CO_2 removal and 1.5°C: Sharing the Gains from Inter-regional Cooperation using a Game-Theoretic Approach

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Abstract – Containing the effect of global warming is a major objective that can hardly be achieved in a timely manner absent the future sizeable deployment of a mix of carbon dioxide removal (CDR) methods, including Afforestation/Reforestation (AR), Bioenergy with Carbon Capture and Storage (BECCS), and Direct Air Carbon Capture and Storage (DACCS). Yet, the international nature of that deployment and its large expected common cost raise important public policy questions pertaining to both its cost-effectiveness and the associated cost-sharing problem among the participating nations. To explore them, the present paper proposes an original approach that combines an engineering perspective with concepts drawn from the theory of cooperative games. Indeed, we apply the MONET model – a detailed engineering-based representation of least-cost CDR future deployments – to evaluate the cost data needed to apply standard solution concepts proposed in game theory. Our analysis provides three highlights that may serve current international climate policy discussion. First, we reiterate that international cooperation reduces the cost of deploying CDR to levels that are compliant with the Paris Agreement. Second, our case study demonstrates that considerable financial flows from the UK, UE and US to Brazil and China are required for cooperation to be conceivable. Third, we show how critical it is to develop fair and mutually acceptable cost allocations for international cooperation to succeed. Finally, we examine how cooperation might result in a coordination cost.

1 Introduction

To limit global warming, humanity will most likely have to become carbon negative by the end of the century [1]. In other words, more CO_2 should be removed from the atmosphere than emitted. To that aim, research on Carbon Dioxide Removal (CDR) methods is gaining momentum (twelve methods are cited in IPCC's 2022 report on mitigation pathways: Pathak et al., 2022). In particular, Afforestation/Reforestation (AR) [3], Bioenergy with Carbon Capture and Storage, (BECCS) [4], and Direct Air Carbon Capture and Storage (DACCS) [5] are increasingly represented in Integrated Assessment Models (IAMs) [6].

Under 1.5°C scenarios, IAMs require 190 to 1,190 $GtCO_2$ CDR by 2100 [7,8]. To illustrate, 1,190 $GtCO_2$ CDR is equivalent to removing 33 times our current annual emissions from the atmosphere [9]. These large scale projections have raised concerns concerning competition for resources, biodiversity, and social justice [10–13]. More research on sustainability bounded CDR pathways is required [12]. Additionally, IAMs usually rely on a global cost-optimization, thereby implicitly positing that a benevolent social planner controls all CDR investments. In practice, the incentives to invest in CDR vary greatly by country due to their common but differentiated responsibility towards climate change. Hence, the previously mentioned CDR projections rely on successful international cooperation [14]. Chiquier et al. (2022) show that, without international cooperation, it becomes less likely to deploy CDR to levels compatible with the Paris Agreement, and the related costs rise by 51–69%.

The Paris Agreement acknowledges the necessity for international cooperation. Article 6 outlines how countries may "pursue voluntary cooperation" to meet their climate targets, and Article 6.2. lays down the foundations for exchanging emission reductions and removals through bilateral or multilateral agreements between countries. The resulting credits are named Internationally Transferred Mitigation Outcomes (ITMOs). ITMOs would make it possible for countries to account for carbon removal that takes place in other countries in their own climate target (or Nationally Determined Contribution). While these deployments are encouraging, the possibility of exchanging carbon removal credits is not sufficient to ensure cooperation: the gains from cooperation must also be shared in a mutually acceptable manner for multilateral agreements to succeed.

The purpose of this paper is to examine whether international cooperation is feasible to deploy CDR at levels compatible with the Paris Agreement. Specifically, we assess whether the gains from international cooperation can be shared in an incentive-compatible manner.

We propose an original combination of two markedly different tools. The first one is the previously developed Modelling and Optimization of Negative Emissions Technologies (MONET) framework that is stemmed from the engineering literature [13,15]. The MONET model provides a large-scale computerized dynamic representation of CDR deployment, with a particular focus on AR, BECCS and DACCS. MONET is a deterministic, discrete-time, finite-horizon model that is formulated as a linear-programming problem solved numerically. Using this optimization model, a series of simulations under different scenarios are conducted to determine the least-cost CDR deployment for any subgroup of countries, which are: Brazil, China, the United Kingdom (UK), the European Union (EU), and the United States of America (USA). These results obtained with MONET are then combined with our second tool: cost-sharing notions drawn from the theory of cooperative game. For cooperative games, various solutions have been proposed to share cost in a mutually acceptable and fair manner. In this paper, we compare several standard classical solution concepts from cooperative game theory – the core, the Shapley value, and variants of the nucleolus – to investigate how the cost of future CDR deployment should be apportioned among countries in the event of cooperation. Overall, this approach provides valuable insights to public decision makers, stakeholders and scholars interested in the economics of these emerging CDR technologies.

