Aspects of Coalitions for Environmental Protection under Co-utility

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Abstract The game theoretic modeling of coalitions for environmental protection within the framework of a new concept of co-utility [8] is analysed. The co-utility concept can be described by two elements. Firstly, agents can improve their payoffs by collaborating with each other. Secondly, the outcome of collaboration is stable. The similarity of co-utility with common concepts of coalition stability for environmental protection is shown. But the co-utility concept is more extensive and can serve as an umbrella in all applications where agents have room for simultaneous improvements of payoffs. The development from a myopically stable outcome to a farsightedly stable outcome is discussed.

1 Introduction

The body of literature on coalitions for environmental protection (or International Environmental Agreements (IEA)) shows two conflicting views. One is rooted in cooperative game theory and concludes that the grand coalition is stable by using the core concept and by implementing transfers, as countries have different benefits and cost functions from pollution abatement [6, 9, 5]. The other view is rooted in the non-cooperative game theory, which has become the dominant path in the literature [1, 2, 4, 11, 24, 17, 22]. This paper investigates coalitions for environmental protection within the framework of *the co-utility concept* [8].

Co-utility is going to be defined based on stability and profitability. Co-utility can be described by two conditions:

1. The first condition requires that at least a part of all countries can increase the payoff (or profit) simultaneously by forming *a co-utile outcome*. The more gen-

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eral notion of outcome when modeling coalitions for environmental protection is a coalition structure, and a co-utile outcome is also is a special type of coalition structure.
2. The second condition requires that *a co-utile outcome be stable*, which means that no country or group of countries prefer to deviate from this co-utile outcome. It is obvious that this second condition is closely connected to the stability concept. As there are different stability notions, we will have different forms of co-utility notions.

Taking our previous papers [21], [23] [19] and [20] as a starting point, we discuss coalitions for environmental protection within the framework of co-utility. This paper is organized as follows. Section 2 presents the game-theoretic model and considers the *single myopically and farsightedly* stable coalition co-utile outcomes. Section 3 presents a discussion of the development of a single coalition co-utile outcome from the myopic co-utility space to the farsighted co-utility space. Section 4 lists the conclusions. The Appendix presents a brief description of the FUND model, which provides the cost-benefit functions for greenhouse gas mitigation, the case study of this paper.

2 Our model

There are 16 world regions (we name the set of all regions by N) in our game-theoretic model of IEAs (or coalitions), which are shown in the first column of Table 1. At the beginning, the link between the economic activity and the physical environment is established in order to generate the integrated assessment model. This link is established through a social welfare function calibrated to the FUND model (see Equation (3) in the Appendix). The social welfare function captures the profit from pollution and the environmental damage. Following this approach, countries play a two-stage game. In the first stage, each country decides whether to join the coalition $C \subseteq N$ and become a signatory (or coalition member) or stay singleton and non-signatory (membership game). These decisions lead to a *co-utile outcome* or *coalition structure S* with *c* coalition-members and *16-c* non-members. A coalition structure fully describes how many coalitions are formed (*we are going assume that we have only one coalition*[1]), how many members each coalition has and how many singleton players there are. In the second stage, every country decides on emissions. Within the coalition, players play cooperatively (by maximizing their joint welfare) while the coalition and single countries compete in a non-cooperative way (by maximizing their own welfare).

In order to be able to compare the payoffs of the coalition members, we need to introduce the definition of partition function. Let us recall that $N = \{1, ..., 16\}$ is the set of regions (players), and that nonempty subsets of N are called coalitions. A

[1] For the case of multiple coalitions (or a general coalitions structure) refer to [21], [23] and [19].

partition[2] **a** is a set of disjoint coalitions, $\mathbf{a} = \{C_1, C_2, ..., C_k\}$, so that their union is N; the set of all partitions is $\mathscr{P}$, and the set of all the partitions where coalition C is part of, is $\mathscr{P}(C)$.

Definition 9.1. The partition function is a mapping $\Pi : (C, \mathscr{P}) \mapsto \Re$ where $C \in \mathscr{P}$, which assigns a value to each coalition in every partition.

Definition 9.2. The per-member partition function is a mapping $\pi(i)_{i\in C} : (C, \mathscr{P}) \mapsto \Re$ where $C \in \mathscr{P}$, which assigns a payoff value $\pi(i)^*_{i\in C}(C, \mathscr{P})$ to every member of each coalition in every partition.

