shows that the marginal benefits from individual direct emissions are equal to the marginal damage costs from direct emissions. From this FOC, it is clear that each country chooses the same emission level $e_i^{NS} = e_j^{NS} = e^{NS}$.

The FOC with respect to f_i is:

$$\frac{\partial U_i}{\partial f_i} = 0 \Leftrightarrow \gamma A_f(f_i) - D_E(E)\frac{\partial E}{\partial f_i} = 0 \Leftrightarrow \gamma A_f(f_i) = \alpha D_E\left(\sum_{i=1}^{n}(e_i + \alpha f_i)\right) \tag{4}$$

This condition indicates that the marginal net benefits from changes in diets are equal to the marginal damage costs from those changes. This FOC implies that each country chooses the same nutritional policy, hence the same implied changes in diets $f_i^{NS} = f_j^{NS} = f^{NS}$.

These conditions indicate that each country chooses the same levels of direct emissions and changes in diets at the equilibrium. Then, the FOCs can be written as follows:

$$B_e(e^{NS}) = D_E\left(n(e^{NS} + \alpha f^{NS})\right) \tag{5}$$

$$\gamma A_f(f^{NS}) = \alpha D_E\left(n(e^{NS} + \alpha f^{NS})\right) \tag{6}$$

The Hessian matrix of the second derivatives of the payoff function is given by:

$$H^{NS} = \begin{pmatrix} \frac{\partial^2 U_i}{\partial e_i^2} & \frac{\partial^2 U_i}{\partial e_i \partial f_i} \\ \frac{\partial^2 U_i}{\partial f_i \partial e_i} & \frac{\partial^2 U_i}{\partial f_i^2} \end{pmatrix} = \begin{pmatrix} B_{ee} - D_{EE} & -\alpha D_{EE} \\ -\alpha D_{EE} & \gamma A_{ff} - \alpha^2 D_{EE} \end{pmatrix} \tag{7}$$

The first determinant of H^{NS}, $D_1 = B_{ee} - D_{EE}$, is negative by Assumption $a)$ and the second one $D_2 = Det(H^{NS}) = B_{ee}\left(\gamma A_{ff} - \alpha^2 D_{EE}\right) - \gamma D_{EE} A_{ff}$ is positive by Assumptions $a)$ and $b)$. Thus H^{NS} is defined positive and U_i is strictly concave. Then there is a unique solution to the optimization program (2), (e^{NS}, f^{NS}) defined by Equations 5 and 6.

The total payoff function is then given by:

$$W^{NS} = nU^{NS} = n\left[\gamma A(f^{NS}) + B(e^{NS}) - D\left(n(e^{NS} + \alpha f^{NS})\right)\right]. \tag{8}$$

4.1.2 Benchmark Case

In the benchmark case, there are no additional emissions from the nutritional policy, i.e., $\alpha = 0$. We also assume that in this case, there is no political bias towards the implementation of nutritional policies, i.e., $\gamma = 1$, to match the canonical model used in the literature on IEAs. Changes in diets induced by the nutritional policy are still a private good, but without negative or positive externalities; we then have $E_i = e_i$.

The FOCs imply that each country chooses the same emission level $e_i^{NB} = e_j^{NB} = e^{NB}$, and the same nutritional policy, hence the same implied changes in diets $f_i^{NB} = f_j^{NB} = f^{NB}$. The solution is implicitly defined by

$$B_e(e^{NB}) = D_E\left(ne^{NB}\right) \tag{9}$$

$$A_f(f^{NB}) = 0 \tag{10}$$

The Hessian matrix of the second derivatives of the payoff function is given by:

$$H^{NB} = \begin{pmatrix} B_{ee} - D_{EE} & 0 \\ 0 & A_{ff} \end{pmatrix} \tag{11}$$

The quasi-concavity requires that the sign of the two following determinants alternates: $D_1 < 0$ and $D_2 > 0$. We note that $D_1 = B_{ee} - D_{EE} < 0$ by Assumption a), and that $D_2 = Det(H^{NB}) = (B_{ee} - D_{EE})A_{ff} > 0$ by Assumptions a) and b).

The total payoff function at the Nash equilibrium is then given by:

$$W^{NB} = nU^{NB} = n[A(f^{NB}) + B(e^{NB}) - D(ne^{NB})]. \tag{12}$$

For both the main and benchmark cases, we now analyze the links between strategic variables, e_i and f_i, given that global GHG emissions are equal to $E = E_{-i} + e_i + \tilde{e}_i = E_{-i} + e_i + \alpha f_i$ for the main case, and to $E = E_{-i} + e_i$ for the benchmark case.

Proposition 1 (Slopes of Reaction Functions in Emissions and Changes in Diet). *The slope of the reaction function in:*

(i). emissions space $e_i = g_i(E_{-i})$ is given by

$$\begin{aligned} g_i^{'}(E_{-i}) &= \frac{de_i}{dE_{-i}} = \frac{\gamma A_{ff} D_{EE}}{Det(H^{NS})} < 0 \textit{ in the main case.} \\ g_i^{'}(E_{-i}) &= \frac{de_i}{dE_{-i}} = \frac{D_{EE}}{B_{ee} - D_{EE}} < 0 \textit{ in the benchmark case.} \end{aligned}$$

(ii). changes in diet-other's emissions space $f_i = k_i(E_{-i})$ is given by

$$\begin{aligned} k_i^{'}(E_{-i}) &= \frac{df_i}{dE_{-i}} = \frac{\alpha B_{ee} D_{EE}}{Det(H^{NS})} \textit{ and } \operatorname{sgn}\left(\frac{df_i}{dE_{-i}}\right) = \operatorname{sgn}(-\alpha) \textit{ in the main case.} \\ k_i^{'}(E_{-i}) &= \frac{df_i}{dE_{-i}} = 0 \textit{ in the benchmark case.} \end{aligned}$$

(iii). changes in diet-total emissions space $f_i = z_i(E)$ is given by

$$\begin{aligned} z_i^{'}(E) &= \frac{df_i}{dE} = \frac{\alpha D_{EE}}{\gamma A_{ff}} \textit{ and } \operatorname{sgn}\left(\frac{df_i}{dE}\right) = \operatorname{sgn}(-\alpha) \textit{ in the main case.} \\ z_i^{'}(E) &= \frac{df_i}{dE} = 0 \textit{ in the benchmark case.} \end{aligned}$$

Proof. See appendix A. □

The first statement highlights whether emission levels are strategic substitutes or complements. In this game, they are always substitutes if we exclude the case $D_{EE} = 0$ in which case the reaction functions are orthogonal corresponding to dominant strategies. In the case of convex damage functions, a country always reacts to a reduction of total emissions by other countries by an increase in its direct emissions ("leakage" effect).

In the main case, the other two statements rely on the sign of the parameter α. The second statement stresses that when $\alpha < 0\,(> 0)$, a country reacts to a reduction of total emissions by other countries (E_{-i}) by a decrease (increase) in the nutritional policy through changes in diet, inducing a lower effort to reduce indirect emissions. This can be viewed as an "indirect leakage" effect, that is, a leakage effect through the nutritional policy. This indirect leakage effect is also observed in the third statement: when $\alpha < 0\,(> 0)$, a country reacts to a reduction of global emissions (E) by a decrease (increase) in the nutritional policy through changes in diet, inducing a lower effort to reduce indirect emissions

In the benchmark case, there is no link between others' total emissions E_{-i} and individual changes in diets f_i. This also holds for the total level of emissions E. This result is expected as, in the benchmark case, the emissions of a country are not altered by indirect emissions from nutritional policies.

4.2 Full cooperative solution

We now investigate the full cooperative solution, marked by "OS" for the main case, and by "OB" for the benchmark case.

4.2.1 Main case

The social planner maximizes the total payoff of the n countries with respect to e_i and f_i for all i:

$$\max_{e_1,\ldots,e_n,f_1,\ldots,f_n} W = \sum_{i=1}^{n} U_i(e_i, f_i) = \sum_{i=1}^{n} [(\gamma A(f_i) + B(e_i))] - nD\left(\sum_{i=1}^{n}(e_i + \alpha f_i)\right) \tag{13}$$

This solution does not represent a social optimum because governments are assumed to have a bias towards implementing the nutritional policy instead of a climate mitigation policy, i.e., $\gamma > 1$.

The FOC condition with respect to e_i writes $B_e(e_i) = nD_E\left(\sum_{i=1}^{n}(e_i + \alpha f_i)\right) \ \forall i$.

The FOC condition with respect to f_i writes $\gamma A_f(f_i) = \alpha n D_E\left(\sum_{i=1}^{n}(e_i + \alpha f_i)\right) \ \forall i$.

These conditions indicates that the social planner chooses the same levels of emissions and changes in diets for all countries. Then, the FOCs can be written as follows:

$$B_e(e^{OS}) = nD_E(n(e^{OS} + \alpha f^{OS})) \tag{14}$$

$$\gamma A_f(f^{OS}) = \alpha n D_E(n(e^{OS} + \alpha f^{OS})) \tag{15}$$

The first condition shows that the marginal benefits from individual direct emissions are equal to the *sum* of the marginal damage costs from direct emissions for all countries. Here, the social planner takes into account the negative externalities from direct emissions across countries.

The second condition indicates that the marginal net benefits from changes in diets are equal to the *sum* of the marginal damage costs from changes in diets. Here, the social planner takes into account the negative or positive externalities of emissions associated with changes in diets.