At an empirical level, this paper contributes to the small, and very much needed, literature attempting to shed light on the economics of international cooperation in deploying CDR [14,15]. Other related works, though more loosely connected to our methodology and not focused on CDR deployment, have explored the formation of "climate clubs" and environmental coalitions [16–20]. This paper represents the very first application of notions rooted in cooperative game theory to the case of international CDR deployment.

Our analysis provides four highlights. First, we repeat that international cooperation leads to substantial cost reduction in deploying CDR to levels compatible with the Paris Agreement. Second, our case study shows that substantial financial transfers need to be directed towards Brazil in China for cooperation to be possible. Third, we illustrate the importance and complexity of designing fair and mutually acceptable cost allocations to ensure the success of international cooperation. Finally, we discuss whether the transaction costs related to cooperation can be covered.

The paper is organized as follows. In the next section, we present our modelling framework and details the game theoretic notions used to examine the cooperation among these players. Section 3 presents our results and the last section offers a summary and some concluding remarks.

2 Methodology

In this section, we first present an overview of the modeling framework used to determine a cost-efficient deployment of CDR technologies. Then, we describe the data and the scenarios considered in the analysis. Lastly, a final subsection discusses the solution strategy for sharing the cost.

2.1 Overview of the MONET framework

This study is based on the Modelling and Optimisation of Negative Emissions Technologies (MONET) framework, developed previously [13,15] to provide insights into the cost-optimal spatio-temporal deployment of CDR pathways to deliver at the Paris Agreement's scale. From an economic perspective, the MONET framework can be described as a detailed partial equilibrium model that is formulated as a deterministic LP optimization problem with a perfect foresight approach — whereby a supranational benevolent social planner is posited to determine the future optimal deployment of CDR pathways across a given group of regions. The social planner's objective is to minimize the present discounted value of the future stream of operating and capital expenses over the entire planning horizon. The planner's decisions must also verify a large set of constraints that describe: (i) the CDR targets to be met either at the global or at the regional levels that will be further discussed in the next subsection; (ii) a series of bio-geophysical constraints that capture sustainability limitations pertaining to the availability of land availability, biomass supply and maximum water stress; (iii) a number of CDR method-specific constraints encompassing feasibility limitations that have an engineering and/or industrial nature (*e.g.*, to account for construction periods, possible restrictions in the ramping rates, or limitations in the operating lifetimes of the installed equipment) or that are nature-based (*e.g.*, to account for maximum possible afforestation rates or requirements to maintain forest CO_2 sinks in perpetuity); (iv) the regional geological endowment in CO_2 storage capabilities. As the MONET framework has already been described previously [13,15], the detailed description of the above-mentioned constraints can be found in Annex A, with the exception of the long-term CDR targets.

2.2 Data and scenarios

2.2.1 Data and empirical specification

The MONET framework is here calibrated to capture the essential features of future inter-regional deployment of CDR pathways. It considers a planning horizon covering the period 2020–2100 (decomposed in ten-year steps), and includes here 3 CDR methods — afforestation/reforestation (AR), bioenergy with carbon capture and storage (BECCS), and direct air capture and CO_2 storage (DACCS) — across 5 regions[1] — Brazil, China, the EU-27, the UK and the USA. Together, these regions accounted for 32% of the global population, 63% of global GDP, and 54% of GHG emissions in 2018 [21]. Therefore, although this is not a global analysis, it is reasonable to say that it can provide policy-relevant insights into global climate change mitigation, as well as feasible and sustainable deployment of CDR.Note that by construction, this spatial delineation can easily be adapted to determine the least-cost CDR deployment at either the inter-regionallevel, *i.e.* by considering the grand coalition gathering these 5 regions, or a more restricted one by solely accounting for a subgroup of these 5 regions.