The per-member partition function $\pi(i)_{i\in C}(C, \mathscr{P}(C))$ gives **a payoff value (or a profit)** $\pi(i)^*_{i\in C}(C, \mathscr{P}(C))$ (from now on I will write simply $\pi(i)^*_{i\in C}$) to every coalition member. This helps us to transform the preference relation to a comparison of coalition member payoffs. We would like to emphasise that the cost-benefit function (see Equation (3)) estimated from the FUND model generates our per member partition function.

2.1 Single myopic co-utile outcome

Firstly we would like to make clear that *a co-utile outcome is a coalition*, as we consider only single coalitions. As profitable coalitions (or co-utile outcomes) play a central role in our analysis, we define them from the beginning.

Definition 9.3. The situation in which each country maximizes its own profit, and the maximum coalition size is one is referred to as the fully non-cooperative structure.

A coalition that performs better than the fully non-cooperative structure is a *profitable coalition*. The definition of a profitable coalition is introduced below.

Definition 9.4. A coalition C is profitable (or individually rational) if and only if it satisfies the following condition:

$$\forall i \in C \quad \pi(i)^*_C \geq \pi(i)^*_{ind}$$

where $\pi(i)^*_C$, $\pi(i)^*_{ind}$ are the profits of country i as a member of C and in the fully non-cooperative structure, respectively.

Now we are able to state a formal definition of co-utile outcome.

Definition 9.5. A co-utile outcome is a profitable and stable coalition structure.

[2] A characteristic function approach would have been sufficient for this paper but we prefer to stick to the approach of our former papers [23] and [19], whcih allows for a more general approach..

We are going to employ myopic and farsighted stability in order to characterise a co-utile outcome. Myopic stability considers only single-player moves. In other words, players are myopic if they see only one move ahead. A country that leaves (or joins) the coalition assumes that the rest of coalition members stay in the coalition and singletons (the countries that do not belong to coalition) remain non-members.

Definition 9.6. A coalition **C** is myopically stable (or a myopic co-utile outcome) if and only if:

- C is profitable;
- C is internally myopically stable: $\forall$ player $i \in C, \quad \pi(i)^*_{i\in C} > \pi(i)^*_{C\setminus\{i\}}$;
- C is externally myopically stable: $\forall$ player $j \in C$
  $\pi(j)^*_{C\setminus\{j\}} > \pi(j)^*_{j\in C}$ or $\exists\ i \in C \,|\, \pi(i)^*_{C\cup\{j\}} < \pi(i)^*_{j\notin C}$,

where $\pi(i)^*$ $\pi(j)^*$ are profit function values of countries i and j.

The first condition of Definition 9.6 requests that the coalition C be profitable[3]; the second condition states that the coalition C is internally myopically stable only if the profit of every coalition member that leaves the coalition C decreases; the third condition states that the coalition C is externally myopically stable if, for every country that joins the coalition C, the profit decreases for the joining country or for a previous member of the coalition. In open membership games, the definition of myopic stability requests only that a country that joins a coalition reduces its profit [1]. It is more realistic (as an exclusive membership game in our case) to add the second part that a previous member of the coalition reduces its profit. In the beginning all profitable coalitions are found. Finding all profitable coalitions can be done using a simple algorithm, although at a considerable computational effort. Then, for every coalition: i) check if all its members have higher profit compared to a fully non-cooperative structure; ii) check internal and external myopic stability.

2.2 Farsighted stability and farsighted co-utile outcomes

It is clear that we need to consider only *profitable coalitions*[4]. Considering only profitable coalitions also reduces the computational effort required to find farsightedly stable coalitions. Before presenting our approach to finding farsighted co-utile outcomes, the definitions of *inducement process*, *credible objection*, and *farsighted stability* are presented below.

Definition 9.7. A coalition C_l can be induced from any coalition C_1 if and only if:

- there exist $C_1, C_2 \ldots C_{l-1}, C_l$,
  where $\pi^*_l(i) \geq \pi^*_1(i) \quad \forall i \in C_l$ and $C_q \cap C_r \neq \emptyset$ for $q, r \in [1...l]$

[3] Myopic stability is usually defined without the condition of profitability, but we focus on myopically stable coalitions which are profitable.