The Hessian matrix of the second derivatives of the welfare function, H^{OS}, is a symmetric matrix of size $2n$ with $\frac{\partial^2 W}{\partial e_i^2} = B_{ee} - nD_{EE}$, $\frac{\partial^2 W}{\partial e_i \partial e_j} = -nD_{EE}$, $\frac{\partial^2 W}{\partial e_i \partial f_j} = n\alpha D_{EE}$, $\frac{\partial^2 W}{\partial f_i^2} = \gamma A_{ff} - n\alpha^2 D_{EE}$, and $\frac{\partial^2 W}{\partial f_i \partial f_j} = -n\alpha^2 D_{EE} \quad \forall i, j$. Due to Assumptions $a)$ and $b)$, all the eigenvalues of the matrix H^{OS} are negative; therefore, the welfare function is quasi-concave. As a result, there is a unique solution to the optimization program (13), (e^{OS}, f^{OS}) defined by Equations 14 and 15.

The total payoff of countries at the full cooperative solution is then given by:

$$W^{OS} = nU^{OS} = n\left[\gamma A(f^{OS}) + B(e^{OS}) - D(n(e^{OS} + \alpha f^{OS})\right]. \tag{16}$$

4.2.2 Benchmark case

At the benchmark case, the social planner chooses the same levels of emission $e_i^{OB} = e_j^{OB} = e^{OB}$ and changes in diet $f_i^{OB} = f_j^{OB} = f^{OB}$ for each country. The solution is defined as follows:

$$B_e(e^{OB}) = nD_E(ne^{OB}) \tag{17}$$

$$A_f(f^{OB}) = 0 \tag{18}$$

The associated Hessian matrix is: H^{OB} i a symmetric matrix of size $2n$ with $\frac{\partial^2 W}{\partial e_i^2} = B_{ee} - nD_{EE}$, $\frac{\partial^2 W}{\partial e_i \partial e_j} = -nD_{EE}$, $\frac{\partial^2 W}{\partial e_i \partial f_j} = 0$, $\frac{\partial^2 W}{\partial f_i^2} = A_{ff}$, and $\frac{\partial^2 W}{\partial f_i \partial f_j} = 0 \quad \forall i,\, j$. Due to Assumptions $a)$ and $b)$, all the eigenvalues of the matrix H^{OB} are negative; therefore, the welfare function is quasi-concave. As a result, there is a unique solution, (e^{OB}, f^{OB}) defined by Equations 17 and 18.

The total payoff of countries at the full cooperative solution is then given by:

$$W^{OB} = nU^{OB} = n\left[A(f^{OB}) + B(e^{OB}) - D(ne^{OB})\right]. \tag{19}$$

4.3 Climate agreement

We finally investigate the climate agreement solution, marked by "CS" for the main case, and by "CB" for the benchmark case. Here, countries cooperate only on climate mitigation policies through direct emissions. Each country continues to choose its nutritional policy unilaterally and non-cooperatively.

4.3.1 Main case

The climate agreement program writes as follows

$$\max_{e_1,\dots,e_n} \sum_{i=1}^{n} U_i(e_i, f_i) = \sum_{i=1}^{n} \left[\gamma A(f_i) + B(e_i)\right] - nD\left(\sum_{i=1}^{n}(e_i + \alpha f_i)\right). \tag{20}$$

The n FOCs give that

$$B_e(e_i) = nD_E\left(\sum_{i=1}^{n}(e_i + \alpha f_i)\right)\ \forall i. \tag{21}$$

The Hessian matrix of the second derivatives of the welfare function is given by H^{CS}, a symmetric matrix of size n with $\frac{\partial^2 W}{\partial e_i^2} = B_{ee} - nD_{EE}$, $\frac{\partial^2 W}{\partial e_i \partial e_j} = -nD_{EE} \quad \forall i,\ j$. Due to Assumptions $a)$ and $b)$, all the eigenvalues of the matrix H^{CS} are negative; therefore, the welfare function is quasi-concave.

Levels of changes in diet are given by similar FOCs to Equation (4), that is,

$$\gamma A_f(f_i) = \alpha D_E\left(\sum_{i=1}^{n}(e_i + \alpha f_i)\right)\ \forall i. \tag{22}$$

The second order condition is satisfied because of the Assumptions $a)$ and $b)$.

From Equations (21) and (22), we obtain that $e_i = e_j = e^{CS}$ and $f_i = f_j = f^{CS}$, and the following climate agreement solution:

$$B_e(e^{CS}) = nD_E\left(n(e^{CS} + \alpha f^{CS})\right) \tag{23}$$

$$\gamma A_f(f^{CS}) = \alpha D_E\left(n(e^{CS} + \alpha f^{CS})\right) \tag{24}$$

As a result, there is a unique solution to the optimization program (20), (e^{CS}, f^{CS}) defined by Equations 23 and 24.

The total payoff of all countries at the climate agreement is then given by:

$$W^{CS} = nU^{CS} = n\left[\gamma A(f^{CS}) + B(e^{CS}) - D(n(e^{CS} + \alpha f^{CS}))\right]. \tag{25}$$

4.3.2 Benchmark case

At the Benchmark case, the FOCs imply that each country has the same emission level $e_i^{CB} = e_j^{CB} = e^{CB}$ and the same level of changes in diet $f_i^{CB} = f_j^{CB} = f^{CB}$. The solution is:[6]

$$B_e(e^{CB}) = nD_E\left(ne^{CB}\right) \tag{26}$$

$$A_f(f^{CB}) = 0 \tag{27}$$

The total payoff of countries at the climate agreement solution is then given by:

$$nU^{CB} = n\left[A(f^{CB}) + B(e^{CB}) - D(ne^{CB})\right]. \tag{28}$$

5 Comparison of Policy Variables

In this section, our objective is to compare the equilibrium levels of direct emissions, changes in diet and total emissions within and between the institutional arrangements. Within-comparison includes the comparison of policy variables between the different institutional arrangements for both the benchmark and main cases. Between-comparison involves first the comparison between the benchmark and main cases. Secondly, it involves the comparison of policy variables in the case when countries are myopic, i.e., they do not take into account the indirect emissions from changes in diets in their climate damage function, with the full cooperative solution. This comparison helps characterizing the bias from misinformation on the environmental effects of nutritional policies.

5.1 Benchmark case vs. main case

Here, we compare the results of the benchmark and the main model for each institutional arrangement.

[6] The second order conditions are automatically satisfied thanks to Assumptions $a)$ and $b)$.

Proposition 2. *(i). The nutritional policy is more ambitious in the main model compared to the benchmark case, i.e., $f^{jS} > f^{jB}$ when $\alpha < 0$, for $j = N, C, O$. The reverse holds when $\alpha > 0$.*

(ii). The individual direct emission level is higher in the main model compared to the benchmark case, i.e., $e^{jS} > e^{jB}$ when $\alpha < 0$, for $j = N, C, O$. The reverse holds when $\alpha > 0$.

(iii). The total level of emissions is higher (lower) in the main model compared to the benchmark case, $E^{jS} > E^{jB}$ ($E^{jS} < E^{jB}$), when $\alpha > \alpha_j^{BS}$ ($\alpha < \alpha_j^{BS}$), with α_j^{BS} having the same sign as α, for all $j = N$, C, and O.

Proof. See appendix B. □

The logic behind the first statement, regarding the nutritional policy, is quite intuitive. In the main model, when the nutritional policy allows to decrease GHG emissions generated by a country ($\alpha < 0$), there are two means for the country to reduce its level of emissions: via direct emissions or indirect emissions through changes in diet. In the main model, the nutritional policy through the healthy changes in diets helps the country to reduce its emissions, while this effect is absent in the benchmark case. The same nutritional policy also leads to public health benefits. Hence, an individual country has an incentive to implement a more ambitious nutritional policy than in the benchmark case when $\alpha < 0$. The reverse holds for $\alpha > 0$.

The second statement is a consequence of the first one. When $\alpha < 0$, we know that the nutritional policy is more ambitious in the main model than in the benchmark case. This decreases the environmental damages, which gives the possibility to the country to increase its direct emissions.

The last statement stems from the two previous statements. In the benchmark case, the nutritional policy has no impact on emissions ($\alpha = 0$); thus, the total level of emissions matches the level of direct emissions. In the main case, the overall level of GHG emissions depends not only on the sign of emission changes due to the nutritional policy, but also on its magnitude. If this magnitude is relatively low ($|\alpha| < |\alpha_j^{BS}|$), then the impact of direct emissions prevails on the impact of indirect emissions. Hence, global GHG emissions are lower in the main model compared to the benchmark case when the nutritional policy inducing changes in diet slightly increases GHG emissions generated by a country or, conversely, when the nutritional policy allows a country to strongly reduce its emissions.

5.2 Benchmark case: institutional arrangements

Here, we compare the outcomes of the Nash equilibrium, the full cooperative solution, and the climate agreement in the benchmark case.

Proposition 3. *When there are no additional emissions from the nutritional policy ($\alpha = 0$) and no political bias towards the implementation of nutritional policies ($\gamma = 1$), comparisons between the outcomes of the Nash equilibrium (NB), the full cooperative solution (OB), and the climate agreement (CB) give the following results in terms of*

(i). direct emissions generated by each country: $e^{NB} > e^{OB} = e^{CB}$

(ii). healthy changes in diet in each country: $f^{NB} = f^{OB} = f^{CB}$

(iii). total level of emissions: $E^{NB} > E^{OB} = E^{CB}$

Proof. (i). The right-hand-side (RHS) of Equations (17) and (26) are larger than the RHS of Equation (9). As the left-hand-side (LHS) of these three equations ($B_e(e)$) is decreasing by Assumption a), one obtains that $e^{NB} > e^{OS} = e^{CB}$. *(ii).* From Equations (10), (18), and (27), the result follows. *(iii).* As $E = \sum_{i=1}^{n} e_i = ne$, the result obtains. □

As changes in diets induced by the nutritional policy have now no negative or positive externalities in terms of GHG emissions, the full cooperative solution and the climate agreement give exactly the same results. As expected, due to the negative externalities of GHG emissions, emissions under the non-cooperative equilibrium are higher than those under the full cooperative solution and the climate agreement.

5.3 Main case: institutional arrangements

Here, we compare the outcomes of the Nash equilibrium,the climate agreement, and the full cooperative solution in the main model for symmetric countries.