Prices and costs are nominated in constant 2018 dollars. The parameterization of the costs and technologies is consistent with the one in [15] and is detailed in Appendix A. We assume a positive discount rate which remains constant over the entire planning horizon, and for which we use a 3% value[2]. To gain further insights on the importance of that parameter, we also consider a value of 7% in Appendix B.

2.2.2 Long term CDR targets

Cumulative CDR targets are key optimisation constraints of the MONET framework. Here, we use cumulative CDR targets that are consistent with climate mitigation pathways from the IPCC Special Report on Global Warming of 1.5°C (SR15) [7,22]. Among the four illustrative pathways of the SR15, we select the IPCC P3 pathway, characterized as a middle-of-the-road scenario in which societal and technological development follows historical patterns. In this scenario, emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

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[1] *The MONET framework incorporates a more disaggregated spatial representation that considers the state/provincial scale for the USA, China and Brazil, and the regional scale for the EU-27 and the UK. Accordingly, the 5 regions at hand are further decomposed into 135 sub-regions. Yet, for concision, the present discussion solely concentrates on the regional aggregates and omit the sub-regional level.*

[2] *We choose the discount rates 3% and 7% based on U.S. Federal guidance in Circular A-4 by the Office of Management and Budget.*

Owing to their relatively low spatial granularities, the IPCC climate mitigation pathways illustrated in the SR15 fail to provide insight on the CDR deployments that are necessary at a national scale, which the level at which climate mitigation policies, e.g. net-zero targets, are implemented, or negative emissions credits could be traded within (international/inter-regional) carbon markets. Furthermore, these illustrative pathways assume that CDR can be delivered at scale principally via AR and BECCS technology [23], thereby failing to elaborate on how other CDR methods could be integrated and co-deployed.

Here, we apply a responsibility-based burden-sharing principle [24] to allocate regional CDR targets, i.e. to each region considered in the MONET framework. Global CDR targets from the IPCC P3 scenario are therefore distributed in proportion to each region's cumulative historic GHG emissions [25,26]. This is shown in Table 1. Note that neither the IPCC illustrative pathway, nor the burden-sharing principle used in this study are meant to be prescriptive; rather, they are a proxy for a socio-economically fair allocation of 1.5°C-consistent CDR objectives. Particularly, other burden-sharing have been proposed in the literature, based on capacity, sovereignty or equity and equality [27,28]. Pozo et al. (2020) investigated the feasibility of delivering CDR at the national level, within the EU, based on different burden-sharing principles.

Table 1: Implications of the responsibility-based burden-sharing principle based on cumulative historic GHG emissions on the allocation of the IPCC P3 CDR targets at the national scale in MONET.

Regions	**Cumulative GHG emissions 1850–2019 ($Gt\ CO_2$)[a]**	**Proportion of CDR targets (%)**	**Cumulative P3 target 2100 ($Gt\ CO_2$)**
Brazil	47	1.8	7
China	357	13.7	56
EU-27	410	15.7	64
UK	110	4.2	17
USA	557	21.3	87
Total MONET regions	1,482	56.7	231
Total World	2,612	100.0	408

2.2.3 *Two main cooperation scenarios: standalone and grand coalition*

We focus on non-market cooperation between countries by allowing the aggregation of national CDR targets. For example: let us assume that Brazil and the USA decide to cooperate, thereby forming a coalition. The two countries will aim to reach their joint target of 94 $GtCO_2$ carbon removal rather than their individual targets of 7 and 87 $GtCO_2$, respectively. Resource exchanges (mainly biomass and liquified CO_2) are only allowed within a coalition[3].

We assess all cooperative configuration by iteratively solving MONET. In other words, we determine the least-cost CDR deployment for any of the subgroup of regions that can be formed by combining the five regions above. The resulting cost data are used as an input for the cooperative game-theoretic discussions below. In the result analysis, we will focus on two scenarios: standalone and grand coalition. In the standalone scenario, regions can only use their domestic resources to reach their CDR target. In the grand coalition scenario, the five regions cooperate to reach their aggregated CDR target.

2.3 Sharing the cost, a cooperative game theoretic perspective

If some or all regions agree to cooperate, the costs of reaching their CDR target must be divided among the members of the coalition in a manner that allows successful cooperation. In the remainder of this section, we explicitly write out the conceptual tools used to investigate the sharing of the costs among the five regions.