[4] If one begins by considering only profitable coalitions, it is sufficient to find all profitable or non-profitable single farsightedly stable coalitions, see Observations 3.2 and 3.3 in [21].

or

- there exist $C_1, C_2 \ldots C_{l-1}, C_l$
  where $\pi_m^*(i) \geq \pi_1^*(i) \quad \forall i \in C_1 \wedge \forall i \notin C_l$ and $C_1 \subset C_2 \subset \ldots \subset C_{l-1} \subset C_l$,

where $\pi_l^*(i),\ \pi_m^*(i),\ \pi_1^*(i)$ are profits, $\pi_1^*(i)$ refers to situations with C_1 and $\pi_l^*(i)$, $\pi_m^*(i)$ with C_l.

The first part of the inducement definition requires that all countries of the coalition C_l do not decrease their profits and indirectly assumes that those countries have started the formation of the final coalition. The second part of the definition requires that all countries that leave the initial coalition C_1 (including free-riding) do not decrease their profits. The definitions of objection and credible objection are presented below:

Definition 9.8. A group of countries G_1 has an objection to a coalition C_1 if there exists another coalition C_n such that C_n can be induced from C_1 and $\pi_n^*(i) \geq \pi_1^*(i) \quad \forall i \in G_1$, where $\pi_n^*(i),\ \pi_1^*(i)$ are profits, $\pi_1^*(i)$ refers to situations with C_1 and $\pi_n^*(i)$ with C_n.

Definition 9.9. A group of countries G_1 has a credible objection to a coalition C_1 if there exists another coalition C_n such that:

- C_n can be induced from C_1 and $\pi_n^*(i) \geq \pi_1^*(i) \quad \forall i \in G_1$;
- no group of countries G_n has a objection to C_n,

where $\pi_n^*(i),\ \pi_1^*(i)$ are profits, $\pi_1^*(i)$ refers to situations with C_1 and $\pi_n^*(i)$ with C_n.

A group of countries has a credible objection to a coalition if there exists an inducement process, and moreover this particular inducement process is the final one (or no group of countries has any objection to the final coalition). Now, it is possible to state the definition of farsighted stability.

Definition 9.10. A coalition C is **farsightedly stable** if no group of countries G has a credible objection to C.

The definition of farsighted stability is based on the definition of the inducement process (no credible objection signifies that the inducement process has come to an end). This means that one needs to trace the inducement process in order to test whether a coalition is farsightedly stable or not. Definition 9.7 makes it clear that there are two main types of inducement process. In the first type, there is a change sequence of coalitions where *the countries in the final coalition* do not decrease their profits. In the second type, there is a change sequence of coalitions where *the countries that leave the initial coalition* do not decrease their profit. There are five classes of inducement process. Three of them belong to the first type of inducement process; the coalition grows bigger; gets smaller; some coalition-members leave the coalition and some others join it. The last two classes of inducement process belong to the second type of inducement process. The fourth class is a special one, namely *free-riding*. One or more countries leaves the coalition and increase their welfare.

The fifth inducement process is also a special inducement process which occurs only in *non-profitable coalitions* that have at least one country that has a welfare smaller than in the fully non-cooperative structure. Those countries are going to leave the coalition (and increase their welfare) *not due to free-riding* but because the joint welfare is distributed unfairly; there is no credible objection against those countries. Even if the coalition is dissolved and a fully non-cooperative structure is reached, their welfare is higher than in the initial non-profitable coalition.

3 From a myopic co-utile outcome to a farsighted co-utile outcome: a discussion

This section provides a description of the way from the single coalition myopic co-utile outcome (or simply myopically stable coalition) (USA, CHI, NAF) to the farsighted co-utile outcome $(USA, LAM, SEA, CHI, NAF, SSA)$. There is no free-riding initiative in the coalition (USA, CHI, NAF), as the coalition is internally myopically stable. This indicates that if a country leaves the coalition, it decreases its profit. Therefore, a myopic coalition formation ends when free-riding appears. On the opposite, the farsightedly stable coalition formation does not end when free-riding appears, but it ends when the profitability condition is not satisfied any further. As a consequence, one can design the following scheme for portraying a way from a myopic coalition to a farsightedly stable coalition:

$$(USA, CHI) \Rightarrow \underbrace{(USA, CHI, NAF)^{ds}}_{myopic\ stable\ coalition} \Rightarrow \underbrace{(USA, CHI, NAF, SSA)}_{free-riding\ appears} \Rightarrow \ldots$$

$$\Rightarrow \underbrace{(USA, LAM, SEA, CHI, NAF, SSA)^{fs}}_{profitability\ condition\ can\ not\ be\ satisfied\ further}.$$