Proposition 4. *When public nutritional policies induce similar effects on GHG emissions in all countries ($\alpha_i = \alpha_j = \alpha \lesseqgtr 0$), comparisons between the outcomes of the Nash equilibrium (NS), the climate agreement (CS), and the full cooperative solution (OS) give the following results in terms of*

(i). direct emissions generated by each country: $\quad e^{CS} < e^{OS} < e^{NS} \quad \forall \alpha$

(ii). healthy changes in diet in each country, and the related indirect emissions generated by each country:

$$\left.\begin{array}{ll} f^{OS} \geq f^{NS} > f^{CS} & \text{when } \alpha < 0 \\ f^{OS} \leq f^{NS} < f^{CS} & \text{when } \alpha > 0 \end{array}\right\} \quad \Leftrightarrow \quad \tilde{e}^{OS} < \tilde{e}^{NS} < \tilde{e}^{CS} \quad \forall \alpha$$

(iii). total level of emissions: $\quad E^{OS} < E^{NS} \quad \forall \alpha,$

there exists a value of α, $\alpha^{CO} > 0$, such that if $\alpha \in [-\alpha^{CO}, \alpha^{CO}]$, $E^{CS} \leq E^{OS}$ and $E^{CS} > E^{OS}$ otherwise, and

there exists a value of α, $\alpha^{NC} > 0$, such that if $\alpha \in [-\alpha^{NC}, \alpha^{NC}]$, $E^{CS} \leq E^{NS}$ and $E^{CS} > E^{NS}$ otherwise.

This can be summarized in the following table:

$\|\alpha\| < \alpha^{CO}$	$E^{CS} < E^{OS} < E^{NS}$
$\alpha^{CO} < \|\alpha\| < \|\alpha^{NC}\|$	$E^{OS} < E^{CS} < E^{NS}$
$\|\alpha\| > \|\alpha^{NC}\|$	$E^{OS} < E^{NS} < E^{CS}$

Proof. See appendix C. □

Proposition 4 implies several results. Regarding (individual) direct emissions, the climate agreement leads to a lower level than the full cooperative solution and the Nash equilibrium, because direct emissions are the unique variable chosen cooperatively in the climate agreement while in the full agreement the indirect emissions are also cooperatively chosen through the nutritional policy and the related changes in diets.

Regarding (individual) indirect emissions, their level is lowest at the full cooperative solution, followed by the Nash equilibrium and the climate agreement. Thus, the full cooperative solution is the most effective institutional arrangement to reduce indirect emissions related to healthy diets and the climate agreement is the worst one. As in the climate agreement, each country chooses very low direct emissions and the nutritional policy is chosen in a non-cooperative way, each country maximizes its payoff by choosing a national nutritional policy inducing high indirect emissions.

Regarding global emissions, as expected, global emissions are lower under the full agreement than under non-cooperation. As we have shown, the full agreement leads to lower direct and indirect emissions than under the Nash equilibrium. This result is explained by the fact the full agreement correctly internalizes global externalities from both direct emissions and indirect emissions associated to the nutritional policy.

Interestingly, the comparison of the climate agreement with other equilibria depends on the magnitude of the impact of nutritional policy on emissions, that is, the level of $|\alpha|$. This comes from the fact that the climate agreement leads to the lowest level of direct emissions but to the highest level of indirect emissions. If the impact of nutritional policy on emissions is low, the climate agreement leads to the lowest global emissions. If the nutritional policy induces a high (positive or negative) variation in GHG emissions through changes in diets, global emissions are lower with a full agreement than without any agreement or with the partial climate agreement. Even more interesting is the observation that the overall emissions could be lower in non cooperation than in climate agreement. Climate negotiations lead to a low level of direct emissions. When is $\alpha < 0$, the nutritional policy is, however, not ambitious enough, while it would pay to use it more generously in the cases where the indirect mitigation tool were powerful ($|\alpha| > \alpha^{NC}$).

5.4 Myopic countries vs. cooperative solutions

Here, our objective is to investigate the role of information detained by countries about the environmental impacts of their nutritional policy on global mitigation. Is it necessarily bad for the environment that countries are not informed about the impacts of nutritional policy on GHG emissions? This could be an option to limit the extent of the free-rider problem related to the indirect leakage from the nutritional policy. We thus study here the case of myopic countries which are not informed about the environmental impacts of their nutritional policy. For that, we compare the level of global emissions in the full cooperative solution (OS) and the climate agreement (CS) under full information, with the case in which countries are myopic (about the impact of the nutritional policy on GHG emissions) when they negotiate a climate agreement. To do that, regarding the climate agreement in the benchmark case (CB), we should also account for indirect emissions generated by the nutritional policy. Thus, we define $\tilde{E}^{CB} = E^{CB} + n(\alpha f^{CB}) = n(e^{CB} + \alpha f^{CB})$ as the effective GHG emissions for the climate agreement in the benchmark case.

Proposition 5. *When public nutritional policies induce similar effects on GHG emissions in all countries ($\alpha_i = \alpha_j = \alpha \lesseqgtr 0$), comparisons between the outcomes of the climate agreement in the benchmark case (CB), the climate agreement in the main case (CS), and the full cooperative solution in the main case (OS) give the following results in terms of*

(i). direct emissions generated by each country:

$$e^{CB} < e^{CS} < e^{OS} \quad \textit{when } \alpha < 0$$
$$e^{CS} < e^{OS} < e^{CB} \quad \textit{when } \alpha > 0$$

(ii). healthy changes in diet in each country, and the related indirect emissions generated by each country:

$$\left.\begin{array}{ll} f^{CB} < f^{CS} < f^{OS} & \textit{when } \alpha < 0 \\ f^{CB} > f^{CS} > f^{OS} & \textit{when } \alpha > 0 \end{array}\right\} \quad \Leftrightarrow \quad \tilde{e}^{OS} < \tilde{e}^{CS} < \tilde{e}^{CB} \quad \forall \alpha$$

(iii). total level of emissions:

	$\alpha < 0$	$\alpha > 0$
$\lvert\alpha\rvert < \alpha^{CO}$	$\tilde{E}^{CB} < E^{CS} < E^{OS}$	$E^{CS} < E^{OS} < \tilde{E}^{CB}$
$\alpha^{CO} < \lvert\alpha\rvert < \lvert\tilde{\alpha}_1\rvert$	$\tilde{E}^{CB} < E^{OS} < E^{CS}$	
$\lvert\tilde{\alpha}_1\rvert < \lvert\alpha\rvert < \lvert\tilde{\alpha}_2\rvert$	$E^{OS} < \tilde{E}^{CB} < E^{CS}$	$E^{OS} < E^{CS} < \tilde{E}^{CB}$
$\lvert\alpha\rvert > \lvert\tilde{\alpha}_2\rvert$	$E^{OS} < E^{CS} < \tilde{E}^{CB}$	

Proof. See appendix D. □

Regarding (individual) direct emissions, when $\alpha < 0$, due to the possible compensation between indirect and direct emissions through the nutritional policy in the main case, the climate agreement in the benchmark case allows each country to produce fewer emissions than the climate or full agreement in the main case. Conversely, when when $\alpha > 0$, the climate agreement in the benchmark case, which does not take into account additional emissions from the nutritional policy, is the worse situation in terms of direct emissions. When a country does not know the effects of its nutritional policy on GHG emissions when it negotiates its direct level of emissions with others, it avoids the indirect leakage effect.

In terms of indirect emissions, we show that the full agreement in the main case is the best arrangement, followed by the climate agreement in the main case, and the climate agreement in the benchmark case. When the nutritional policy impacts GHG emissions through changes in diets, whether positively or negatively, under full information, in the full agreement, the nutritional policy is optimally used to reduce indirect emissions.

The third statement allows us to deduce several interesting results in terms of global emissions. First, when the magnitude of emission changes induced by the nutritional policy is relatively high, whatever the direction of these changes, the best institutional arrangement is the full cooperative arrangement taking into consideration the positive or negative impact of changes in diets on GHG emissions. Indeed, when α is high in absolute value, the level of global emissions is mainly determined by indirect emissions (see the ranking in *Proposition 5 (ii)*). Second, when the magnitude of emission changes induced by the nutritional policy is relatively low, the best institutional arrangement depends on the sign of the impact of the nutritional policy on GHG emissions. Indeed, when α is very low in absolute value ($|\alpha| < \alpha^{CO}$), the level of global emissions is mainly determined by direct emissions (see the ranking in *Proposition 5 (i)*). In this case, when the nutritional policy decreases GHG emissions ($\alpha < 0$), it is better not to take this information into account in climate negotiations. The reverse holds when the nutritional policy increases GHG emissions ($\alpha > 0$).

In order to analyze the welfare of the countries and understand their preferences for one or the other institutional arrangement, we resort to numerical calculations for the case of the quadratic benefit and cost functions.

6 Example with Quadratic Functions

We adopt the following quadratic functional forms:

$B(e_i) = b_1 e_i - \frac{b_2}{2} e_i^2$ with $b_1 > 0$ and $b_2 > 0$.
$D(E) = \frac{d}{2} E^2$ with $d > 0$.
$A(f_i) = (a_1 f_i - \frac{a_2}{2} f_i^2)$ with $a_1 > 0$ and $a_2 > 0$.

The payoff function then writes:

$$\Pi_i = \gamma \left(a_1 f_i - \frac{a_2}{2} f_i^2 \right) + \left(b_1 e_i - \frac{b_2}{2} e_i^2 \right) - \frac{d}{2} E^2 \text{ with } E = E_i + E_{-i} = (e_i + \alpha_i f_i) + E_{-i}.$$

These functional forms should respect the assumptions of the model:

- $E_i = e_i + \alpha f_i > 0$.
- $D_E = dE > 0$ and $D_{EE} = d > 0$.
- $A_f = a_1 - a_2 f_i >< 0$ and $A_{ff} = -a_2 < 0$.
- $B_e = b_1 - b_2 e_i > 0$ and $B_{ee} = -b_2 < 0$.