2.3.1 Formulation of the problem

We assume that each region is a player and let $N = \{1,..,n\}$ denote the grand coalition that gathers all the regions under scrutiny. We use i to denote $\{i\}$ a particular element in N, and S to denote any subgroup of players S that can be formed in N. We consider the cost function C that gives $C(S)$, present discounted cost to install and operate the optimal CDR mix for the regions in S.

<u>The core</u>

The cost allocation problem comes down to finding a cost vector $x \in \mathbb{R}^n$ where x_i is the cost allocated to region i. A first condition is that the cost allocation must be efficient, that is:

$$\sum_{i\in N} x_i = C(N) \qquad (1)$$

Previous studies on MONET support that CDR cooperation leads to overall cost reduction [14,15]. However, from the point of view of a subgroup S, some cost allocations may lead to a greater cost than in standalone. For such cost allocations, it becomes irrational for S to cooperate. Therefore, the following condition must be met:

$$\sum_{i\in S} x_i \leq C(S) \qquad \forall S \subset N \qquad (2)$$

The core of the game [30] consists of all cost allocation vectors x that satisfy conditions (1) and (2). It should be noted, however, that the core can be empty. We then define the amplitude of the core for a player i: $a_i = [x_{i_{min}}, x_{i_{max}}]$, where $x_{i_{min}}$ and $x_{i_{max}}$ are the lowest and highest cost that can be attributed to the player i within the core.

2.3.2 Cost allocations

A minimal condition for a cost allocation vector x to be mutually acceptable is belonging to the core: any imputation outside the core can be blocked by a coalition that would face a lower cost

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[3] *It can be argued that the assumption of no resource exchanges outside the coalition makes our case study less realistic. However, this simplifying assumption greatly eases interpretation, as it allows to overlook the effects of resource competition between complementary coalitions. These effects are outside the scope of our study.*

by disbanding [31]. An important challenge, however, is to find a solution concept that selects a unique cost vector within the core. In the present paper, we explore three solution concepts: the nucleolus, the per capita nucleolus, and the disruptive nucleolus.

Shapley value

The Shapley value allocates a unique cost vector by assigning each player its "average marginal contribution" to the game. Let us assume that the grand coalition is formed by adding regions i in a given sequence. Each participant i receives a benefit equal to the cost reduction $C(S\backslash i) - C(S)$ it offers to the coalition $S\backslash i$ formed just before. The Shapley value then accounts for all possible sequences by assuming a probability of $\frac{1}{N!}$ for each permutation of the grand coalition. We note $|S|$ the cardinality of subgroup S. Hence:

$$x_i = \sum_{S\subseteq N:i\in S} \frac{|S\backslash i|!|N\backslash S|!}{|N|!} (C(S\backslash i) - C(S)), \qquad \forall i \in N \qquad (3)$$

The allocation of average marginal contributions to each player, as defined by the Shapley value, might be regarded a justification for the solution concept in and of itself. Additionally, the Shapley value yields a unique solution, while satisfies a set of three useful axioms (Shapley, 1953). However, the Shapley value can be outside of the core.

The nucleolus

A first solution concept is the nucleolus proposed by Schmeidler (1969). It returns a unique cost allocation it satisfies an appealing property: it always belongs to the core when it is non-empty.

Let S be a nonempty coalition unequal to N. The excess of S at x, denoted by $e(S,x)$, is the difference between the cost S faces on its own and the cost S is allocated under imputation x:

$$e(S,x) = C(S) - \sum_{i\in S} x_i \qquad (3)$$

The idea behind the nucleolus is to maximize the smallest satisfaction across coalitions[4], which we represent by maximizing the smallest excess previously introduced. If there are multiple ways to do so, the second-smallest satisfaction is maximized. And so on until a unique solution is found. The algorithm can be described as follows [33]:

Find all cost allocations x for which the minimum excess among all coalitions $S \notin \{\emptyset, N\}$ is as large as possible. If there is a unique solution, then that is the nucleolus. If not, go to step 2.

Identify the coalitions for which the minimum excess found in previous steps cannot be increased. Continue with the remaining coalitions: among the allocations x found in the previous step, find those for which the minimum excess is as large as possible. If there is a unique solution, then that is the nucleolus. If not: repeat step 2.