Nevertheless, this is better seen in Fig. 1. Along the y-axis we have the profit of each country in billions of dollars. Along the x-axis, there are some possible coalitions from a fully non-cooperative structure (a_{FNS}) to a myopically stable coalition (USA, CHI, NAF), and it ends with a farsightedly stable coalition $(USA, CHI, NAF, SSA, SEA, LAM)$. When $x = 1$, we have a_{FNS}; when $x = 2$, we have (USA, CHI); when $x = 3$, we have (USA, CHI, NAF); when $x = 4$, we have (USA, CHI, NAF, SSA); when $x = 5$, we have $(USA, CHI, NAF, SSA, SEA)$; and when $x = 6$, we have $(USA, CHI, NAF, SSA, SEA, LAM)$. Every line denotes the variation in welfare (profit) of the respective country when different coalitions are formed. At the beginning of the dotted line, the respective country is not a member of a coalition. At the end of the dotted line, the respective country joins the coalition. Countries that join the coalition improve their profits until the myopic stable coalition (USA, CHI, NAF) is formed. The formation of coalition (USA, CHI, NAF) signifies the end of the myopic co-utility space. After the coalition (USA, CHI, NAF) is formed, every country that joins this coalition reduces its profit. This shows that

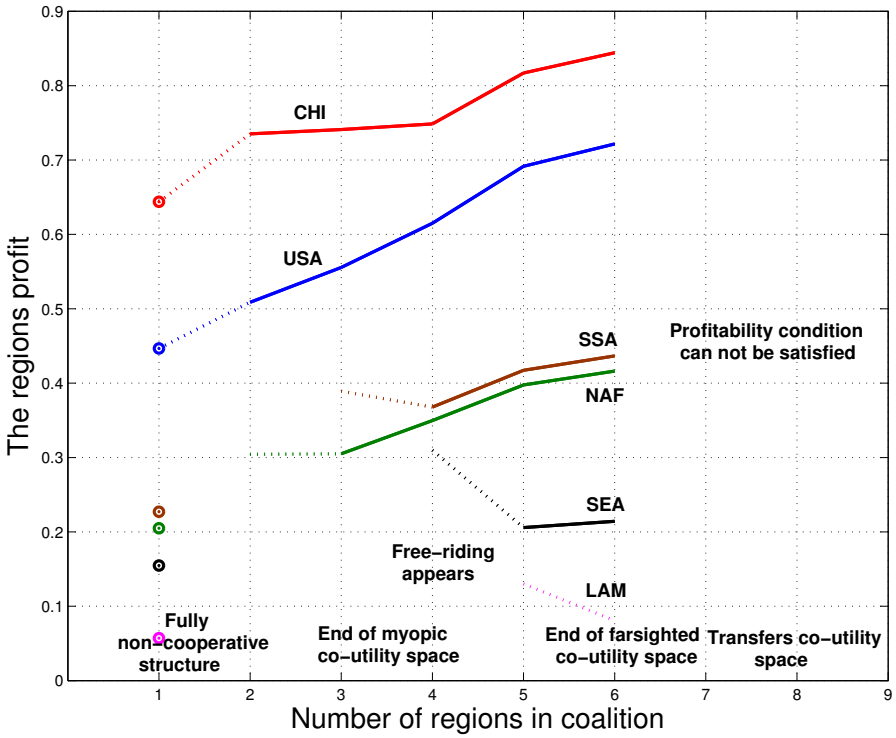


Fig. 1 Development of a single coalition co-utile outcome from myopic co-utile space to farsighted co-utile space. Source: [23] & [20].

the free-riding initiative exists, as these coalitions (all coalitions that contain the coalition (USA, CHI, NAF) as a sub-coalition) are not internally myopically stable. The formation of coalition $(USA, CHI, NAF, SSA, SEA, LAM)$ signifies the end of the farsighted co-utility space. For any enlargement, after the farsightedly stable coalition $(USA, CHI, NAF, SSA, SEA, LAM)$ is formed, the profitability condition is not satisfied any longer. This situation indicates that there is no bigger farsightedly stable coalition as *farsighted stability is a function of profitability*, which is problematical to be realised for a single large coalition: the asymmetry of countries does not permit large profitable coalitions. This is a typical situation in a myopic coalition formation, and shows that myopic stable coalitions are frequently subsets of farsightedly stable coalitions. Moreover, *one can see the farsightedly stable coalition as the "maximum" that can be achieved by in a co-utile outcome without side payments*.