In Appendix F we provide the analytical forms for the equilibrium values of the variables in the quadratic model, for all institutional arrangements. We also list the different conditions that must be met at all institutional arrangements, to be in line with the assumptions of the model.

Below, we first undertake a simulation exercice in order to assess the welfare implications of two nutritional recommendations in the case of Danish, Finnish and French diets. Then, we carry out more systematic numerical simulations on a larger parameter set in order to check the robustness of the results in terms of welfare.

6.1 Assessment of two nutritional policies

Irz et al. (2019) evaluate ex-ante the effects of promoting climate-friendly diet recommendations in Denmark, Finland and France. The simulation approach is based on the combination of three models: a behavioral model of consumption adjustment to dietary constraints, a model of climate impact based on the life-cycle analysis of foods, and an epidemiological model calculating health outcomes. They simulate, among others, two nutritional recommendations: 5% increase in the consumption of fruits and vegetables (hereafter F&V policy), and a 5% decrease in the consumption of all animal products (hereafter AAP policy). Thus, they provide very useful information for Denmark, Finland and France on the associated national GHG emissions to changes in diets coming from the underlying nutritional recommendations.

In contrast to Irz et al. (2019), our simulation exercise evaluates the effects of the two nutritional recommendations by accounting for the free-rider incentives of the countries to provide the global public good, which is climate mitigation. For this exercise, we consider similar countries to be in line with the theoretical model. We thus consider the same parameter values for the (n) countries. We first run simulations for Denmark, assuming that the consumers in all countries adjust their food consumption to dietary constraints as Danish consumers. We then repeat this exercise for Finland and France. In the following, we describe the calibration of the parameters.

Data and estimation

The function of benefit from direct emissions is estimated using data on GDP and national GHG emissions. Data on GDP (current US dollars) and total GHG emissions ($kt\ CO_2eq$) for each country (Denmark, Finland, France) are obtained from the World Bank database, World Development Indicators. The data span from 1960 to 2018. For this panel data, we have estimated the parameters of the following equation with a random-effects panel data model:

$$GDP_{it} = c_1 e_{it} + c_2 e_{it}^2 + \epsilon_{it}$$

We obtain estimates of parameters c_1 and c_2 which are significant at 5% significant level. These estimates imply the following values of the parameters in our model: $b_1 = 17,500,000$ and $b_2 =$

46.08.

We have not been able to estimate the parameters of the damage function $Damage_{it} = \frac{d}{2}E_t^2$ based on data on climate change costs DARA International (2012), also used by Li and Rus (2019), as the temporal variation in data is absent and the number of countries is only three. Instead, we use the estimates provided for social cost of carbon (SCC) (marginal damage from total emissions) in the literature. Bretschger and Pattakou (2019) reports that SCC in 2010 lies within the range of $20\$/tCO_2$ to $120\$/tCO_2$ and undertakes a calibration with $50\$/tCO_2$ based on a quadratic damage function. In the United States, the Environmental Protection Agency, as well as other federal agencies, use a SCC to value the climate impacts of policies. Since 2017, only national damage is taken into account, and not the global damage considered so far. The recommended value is $5.6\$_{2007}/tC$ for a discount rate of 3% for 2020 (Quinet, 2019). Based on these values, we run simulations for a SCC (parameter d) in the range $[5, 50]$ by a change of 5.

We now come to the calibration of the parameter $\alpha_i = \frac{\widetilde{e_i}}{f_i}$ which measures the proportion of additional national GHG emissions due to a national nutritional policy. In Irz et al. (2019), not all the nutritional recommendations lead to win-win situations with respect to climate and health outcomes. Only the F&V consumption through campaigns of the "five-a-day" type passes the cost-benefit test in all three countries. This scenario leads to the following emissions reductions in absolute value in $kt\ CO_2eq$ and in percentage respectively: Denmark $(-137; -0.7\%)$, Finland $(-49; -0.3\%)$, and France $(-983; -5.1\%)$. By contrast, targeting consumption of all animal products (AAP policy) is only found to be desirable in Denmark and Finland. This scenario leads to following emission changes in absolute value ($kt\ CO_2eq$) and in percentage: Denmark $(-60; -0.3\%)$, Finland $(-28; -0.2\%)$, France $(179; 0.9\%)$. Based on these figures in Irz et al. (2019) and on the formulae $\alpha = \frac{\widetilde{e_i}}{f_i}$, we calibrate the parameter α_i in the case of Dannish, Finnish and French diets (Table 1). As the parameter α must be lower than 1, we normalize arbitrarily the policy variable f_i to 1000. For the F&V policy in Denmark for instance, this gives the following estimate $\alpha_i = \frac{-137}{F\&V} = \frac{-137}{1000} = -0.137$.

We keep the total number of countries as $n = 10$. For the other variables for which the literature does not provide any estimate, we use arbitrary values which ensure the respect of the constraints

Table 1: Calibration of the parameter α_i

	F&V $(+5\%)$	All animal products (-5%)
Denmark	$\alpha = -0.137$	$\alpha = -0.06$
Finland	$\alpha = -0.049$	$\alpha = -0.028$
France	$\alpha = -0.983$	$\alpha = 0.179$

of the model[7]. We obtained results for all simulation runs except the case $\alpha = 0.179$ which violates these constraints.

For reporting the simulation results, we mainly focus on the comparison of total emissions and welfare under alternative institutional arrangements in the *main case*. Below, we gather the simulation runs for which we obtain similar qualitative results.

Very small α in absolute value: Dannish AAP policy ($\alpha = -0.06$); Finnish F&V policy ($\alpha = -0.049$); Finnish AAP policy ($\alpha = -0.028$)

In the main case, we note that in all relevant cases $(2,100$ cases), full cooperation is always the best arrangement, followed by the climate agreement, and the non-cooperation. In this case, the climate agreement always outperforms the non-cooperation in terms of welfare. As can be remarked by looking at the relatively low values of parameter α in absolute value, all the cases here correspond to a low effect of nutritional policy in saving GHG emissions. Thus, in non-cooperation, using the nutritional policy in addition to the climate policy for climate purposes does not pay in terms of welfare.

Small α in absolute value: Dannish F&V policy ($\alpha = -0.137$)

We note that in all relevant cases $(2,100$ cases), full cooperation is always the best arrangement in terms of welfare. Only in a minority of 50 cases, countries are better off in non-cooperation than in a climate agreement that imposes a too low level of direct emissions to the countries (*Proposition 4*). Otherwise, the climate agreement outperforms the non-cooperative solution in terms of welfare.

[7]We consider the following parameter constellations: Parameters a_1 moves from 1 to 5 by 1; a_2 moves from 1 to 2 by 1; γ moves from 1.1 to 3.1 by 0.1.

Large α in absolute value: French F&V policy ($\alpha = -0.983$)

Here, we note that in all relevant cases ($2,100$ cases), by no surprise full cooperation is always the best arrangement. Strikingly, the non-cooperation always outperforms the climate agreement. Differently from the previous cases, here parameter α is very large in absolute value meaning that the nutritional policy is able to reduce GHG emissions in a large extent. Consequently, not using this instrument in climate negotiations worsens the welfare, compared to the non-cooperation.

In the following, we undertake more systematic simulations in order to check the robustness of our previous results, but also to investigate other cases not studied in the previous section.

6.2 Robustness checks and other numerical results

We first consider parameter constellations[8] $b_1, b_2, a_1, a_2, d, \alpha, \gamma$ and n that give our total parameter set, which we call set 1 and consists of $199,500$ different combinations. In particular, we consider the subset of set 1 with parameter constellations which satisfy the contraints of the theoretical model. We call this set 2; it consists of $94,500$ elements when $\alpha < 0$, and it consists of 882 elements when $\alpha > 0$. This simulation exercice allows us to investigate the cases with $\alpha > 0$, which was not possible with the previous assessment of nutritional recommendations. For *each simulation run*, we compare the levels of total emissions and welfare achieved in the alternative institutional arrangements.

Comparisons in the main case

In the main case, we note that no matter the sign of α, the ranking of institutional arrangements in terms of total pollution is always: $E^{OS} < E^{CS} < E^{NS}$. Regarding total welfare, for the parameter constellations pertaining to $\alpha > 0$, the ranking of institutional arrangements in terms of welfare is as follows $W^{NS} < W^{CS} < W^{OS}$: non-cooperation is the worst institutional arrangement in terms of welfare in these cases. When $\alpha > 0$, notice that welfare ranking follows closely the ranking of total pollution. This is not always the case when $\alpha < 0$. As expected, full cooperation is

[8]Parameters a_1 and d move from 1 to 5 by 1; b_2 and a_2 move from 1 to 2 by 1; b_1 moves from 10 to 50 by 10; α moves from -0.9 to 0.9 by 0.1; γ moves from 1.1 to 3.1 by 0.1; n is equal to 10.

always the best arrangement. In a minority of $14,200$ cases (over $94,500$ cases in total), countries are better off in non-cooperation than in a climate agreement that imposes a too low level of direct emissions to the countries (*Proposition 4*). These findings confirm the previous results obtained for specific nutritional recommendations. The value-added of the assessment exercice undertaken before is to highlight that these cases correspond to specific values of parameter α (when $\alpha < 0$). As observed before, countries might be better off in non-cooperation than in a climate agreement when α is not too small in absolute value (as in the case of French F&V policy). In these cases, emissions savings induced by changes in diets are sufficiently large that it is penalizing not to use the nutritional policy in climate negotiations.