4 Conclusions

This paper has examined coalitions for environmental protection within the framework of co-utility [8]. The FUND model provides the cost-benefit functions of pollution abatement. The structure and dynamics of the damage-cost functions of the FUND model influence the results.

The myopic stability concept presumes that the players are myopic and that the formation of the co-utile outcome consists of only single-player moves. The farsighted stability takes into account the farsightedness of the players; this indicates that every country that takes deviations into account realises that a deviation may trigger further deviations that can worsen its initial position.

The largest single farsightedly stable coalition and myopically stable coalition are small. Myopic stability implies that free-riding makes it difficult to have large single stable coalitions. By contrast, farsighted stability implies that, due to asymmetry, the profitability condition is problematic to be satisfied for large single farsightedly stable coalitions. We demonstrate that myopically stable coalitions are often subcoalitions of farsightedly stable coalitions. Moreover, farsightedly stable coalitions can be frequently the largest stable coalitions that game theory without side payments can realize. In real-world coalition formation, such as the Kyoto protocol, it is more reasonable to suppose that a part of the countries is myopic and that another part is farsighted. As a result, we should expect coalitions that are bigger than myopically stable but smaller than farsightedly stable coalitions. It will be interesting to consider more detailed regions and a game-theoretic approach that considers side payments.

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Appendix. The FUND model

This paper uses version 2.8 of the Climate Framework for Uncertainty, Negotiation and Distribution (FUND). Version 2.8 of FUND corresponds to version 1.6, described and applied by [28, 29, 30, 33], except for the impact module, which is described by [31, 32] and updated by [15]. A further difference is that the current version of the model distinguishes 16 instead of 9 regions. Finally, the model considers emission reduction of methane and nitrous oxide as well as carbon dioxide, as described by [34].

Essentially, FUND consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, viz. the United States of America (USA), Canada (CAN), Western Europe (WEU), Japan and South Korea (JPK), Australia and New Zealand (ANZ), Central and Eastern Europe (EEU), the former Soviet Union (FSU), the Middle East (MDE), Central

America (CAM), South America (LAM), South Asia (SAS), Southeast Asia (SEA), China (CHI), North Africa (NAF), Sub-Saharan Africa (SSA), and Small Island States (SIS). The model runs from 1950 to 2300 in time steps of one year. The primary reason for starting in 1950 is to initialize the climate change impact module. In FUND, the impacts of climate change are assumed to depend on the impact in the previous year, in this way reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be poorly represented in the first few decades of the model runs. The period of 1950-1990 is used for the calibration of the model, which is based on the IMAGE 100-year database [3]. The period 1990-2000 is based on observations of the World Resources Databases [35]. The climate scenarios for the period 2010-2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f [14]. The 2000-2010 period is interpolated from the immediate past, and the period 2100-2300 extrapolated.

The scenarios are defined by the rates of population growth, economic growth, autonomous energy efficiency improvements as well as the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide. The scenarios of economic and population growth are perturbed by the impact of climatic change. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the number of births. Heat stress only affects the urban population. The share of the urban population among the total population is based on the World Resources Databases [35]. It is extrapolated based on the statistical relationship between urbanization and per-capita income, which are estimated from a cross-section of countries in 1995. Climate-induced migration between the regions of the world also causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The market impacts are dead-weight losses to the economy. Consumption and investment are reduced without changing the savings rate. As a result, climate change reduces long-term economic growth, although consumption is particularly affected in the short-term. Economic growth is also reduced by carbon dioxide abatement measures. The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be accelerated by abatement policies, an option not considered in this paper.

The endogenous parts of FUND consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean surface temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured

in parts per million, is represented by the five-box model of [16]. Its parameters are taken from [12]. The model also contains sulphur emissions [34].

The radiative forcing of carbon dioxide, methane, nitrous oxide and sulphur aerosols is determined based on [25]. The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by the radiative forcing RF), with a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents. Regional temperature follows from multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs [18]. The global mean sea level is also governed by a geometric build-up, with its equilibrium level determined by the temperature and a half-life of 50 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of [13].