Implications of misinformation related to emissions

We finally investigate the welfare implications of misinformation related to the impacts of healthy changes in diet on emissions. When countries are not informed about these impacts, the effective level of total emissions is given by $\tilde{E}^{CB} = E^{CB} + n(\alpha f^{CB}) = n(e^{CB} + \alpha f^{CB})$. We compare this level of total pollution to those when countries negotiate agreements with full information. We obtain the following results: $sgn(\tilde{E}^{CB} - E^{OS}) = sgn(\alpha)$ and $sgn(\tilde{E}^{CB} - E^{CS}) = sgn(\alpha)$. To summarize:

- When $\alpha < 0$, the ranking is $\tilde{E}^{CB} < E^{OS} < E^{CS}$.
- When $\alpha > 0$, the ranking is $E^{OS} < E^{CS} < \tilde{E}^{CB}$.

These results indicate that providing full information is beneficial for the environment if this information is "pessimistic", namely that healthy changes in diet increase a country's emissions ($\alpha > 0$).

The question now is to know whether this is also holds for welfare. Remember that the payoff of myopic countries (about the impact of the nutritional policy on GHG emissions) when they negotiate a climate agreement is: $\tilde{U}^{CB} = \gamma \left(a_1 f^{CB} - \frac{a_2}{2} f^{CB\,2} \right) + \left(b_1 e^{CB} - \frac{b_2}{2} e^{CB\,2} \right) - \frac{d}{2} (\tilde{E}^{CB})^2$.

We compare this payoff with the payoff of countries when they negotiate a climate agreement or a full agrement with full information. We find that no matter the sign of α, the climate agreement negotiated by biased governments always underperforms in terms of total welfare agreements negotiated by governments with full information (either on climate only, or on both climate and nutritional policies). In terms of welfare, it always pays to provide the whole information to governments negotiating mitigation and/or nutritional policies allowing them to choose the economically optimal levels of policy instruments.

7 Conclusion

The aim of this paper was to analyze the interactions at the international level between countries' nutritional and climate mitigation policies. In particular, this study has investigated whether countries' decentralized nutritional policies crowd-in or crowd-out their climate mitigation efforts.

To undertake this analysis, we have developed a global public good game where each country implements both a nutritional policy and a climate mitigation policy, with a bias to prioritize the former policy. A nutritional policy could take the form of a standard or a tax aiming at reducing the consumption of animal products (such as red meat) or equivalently at increasing the relative consumption of vegetal products (over animal products). Changes in diets induced by a nutritional policy leads, one the one hand, to health benefits at the national level. On the other hand, these changes in diet increase or decrease the GHG emissions of the country at the origin of these changes. As GHG emissions are a public "bad", these additional or reduced emissions provoke negative or positive externalities to other countries.

In this framework, we compare different institutional arrangements. In particular, we ask whether countries should negotiate an agreement on climate policies only (climate agreement), or an agreement on both climate and nutritional policies (full agreement). To this end, we compare the outcomes of the non-cooperative situation represented by a Nash equilibrium, a climate agreement, and the full agreement.

We obtain several interesting theoretical results. First, in addition to leakage in countries' direct emission strategies, our model highlights a novel leakage effect through the nutritional policy. The effects of nutritional policies on the free-rider incentives for mitigation depend on the impact of healthy diets in terms of GHG emissions. When healthy changes in diet allow the countries to reduce their emissions ($\alpha < 0$), then a country reacts to a reduction of total emissions by other countries by a decrease in its nutritional policy, inducing a lower effort to reduce indirect emissions. This can be viewed as an "indirect leakage" effect, that is, a leakage effect through the nutritional policy. Consequently, the free-rider incentives are present through two channels: direct emissions and indirect emissions via the nutritional policy, which reinforces the free-rider problem for public good provision.

In terms of global emissions, our theoretical results show that the best arrangement depends on the extent of the impact of healthy changes in diets on emission levels (magnitude of $|\alpha|$), and not on their direction. It is better to cooperate both on climate mitigation and nutritional policies when healthy changes in diets have a large impact on emissions, whatever the direction of this impact. As the extent of indirect emission externalities is large in this case, an agreement only on climate policies is not sufficient as it fails to internalize externalities from indirect emissions.

We have also investigated whether it is necessarily bad for the environment that countries are not informed about the impacts of nutritional policy on GHG emissions. This could be an option to cancel the free-rider problem related to the indirect leakage from the nutritional policy. Our theoretical results on the role of information highlight again the importance of the magnitude of emission changes induced by the nutritional policy. When this magnitude is relatively high, whatever the direction of these changes, it is better to provide the full information to countries and let them negotiate a full agreement over their climate and nutritional policies. In contrast, when this magnitude is very low and the nutritional policy decreases GHG emissions, then it is better to negotiate over the climate policy only, without providing information to countries about the environmental impacts of their nutritional policies.

Finally, in terms of total welfare, our numerical simulations first show that in some cases (for instance when $|\alpha|$ is large in the case α is negative), non-cooperation could outperform a climate agreement alone. In these cases, not using the nutritional policy as an alternative mitigation strategy in climate negotiations worsens the welfare, compared to the non-cooperation. Second, as expected, in terms of welfare, it is always better to cooperate both on climate mitigation and nutritional policies as in the full agreement, the nutritional policy is optimally used to reduce indirect emissions. These results seem to be in line with the recent EU New Green Deal and its from Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system. Farm to Fork Strategy foresees European-wide initiatives so that European diets are in line with nutritional recommendations.

References

d'Aspremont, C., Jacquemin, A., Gabszewicz, J. J., Weymark, J. A. (1983). On the stability of collusive price leadership. Canadian Journal of economics, 17-25.

Aleksandrowicz, L., Green, R., Joy, E. J., Smith, P., Haines, A., 2016. The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: a systematic review. PloS one 11(11).

Barrett, S. (1994). Self-enforcing international environmental agreements. Oxford Economic Papers, 878-894.

Barrett, S. (2003). Environment and statecraft: The strategy of environmental treaty-making. OUP Oxford.

Barrett, S. (2006). Climate treaties and "breakthrough" technologies. American Economic Review, 96(2), 22-25.

Battaglini, M., Harstad, B. (2016). Participation and duration of environmental agreements. Journal of Political Economy, 124(1), 160-204.

Bayramoglu, B., Finus, M., Jacques, J. F. (2018). Climate agreements in a mitigation-adaptation game. Journal of Public Economics, 165, 101-113.

Bretschger, L., Pattakou, A. (2019). As bad as it gets: how climate damage functions affect growth and the social cost of carbon. Environmental and resource economics, 72(1), 5-26.

Carraro, C., Siniscalco, D. (1993). Strategies for the international protection of the environment. Journal of public Economics, 52(3), 309-328.

Dangour, A. D., Mace, G., Shankar, B., 2017. Food systems, nutrition, health and the environment. The Lancet Planetary Health, 1(1), e8–e9.

DARA International (2012). Climate Vulnerability Monitor 2nd Edition: A Guide to the Cold Calculus of a Hot Planet. Accessed: 2015-06-24.

Doro, E., Réquillart, V., 2018. Sustainable diets: are nutritional objectives and low-carbon-emission objectives compatible? TSE Working Papers 18-913, Toulouse School of Economics.

El-Sayed, A., Rubio, S. J. (2014). Sharing R&D investments in cleaner technologies to mitigate climate change. Resource and Energy Economics, 38, 168-180.

European Commission, 2014. The 2014 EU Summit on Chronic Diseases. Brussels, 3 and 4 April 2014, Conference Conclusions. http://ec.europa.eu/health/major_chronic_diseases/docs/ev_20140403_mi_en.pdf (accessed 20 December 2018).

Finus, M., 2008. Game theoretic research on the design of international environmental agreements: insights, critical remarks, and future challenges. International Review of Environmental and Resource Economics, 2(1), 29-67.

Finus, M., McGinty, M. The anti-paradox of cooperation: diversity may pay. Forthcoming: Journal of Economic Behavior and Organization.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome.

Hoel, M. (1992). International environment conventions: the case of uniform reductions of emissions. Environmental and Resource Economics, 2(2), 141-159.

Hoel, M., de Zeeuw, A. (2010). Can a focus on breakthrough technologies improve the performance of international environmental agreements?. Environmental and Resource Economics, 47(3), 395-406.

Irz, X., Jensen, J. D., Leroy, P., Réquillart, V., Soler, L. G., 2019. Promoting climate-friendly diets: What should we tell consumers in Denmark, Finland and France?, Environmental Science & Policy, *in press*.

Li, H., Rus, H., (2019). Climate Change Adaptation and International Mitigation Agreements with Heterogeneous Countries.Journal of the Association of Environmental and Resource Economists, 6(3).

Macdiarmid, J. I., Douglas, F., Campbell, J., 2016. Eating like there's no tomorrow: Public awareness of the environmental impact of food and reluctance to eat less meat as part of a sustainable diet. Appetite 96, 487–493.

Melaku, Y. A., Renzaho, A., Gill, T. K., Taylor, A. W., Dal Grande, E., de Courten, B., Baye, E., Gonzalez–Chica1, D., Hyppönen, E., Shi1, Z., Riley, M., Adams, R., 2018. Burden and trend of diet-related non-communicable diseases in Australia and comparison with 34 OECD countries, 1990–2015: findings from the Global Burden of Disease Study 2015. European journal of nutrition 1-15.

Mondelaers, K., Verbeke, W., Van Huylenbroeck, G., 2009. Importance of health and environment as quality traits in the buying decision of organic products. British Food Journal 111(10), 1120–1139.

Quinet, A. (2019). La valeur de l'action pour le climat. Rapport de la commission présidée par Alain Quinet. France Stratégie, Rapport.
https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/fs-2019-rapport-la-valeur-de-laction-pour-le-climat_0.pdf

Rosi, A., Mena, P., Pellegrini, N., Turroni, S., Neviani, E., Ferrocino, I., Di Cagno, D., Ruini, L., Ciati, R., Angelino, D., Maddock, J., Gobbetti, M., Brighenti, F., Del Rio, D., Scazzina, F., (2017). Environmental impact of omnivorous, ovo-lacto-vegetarian, and vegan diet. Scientific Reports, 7(1), 6105.

Scarborough, P., Appleby, P. N., Mizdrak, A., Briggs, A. D., Travis, R. C., Bradbury, K. E., Key, T. J., 2014. Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. Climatic change 125(2), 179–192.

Springmann, M., Godfray, H. C. J., Rayner, M., Scarborough, P., 2016. Analysis and valuation of the health and climate change cobenefits of dietary change. Proceedings of the National Academy of Sciences, 113(15), 4146–4151.

UNSCN, 2017. Sustainable diets for healthy people and a healthy planet. United Nations System Standing Committee on Nutrition discussion paper. Rome.

Vieux, F., Darmon, N., Touazi, D., Soler, L. G., 2012. Greenhouse gas emissions of self-selected individual diets in France: changing the diet structure or consuming less?. Ecological economics 75, 91–101.

Appendixes

A Proof of Proposition 1

Here, we investigate the reaction functions at the Nash equilibrium.

The total differential of Equation (3) is:

$$(B_{ee} - D_{EE})de_i - \alpha D_{EE}df_i = D_{EE}dE_{-i} \tag{A1}$$

The total differential of Equation (4) is:

$$-\alpha D_{EE}de_i + (\gamma A_{ff} - \alpha^2 D_{EE})df_i = \alpha D_{EE}dE_{-i} \tag{A2}$$

Equations (A1) and (A2) can be written in matrix form:

$$\begin{pmatrix} B_{ee} - D_{EE} & -\alpha D_{EE} \\ -\alpha D_{EE} & \gamma A_{ff} - \alpha^2 D_{EE} \end{pmatrix} \times \begin{pmatrix} de_i \\ df_i \end{pmatrix} = \begin{pmatrix} D_{EE} \\ \alpha D_{EE} \end{pmatrix} dE_{-i} \tag{A3}$$

$$\Leftrightarrow \begin{pmatrix} de_i \\ df_i \end{pmatrix} = \frac{1}{Det(H^{NS})} \begin{pmatrix} \gamma A_{ff} - \alpha^2 D_{EE} & \alpha D_{EE} \\ \alpha D_{EE} & B_{ee} - D_{EE} \end{pmatrix} \times \begin{pmatrix} D_{EE} dE_{-i} \\ \alpha D_{EE} dE_{-i} \end{pmatrix} \tag{A4}$$

(i). Equation (A4) leads to $\frac{de_i}{dE_{-i}} = \frac{1}{Det(H^{NS})} \gamma A_{ff} D_{EE} < 0$, since $A_{ff} < 0$, $D_{EE} > 0$, and $Det(H^{NS}) > 0$.

(ii). Equation (A4) leads to $\frac{df_i}{dE_{-i}} = \frac{\alpha B_{ee} D_{EE}}{Det(H^{NS})}$ and $\text{sgn}\left(\frac{df_i}{dE_{-i}}\right) = \text{sgn}(-\alpha)$, since $B_{ee} < 0$, $D_{EE} > 0$, and $Det(H^{NS}) > 0$.

(iii). Equations (3) and (4) imply $\gamma A_f(f_i) = \alpha B_e(e_i)$. The total differential of this equation leads to $\frac{df_i}{de_i} = \frac{\alpha B_{ee}}{\gamma A_{ff}}$. Moreover, $\text{sgn}\left(\frac{df_i}{de_i}\right) = \text{sgn}(\alpha)$, since $B_{ee} < 0$ and $A_{ff} < 0$.

(iv). As $E = E_{-i} + e_i + \alpha f_i$, we obtain that $\frac{dE}{df_i} = \frac{dE_{-i}}{df_i} + \frac{de_i}{df_i} + \alpha = \frac{\gamma A_{ff}}{\alpha D_{EE}}$.

Thus, $\text{sgn}\left(\frac{df_i}{dE}\right) = \text{sgn}(-\alpha)$, since $D_{EE} > 0$ and $A_{ff} < 0$.

B Proof of Proposition 2

(i). When $\alpha < 0$, as $D_E > 0$, Equations (6), (24), and (15) imply that $A_f(f^{jS}) < 0$ for $j = N, C, O$. Since f^{jB} is defined as the solution of $A_f(f^{jB}) = 0$ and that the function $A_{ff}(f) < 0$, we have $f^{jS} > f^{jB}, \forall j = N, C, O$.

A similar reasoning applies to the case $\alpha > 0$ and implies that $f^{jS} < f^{jB}, \forall j = N, C, O$.

(ii). We use the method of proof by contradiction.

When $\alpha < 0$, suppose that $e^{jS} \leq e^{jB}$. This implies

$$e^{jS} + \alpha f^{jS} < e^{jB} \quad \Leftrightarrow \quad D_E(n(e^{jS} + \alpha f^{jS})) < D_E(ne^{jB}) \quad \text{since } D_{EE} > 0$$

From Equations (9) and (5) for $j = N$, (26) and (23) for $j = C$, and (17) and (14) for $j = O$, we obtain that

$$B_e(e^{jS}) < B_e(e^{jB}) \quad \Leftrightarrow \quad e^{jS} > e^{jB} \quad \text{since } B_{ee} \leq 0$$

This is in contradiction with $e^{jS} \leq e^{jB}$. Thus (ii) is proved.

A similar reasoning applies to the case $\alpha > 0$ and induces that $e^{jS} < e^{jB}, \forall j = N, C, O$.

(iii). The difference in total emissions between the main model and the benchmark case $(E^{jS} - E^{jB})$ depends on the sign of the term $n\left[e^{jS} - e^{jB} + \alpha f^{jS}\right]$.

When $\alpha < 0$, $e^{jS} > e^{jB}$ and $\alpha f^{jS} < 0$. Therefore, there exists a threshold α_j^{BS} such that

- if $\alpha < \alpha_j^{BS} < 0$, $E^{jS} < E^{jB}$ and
- if $\alpha_j^{BS} < \alpha < 0$, $E^{jS} > E^{jB}, \forall j = N, C, O$.

In the same way, when $\alpha > 0$, $e^{jS} < e^{jB}$ and $\alpha f^{jS} > 0$. Therefore, there exists a threshold α_j^{BS} such that

- if $\alpha > \alpha_j^{BS} > 0$, $E^{jS} > E^{jB}$ and
- if $\alpha_j^{BS} > \alpha > 0$, $E^{jS} < E^{jB}, \forall j = N, C, O$.

To summarize, there exists the threshold α_j^{BS} having the same sign as α, such that, on the one hand, we obtain $E^{jS} > E^{jB}$, when $\alpha > \alpha_j^{BS}, \forall j = N, C, O$. On the other hand, we obtain $E^{jS} < E^{jB}$, when $\alpha < \alpha_j^{BS}, \forall j = N, C, O$.

C Proof of Proposition 4

(i). We will use the method of proof by contradiction to prove that $e^{CS} < e^{OS} < e^{NS}$.

- Suppose that $e^{CS} \geq e^{NS}$, this implies that

$$
\begin{aligned}
B_e(e^{CS}) \leq B_e(e^{NS}) \quad & \text{since } B_{ee} \leq 0 \\
\Leftrightarrow nD_E(n(e^{CS} + \alpha f^{CS})) \leq D_E(n(e^{NS} + \alpha f^{NS})) \quad & \text{from Eq. (23) and (5)} \\
\Leftrightarrow D_E(n(e^{CS} + \alpha f^{CS})) < D_E(n(e^{NS} + \alpha f^{NS})) & \\
\Leftrightarrow \frac{\gamma}{\alpha}(A_f(f^{CS})) < \frac{\gamma}{\alpha}(A_f(f^{NS})) \quad & \text{from Eq. (24) and (6)} \\
\Leftrightarrow \alpha f^{CS} > \alpha f^{NS} \quad \forall \alpha, \; & \text{since } A_{ff} < 0.
\end{aligned} \tag{C5}
$$

And, with Equation (C5), one can also show that

$$
\begin{aligned}
e^{CS} + \alpha f^{CS} < e^{NS} + f^{NS} \quad & \text{since } D_{EE} > 0 \\
\Leftrightarrow e^{CS} - e^{NS} < \alpha(f^{NS} - f^{CS}) &
\end{aligned}
$$

We have shown that $\alpha(f^{NS} - f^{CS}) < 0$, for all α. Then, we obtain that $e^{CS} - e^{NS} < 0$. This is in contradiction with $e^{CS} \geq e^{NS}$. Thus the fact that $e^{CS} < e^{NS}$ is proved.

- Suppose that $e^{CS} \geq e^{OS}$, this implies that

$$
\begin{aligned}
B_e(e^{CS}) \leq B_e(e^{OS}) \quad & \text{since } B_{ee} \leq 0 \\
\Leftrightarrow nD_E(n(e^{CS} + \alpha f^{CS})) \leq nD_E(n(e^{OS} + \alpha f^{OS})) \quad & \text{from Eq. (23) and (14)} \\
\Leftrightarrow D_E(n(e^{CS} + \alpha f^{CS})) \leq D_E(n(e^{OS} + \alpha f^{OS})) & \\
\Leftrightarrow D_E(n(e^{CS} + \alpha f^{CS})) < nD_E(n(e^{OS} + \alpha f^{OS})) & \\
\Leftrightarrow \frac{\gamma}{\alpha}(A_f(f^{CS})) < \frac{\gamma}{\alpha}(A_f(f^{OS})) \quad & \text{from Eq. (24) and (15)} \\
\alpha f^{CS} > \alpha f^{OS} \quad \forall \alpha \; & \text{since } A_{ff} < 0.
\end{aligned} \tag{C6}
$$

And, with Equation (C6), one can also show that

$$\Leftrightarrow e^{CS} + \alpha f^{CS} \leq e^{OS} + f^{OS} \quad \text{since } D_{EE} > 0$$
$$\Leftrightarrow e^{CS} - e^{OS} \leq \alpha(f^{OS} - f^{CS})$$

We have shown that $\alpha(f^{OS} - f^{CS}) < 0$, for all α. Then, we obtain that $e^{CS} - e^{OS} < 0$. This is in contradiction with $e^{CS} \geq e^{OS}$. Thus the fact that $e^{CS} < e^{OS}$ is proved.