The climate impact module, based on [32, 33] includes the following categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems. Climate change related damages can be attributed to either the rate of change (benchmarked at 0.04°C) or the level of change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation [33]. People can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income. The resulting value of a statistical life lies in the middle of the observed range of values in the literature [7]. The value of emigration is set to be 3 times the per capita income [26, 27], the value of immigration is 40 per cent of the per capita income in the host region [7]. Losses of dryland and wetlands due to sea level rise are modelled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 [10]. Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are valued at $2 million per square kilometre on average in the OECD in 1990 [10]. The wetland value is assumed to have a logistic relation to per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other impact categories, such as agriculture, forestry, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their 'natural' units [32]. Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being

fully adapted to new climate conditions are always negative [33]. The impacts of climate change on coastal zones, forestry, unmanaged ecosystems, water resources, diarrhoea, malaria, dengue fever, and schistosomiasis are modelled as simple power functions. Impacts are either negative or positive, and they do not change sign [33]. Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth), heat-related disorders (with urbanization), and ecosystems and health (with higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) [33].

Note that we make use of data only for the year 2005. This is sufficient as static game theory is used but with a sophisticated stability concept.

Table 1 Our data from the year 2005, where α is the abatement cost parameter (unitless), β the marginal damage costs of carbon dioxide emissions (in dollars per tonne of carbon), E the carbon dioxide emissions (in billion metric tonnes of carbon) and Y the gross domestic product, in billions US dollars. Source: FUND.

	α	β	E	Y
USA	0.01515466	2.19648488	1.647	10399
CAN	0.01516751	0.09315600	0.124	807
WEU	0.01568000	3.15719404	0.762	12575
JPK	0.01562780	-1.42089104	0.525	8528
ANZ	0.01510650	-0.05143806	0.079	446
EEU	0.01465218	0.10131831	0.177	407
FSU	0.01381774	1.27242378	0.811	629
MDE	0.01434659	0.04737632	0.424	614
CAM	0.01486421	0.06652486	0.115	388
LAM	0.01513700	0.26839935	0.223	1351
SAS	0.01436564	0.35566631	0.559	831
SEA	0.01484894	0.73159104	0.334	1094
CHI	0.01444354	4.35686225	1.431	2376
NAF	0.01459959	0.96627119	0.101	213
SSA	0.01459184	1.07375825	0.145	302
SIS	0.01434621	0.05549814	0.038	55

The Welfare function of the FUND model

We approximate the FUND model with a linear benefit/quadratic cost structure for the analysis of coalition formation. Specifically, the abatement cost function is represented as:

$$C_i = \alpha_i R_i^2 Y_i, \tag{1}$$

where C denotes abatement cost, R relative emission reduction, Y gross domestic product, index i denotes regions and α is the cost parameter. The benefit function is approximated as:

$$B_i = \beta_i \sum_j^n R_j E_j \tag{2}$$

where B denotes benefit, β the marginal damage costs of carbon dioxide emissions and E unabated emissions. Table 1 gives the parameters of Equations (1) and (2) as estimated by FUND. Moreover, the profit π_i of a country i is given as:

$$\pi_i = B_i - C_i = \beta_i \sum_j^n R_j E_j - \alpha_i R_i^2 Y_i. \tag{3}$$

The second derivative of $d^2\pi_i/dR_i^2 = -2\alpha_i < 0$ as $\alpha_i > 0$. It follows that the profit function of every country i is strictly concave, and as a consequence has a unique maximum. Hence, the non-cooperative optimal emission reduction is found from the first-order optimal condition:

$$d\pi_i/dR_i = \beta_i E_i - 2\alpha_i R_i Y_i = 0 \Rightarrow R_i = \beta_i E_i/(2\alpha_i Y_i). \tag{4}$$

If a region i is in a coalition with a region j, the optimal emission reduction is given by:

$$d\pi_{i+j}/dR_i = 0 \Rightarrow E_i(\beta_i + \beta_j) - 2\alpha_i R_i Y_i = 0 \Rightarrow R_i = (\beta_i + \beta_j)E_i/(2\alpha_i Y_i). \tag{5}$$

Thus, the price for entering a coalition is higher emission abatement at home. The return is that the coalition partners also raise their abatement efforts.

Note that our welfare functions are orthogonal. This indicates that the emissions change of a country does not affect the marginal benefits of other countries (that is the independence assumption). In our game, countries outside the coalition benefit from the reduction in emissions achieved by the cooperating countries, but they cannot affect the benefits derived by the members of the coalition. As our cost-benefit functions are orthogonal, our approach does not capture the effects of emissions leakage. Even so, our cost benefit functions are sufficiently realistic as they are an approximation of the complex model FUND and our procedure of dealing with farsighted stability is also general and appropriate for non-orthogonal functions.

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