- Suppose that $e^{OS} \geq e^{NS}$, this implies that

$$B_e(e^{OS}) \leq B_e(e^{NS}) \quad \text{since } B_{ee} \leq 0$$
$$\Leftrightarrow nD_E(n(e^{OS} + \alpha f^{OS})) \leq D_E(n(e^{NS} + \alpha f^{NS})) \text{ from Eq. (14) and (5)} \tag{C7}$$
$$\Leftrightarrow \frac{\gamma}{\alpha}(A_f(f^{OS})) \leq \frac{\gamma}{\alpha}(A_f(f^{NS})) \quad \text{from Eq. (15) and (6)}$$
$$\Leftrightarrow \alpha f^{OS} \geq \alpha f^{NS} \quad \forall\alpha, \text{ since } A_{ff} < 0.$$

And, with Equation (C7), one can also show that

$$D_E(n(e^{OS} + \alpha f^{OS})) < D_E(n(e^{NS} + \alpha f^{NS}))$$
$$e^{OS} + \alpha f^{OS} < e^{NS} + \alpha f^{NS} \quad \text{since } D_{EE} > 0$$
$$\Leftrightarrow e^{OS} - e^{NS} < \alpha(f^{NS} - f^{OS})$$

We have shown that $\alpha(f^{NS} - f^{OS}) \leq 0$, for all α. Then, we obtain that $e^{OS} - e^{NS} < 0$. This is in contradiction with $e^{OS} \geq e^{NS}$. Thus the fact that $e^{OS} < e^{NS}$ is proved.

(ii). We will use that $e^{CS} < e^{OS} < e^{NS}$ to prove that $\alpha f^{OS} \leq \alpha f^{NS} < \alpha f^{CS}$ for all α.

- Here, we will show that $\alpha f^{NS} < \alpha f^{CS}$ using the proof by contradiction method.

Suppose that $\alpha f^{NS} \geq \alpha f^{CS}, \forall \alpha$, then

$$
\begin{aligned}
f^{NS} &\leq f^{CS} \quad \text{when } \alpha < 0, \\
\Leftrightarrow \gamma(A_f(f^{NS})) &\geq \gamma(A_f(f^{CS})) \quad \text{since } A_{ff} < 0 \\
\Leftrightarrow \alpha D_E(n(e^{NS} + \alpha f^{NS})) &\geq \alpha D_E(n(e^{CS} + \alpha f^{CS})) \quad \text{from Eq. (6) and (24)} \\
\Leftrightarrow D_E(n(e^{NS} + \alpha f^{NS})) &\leq D_E(n(e^{CS} + \alpha f^{CS})) \\
\Leftrightarrow e^{NS} + \alpha f^{NS} &\leq e^{CS} + \alpha f^{CS} \quad \text{since} D_{EE} > 0 \\
\Leftrightarrow \underbrace{e^{NS} - e^{CS}}_{>0} &\leq \underbrace{\alpha(f^{CS} - f^{NS})}_{\leq 0}
\end{aligned}
$$

Since this is impossible, we conclude that when $\alpha < 0$, $f^{NS} > f^{CS}$.

Again, suppose that $\alpha f^{NS} \geq \alpha f^{CS}, \forall \alpha$, then

$$
\begin{aligned}
f^{NS} &\geq f^{CS} \quad \text{when } \alpha > 0, \\
\Leftrightarrow \gamma(A_f(f^{NS})) &\leq \gamma(A_f(f^{CS})) \quad \text{since } A_{ff} < 0 \\
\Leftrightarrow \alpha D_E(n(e^{NS} + \alpha f^{NS})) &\leq \alpha D_E(n(e^{CS} + \alpha f^{CS})) \quad \text{from Eq. (6) and (24)} \\
\Leftrightarrow D_E(n(e^{NS} + \alpha f^{NS})) &\leq D_E(n(e^{CS} + \alpha f^{CS})) \\
\Leftrightarrow e^{NS} + \alpha f^{NS} &\leq e^{CS} + \alpha f^{CS} \quad \text{since } D_{EE} > 0 \\
\Leftrightarrow \underbrace{e^{NS} - e^{CS}}_{>0} &\leq \underbrace{\alpha(f^{CS} - f^{NS})}_{\leq 0}
\end{aligned}
$$

Since this is impossible, we conclude that when $\alpha > 0$, $f^{NS} < f^{CS}$.

- We have shown that $e^{CS} < e^{OS}$, this implies that

$$\begin{aligned}
&B_e(e^{CS}) > B_e(e^{OS}) \quad \text{since } B_{ee} \leq 0 \\
&\Leftrightarrow nD_E(n(e^{CS} + \alpha f^{CS})) > nD_E(n(e^{OS} + \alpha f^{OS})) \quad \text{from Eq. (23) and (14)} \\
&\Leftrightarrow e^{CS} + \alpha f^{CS} > e^{OS} + \alpha f^{OS} \text{ since } D_{ee} > 0 \\
&\Leftrightarrow \underbrace{e^{CS} - e^{OS}}_{<0} > \alpha(f^{OS} - f^{CS}) \\
&\Leftrightarrow \alpha(f^{OS} - f^{CS}) < 0, \text{ that is, } \begin{cases} \text{when } \alpha < 0, \quad f^{CS} < f^{OS} \\ \text{when } \alpha > 0, \quad f^{CS} > f^{OS}. \end{cases}
\end{aligned}$$

- We have shown that $e^{OS} < e^{NS}$, this implies that

$$\begin{aligned}
&B_e(e^{OS}) > B_e(e^{NS}) \quad \text{since } B_{ee} \leq 0 \\
&\Leftrightarrow nD_E(n(e^{OS} + \alpha f^{OS})) > D_E(n(e^{NS} + \alpha f^{NS})) \quad \text{from Eq. (14) and (5)} \\
&\Leftrightarrow \frac{\gamma}{\alpha}(A_f(f^{OS})) > \frac{\gamma}{\alpha}(A_f(f^{NS})) \quad \text{from Eq. (15) and (6)} \\
&\Leftrightarrow \alpha(f^{OS} - f^{NS}) < 0 \quad \forall \alpha, \text{ since } A_{ff} < 0, \\
&\text{that is, } \begin{cases} \text{when } \alpha < 0, \quad f^{NS} < f^{OS} \\ \text{when } \alpha > 0, \quad f^{NS} > f^{OS} \end{cases}
\end{aligned}$$

(iii). The definition of total emissions is given by $E = nE_i = n(e_i + \alpha f_i)$.

We know from (i). and (ii). that $e^{CS} < e^{OS} < e^{NS}$ and $\alpha f^{OS} < \alpha f^{NS} < \alpha f^{CS}$, then $E^{OS} < E^{NS}$, $\forall \alpha$.

Moreover, $E^{OS} - E^{CS} = n[\underbrace{e^{OS} - e^{CS}}_{>0} + \underbrace{\alpha(f^{OS} - f^{CS})}_{<0}]$, then there exists a value of α, $\alpha^{CO} > 0$ such that if $\alpha \in [-\alpha^{CO}, \alpha^{CO}]$, $E^{CS} \leq E^{OS}$. Otherwise, $E^{CS} > E^{OS}$

A similar reasoning applies to the case $E^{NS} - E^{CS}$ and induces that there exists a value $\alpha^{NC} > 0$, such that if $\alpha \in [-\alpha^{NC}, \alpha^{NC}]$, $E^{CS} \leq E^{NS}$. Otherwise, $E^{CS} > E^{NS}$.

D Proof of Proposition 5

(i). From Propositions 2 and 4, it is known that

when $\alpha < 0, \quad f^{CS} > f^{CB}$ and $f^{OS} > f^{CS}$;

when $\alpha > 0, \quad f^{CS} < f^{CB}$ and $f^{OS} < f^{CS}$.

The result is then obvious.

(ii). From Propositions 4, 3, and 2, it is known that $\forall\alpha,\ e^{CS} < e^{OS}$ and

when $\alpha < 0, \quad e^{CB} < e^{CS}$;

when $\alpha > 0, \quad e^{OS} < e^{OB} = e^{CB}$.

The result is then obvious.

(iii). To demonstrate the last statement, we distinguish two cases.

• Case $\alpha > 0$.

From parts (i) and (ii) of this proposition, we obtain that $e^{CB} > e^{OS}$ and $\alpha f^{CB} > \alpha f^{OS}$. Thus, $\tilde{E}^{CB} > E^{OS}$.

From parts (i) and (ii) of this proposition, we obtain that $e^{CB} > e^{CS}$ and $\alpha f^{CB} > \alpha f^{CS}$. Thus, $\tilde{E}^{CB} > E^{CS}$.

From Proposition 4, we know that

when $\alpha < \alpha^{CO}, \quad E^{CS} < E^{OS}$ and

when $\alpha > \alpha^{CO}, \quad E^{CS} > E^{OS}$.

Then, we obtain that, when $\alpha > 0$, $\begin{cases} \text{if} \quad \alpha < \alpha^{CO}, & E^{CS} < E^{OS} < \tilde{E}^{CB} \\ \text{if} \quad \alpha^{CO} < \alpha, & E^{OS} < E^{CS} < \tilde{E}^{CB} \end{cases}$.

• Case $\alpha < 0$.

$\tilde{E}^{CB} - E^{OS} = n[\underbrace{e^{CB} - e^{OS}}_{<0} + \underbrace{\alpha(f^{CB} - f^{OS})}_{>0}]$, then there exists a value of α, $\tilde{\alpha}_1 < 0$ such that if $\alpha < \tilde{\alpha}_1$, $\tilde{E}^{CB} > E^{OS}$; otherwise, $\tilde{E}^{CB} < E^{OS}$.

$\tilde{E}^{CB} - E^{CS} = n[\underbrace{e^{CB} - e^{CS}}_{<0} + \underbrace{\alpha(f^{CB} - f^{CS})}_{>0}]$, then there exists a value of α, $\tilde{\alpha}_2 < 0$ such that if $\alpha < \tilde{\alpha}_2$, $\tilde{E}^{CB} > E^{OS}$; otherwise, $\tilde{E}^{CB} < E^{OS}$.

From Proposition 4, we know that

when $\alpha < -\alpha^{CO}$, $\quad E^{CS} > E^{OS}$ and

when $\alpha > -\alpha^{CO}$, $\quad E^{CS} < E^{OS}$.

Then, we obtain that, when $\alpha < 0$, $\begin{cases} \text{if} & -\alpha^{CO} < \alpha, & \tilde{E}^{CB} < E^{CS} < E^{OS} \\ \text{if} & \tilde{\alpha}_1 < \alpha \leq -\alpha^{CO}, & \tilde{E}^{CB} < E^{OS} < E^{CS} \\ \text{if} & \tilde{\alpha}_2 < \alpha \leq \tilde{\alpha}_1, & E^{OS} < \tilde{E}^{CB} < E^{CS} \\ \text{if} & \alpha \leq \tilde{\alpha}_2 & E^{OS} < E^{CS} < \tilde{E}^{CB} \end{cases}$.

E Table of results

Equilibria	Benchmark Case	Main Case
Nash	$B_e(e^{NB}) = D_E\left(ne^{NB}\right)$	$B_e(e^{NS}) = D_E\left(n(e^{NS} + \alpha f^{NS})\right)$
	$A_f(f^{NB}) = 0$	$\gamma A_f(f^{NS}) = \alpha D_E\left(n(e^{NS} + \alpha f^{NS})\right)$
Climate	$B_e(e^{CB}) = nD_E\left(ne^{CB}\right)$	$B_e(e^{CS}) = nD_E\left(n(e^{CS} + \alpha f^{CS})\right)$
agreement	$A_f(f^{CB}) = 0$	$\gamma A_f(f^{CS}) = \alpha D_E\left(n(e^{CS} + \alpha f^{CS})\right)$
Full	$B_e(e^{OB}) = nD_E(ne^{OB})$	$B_e(e^{OS}) = nD_E(n(e^{OS} + \alpha f^{OS}))$
cooperative	$A_f(f^{OB}) = 0$	$\gamma A_f(f^{OS}) = \alpha nD_E(n(e^{OS} + \alpha f^{OS}))$

F Quadratic Model

F.1 Nash equilibrium: main case

The solution is given by:

$$e^{NS} = \frac{a_2 b_1 \gamma + \alpha^2 b_1 dn - a_1 \alpha d \gamma n}{\alpha^2 b_2 dn + a_2 \gamma (nd + b_2)} \tag{F8}$$

$$f^{NS} = \frac{a_1 d \gamma n - \alpha b_1 dn + a_1 b_2 \gamma}{\alpha^2 b_2 dn + a_2 \gamma (nd + b_2)} \tag{F9}$$

$$E^{NS} = n\left(e^{NS} + \alpha f^{NS}\right) \tag{F10}$$

The payoff function of each country at the Nash equilibrium is:

$$U^{NS} = \gamma\left(a_1 f^{NS} - \frac{a_2}{2} f^{NS^2}\right) + \left(b_1 e^{NS} - \frac{b_2}{2} e^{NS^2}\right) - \frac{d}{2}(E^{NS})^2. \tag{F11}$$

The reactions functions are given by:

$$e_i = \frac{b_1 - \alpha d f_i - dE_{-i}}{b_2 + d} \tag{F12}$$

$$f_i = \frac{\gamma a_1 - \alpha d e_i - \alpha d E_{-i}}{\gamma a_2 + d\alpha^2} \tag{F13}$$

$$f_i = \frac{\gamma a_1 - \alpha d E}{\gamma a_2} \tag{F14}$$

F.2 Nash equilibrium: benchmark case

The solution is given by:

$$e^{NB} = \frac{b_1}{b_2 + dn} \tag{F15}$$

$$f^{NB} = \frac{a_1}{a_2} \tag{F16}$$

$$E^{NB} = ne^{NB} = \frac{nb_1}{b_2 + dn} \tag{F17}$$

The payoff function of each country at the Nash equilibrium is:

$$U^{NB} = \left(a_1 f^{NB} - \frac{a_2}{2} f^{NB^2}\right) + \left(b_1 e^{NB} - \frac{b_2}{2} e^{NB^2}\right) - \frac{d}{2}(E^{NB})^2. \tag{F18}$$

F.3 Full cooperative solution: main case

The solution is given by:

$$e^{OS} = \frac{a_2 b_1 \gamma + \alpha^2 b_1 d n^2 - n^2 a_1 \alpha d \gamma}{\alpha^2 b_2 d n^2 + a_2 \gamma (n^2 d + b_2)} \tag{F19}$$

$$f^{OS} = \frac{a_1 d n^2 \gamma - \alpha b_1 d n^2 + a_1 b_2 \gamma}{\alpha^2 b_2 d n^2 + a_2 \gamma (n^2 d + b_2)} \tag{F20}$$

$$E^{OS} = n \left(e^{OS} + \alpha f^{OS} \right) \tag{F21}$$

The total payoff of the countries at the full cooperative solution is:

$$W^{OS} = n \left[\gamma \left(a_1 f^{OS} - \frac{a_2}{2} f^{OS^2} \right) + \left(b_1 e^{OS} - \frac{b_2}{2} e^{OS^2} \right) - \frac{d}{2} (E^{OS})^2 \right]. \tag{F22}$$

F.4 Full cooperative solution: benchmark case

The solution is given by:

$$e^{OB} = \frac{b_1}{b_2 + n^2 d} < e^{NB} \tag{F23}$$

$$f^{OB} = \frac{a_1}{a_2} = f^{NB} \tag{F24}$$

$$E^{OB} = n e^{OB} = \frac{n b_1}{b_2 + n^2 d} < E^{NB} \tag{F25}$$

The total payoff of countries at the full cooperative solution is:

$$W^{OB} = n U^{OB} = n \left[\left(a_1 f^{OB} - \frac{a_2}{2} f^{OB^2} \right) + \left(b_1 e^{OB} - \frac{b_2}{2} e^{OB^2} \right) - \frac{d}{2} (E^{OB})^2 \right]. \tag{F26}$$

F.5 Climate agreement: main case

The solution is given by:

$$e^{CS} = \frac{a_2 b_1 \gamma + \alpha^2 b_1 dn - n^2 a_1 \alpha d\gamma}{\alpha^2 b_2 dn + a_2\gamma(n^2 d + b_2)} \tag{F27}$$

$$f^{CS} = \frac{a_1 d\gamma n^2 - \alpha b_1 dn + a_1 b_2 \gamma}{\alpha^2 b_2 dn + a_2\gamma(n^2 d + b_2)} \tag{F28}$$

$$E^{CS} = n\left(e^{CS} + \alpha f^{CS}\right) \tag{F29}$$

The total payoff of the countries at the climate agreement is:

$$nU^{CS} = n\left[\gamma\left(a_1 f^{CS} - \frac{a_2}{2} f^{CS^2}\right) + \left(b_1 e^{CS} - \frac{b_2}{2} e^{CS^2}\right) - \frac{d}{2}(E^{CS})^2\right]. \tag{F30}$$

F.6 Climate agreement: benchmark case

The solution is given by:

$$e^{CB} = \frac{b_1}{b_2 + n^2 d} = e^{OB} < e^{NB} \tag{F31}$$

$$f^{CB} = \frac{a_1}{a_2} = f^{OB} = f^{NB} \tag{F32}$$

$$E^{CB} = ne^{CB} = \frac{nb_1}{b_2 + n^2 d} = E^{OB} < E^{NB} \tag{F33}$$

The total payoff of countries at the climate agreement solution is:

$$nU^{CB} = n\left[\left(a_1 f^{CB} - \frac{a_2}{2} f^{CB^2}\right) + \left(b_1 e^{CB} - \frac{b_2}{2} e^{CB^2}\right) - \frac{d}{2}(E^{CB})^2\right]. \tag{F34}$$

F.7 Summary of conditions

The following conditions are to be respected:

- In the main case (in the benchmark case, this condition is absent), the condition $E_i = e_i + \alpha f_i > 0$ is reduced to $(\alpha a_1 b_2 + a_2 b_1) > 0$.
- In the main case (in the benchmark case, this condition is automatically verified), the condition $b_1 - b_2 e_i > 0$ is given by the same condition: $(\alpha a_1 b_2 + a_2 b_1) > 0$.
- The variables at the equilibrium must be positive (interior solutions):

$$\begin{aligned}
e^{NS} &> 0 \Leftrightarrow [\gamma a_2 b_1 + \alpha dn(\alpha b_1 - \gamma a_1)] > 0 \\
e^{CS} &> 0 \Leftrightarrow [\gamma a_2 b_1 + \alpha dn(\alpha b_1 - \gamma a_1 n)] > 0 \\
e^{OS} &> 0 \Leftrightarrow \left[\gamma a_2 b_1 + \alpha dn^2(\alpha b_1 - \gamma a_1)\right] > 0 \\
f^{NS} &> 0 \Leftrightarrow [\gamma a_1 b_2 - dn(\alpha b_1 - \gamma a_1)] > 0 \\
f^{CS} &> 0 \Leftrightarrow [\gamma a_1 b_2 - dn(\alpha b_1 - \gamma a_1 n)] > 0 \\
f^{OS} &> 0 \Leftrightarrow \left[\gamma a_1 b_2 - dn^2(\alpha b_1 - \gamma a_1\right] > 0
\end{aligned}$$