From a computational perspective, Kopelowitz (1967) proposed an algorithm based on a sequence of linear programs. We use an approach developed in [35,36].

Per capita nucleolus

One drawback of the nucleolus is that it is not monotonic, as proved by Megiddo (1974). This prompted Grotte (1970) to define the "per capita nucleolus" (also known as "normalized

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[4] *The nucleolus is usually presented in the context of a payoff game instead of a cost game. In that case, the nucleolus is rather presented as minimizing the largest dissatisfaction.*

nucleolus") to describe a version based on a per capita assessment of excesses. The dissatisfaction of a coalition S for a cost allocation x is then measured by:

$$e(x,S) = \frac{C(S)-\sum_{i\in S} x_i}{|S|} \qquad (4)$$

Grotte demonstrated that the per capita nucleolus is monotonic and always belongs in the core if the core is not empty.

Disruptive nucleolus

The next solution concept we will consider here is the disruptive nucleolus, first proposed for a 3-person game by [31] as a tool for determining a mutually acceptable cost allocation from regional cooperation. Gately's work was later extended for n-person games by [39].

The propensity to disrupt of a coalition S at x is defined as the ratio of what the complementary coalition $N\backslash S$ would lose if the grand coalition N broke up to the amount of what S would lose:

$$d(x,S) = \frac{C(N\backslash S) - \sum_{i\in N\backslash S} x_i}{C(S) - \sum_{i\in S} x_i} \qquad (5)$$

Assuming that only core allocations are proposed to the members of the grand coalition N, the propensity of a given subgroup S to disrupt the grand coalition increases with its allocated cost $\sum_{i\in S} x_i$ (in which case the complementary coalition $N\backslash S$ gets a lower cost allocation). Gately suggest that the concept of propensity to disrupt may be used measure of mutually acceptability of a cost allocation x.

Further, [39] proposed using this ratio as a dissatisfaction measure to be minimized using the same algorithm as for the nucleolus. They also introduce a computational procedure that we apply here. The resulting unique allocation is named disruptive nucleolus. By construction, it also belongs to the strict core if it is non-empty.

3 Results

This section presents four highlights from our analysis. In the first section, we present the results from the MONET framework and show that cooperation significantly reduces the costs of CDR. We then adopt a cooperative game-theoretic approach in the second section and find that large financial transfers toward Brazil and China are needed to ensure successful cooperation. The third section discusses the importance and complexity of choosing a fair and mutually acceptable cost allocation. Finally, we discuss other factors for successful cooperation.

3.1 Cost reduction through cooperation: insights from the MONET framework

The MONET framework identifies the deployment of cost-optimal CDR pathways consistent with the Paris Agreement's 1.5°C objectives under two scenarios. In the grand coalition scenario, all regions cooperate to meet a shared CDR target. In the standalone scenario, each region meets its individual CDR targets without cooperating with the other regions. As discussed in Section 2, we use cumulative CDR targets between 2020 and 2100 consistent with the IPCC P3 mitigation scenario. We discuss here the spatiotemporal composition of these CDR pathways, *i.e.* AR, BECCS and/or DACCS, and their costs, across Brazil, China, the EU, the UK and the USA.

Figure 1 shows the cost-optimal CDR pathways by 2100 in the grand coalition and in all standalone coalitions. With inter-regional cooperation (in the grand coalition), the Paris Agreement's 1.5°C objectives are met with a combination of BECCS (60%) and AR (40%), costing 2,689 billion \$ by 2100, that is (levelized) \$12/tCO_2 (see Table 1) . We observe that most of the CO_2 removal is achieved via BECCS in China, the most cost-efficient region here, *i.e.*, owing to the combination of several bio-geophysical and economic factors, including: well-characterised CO_2 storage capacity; cost-effective biomass supply; and affordable CO_2 transport & storage infrastructures [15]. Importantly, China provides an additional 42 Gt CO_2, over and above its individual 2100 CDR target, that is almost twice (1.8) what it should, without inter-regional cooperation. Brazil also provides an additional 36 Gt CO2, over and above its individual 2100 CDR target, essentially via AR, i.e. owing to warm and humid tropical climates, favourable for the fast and high growth of forests. This is almost six times (5.9) greater than its individual 2100 CDR target.

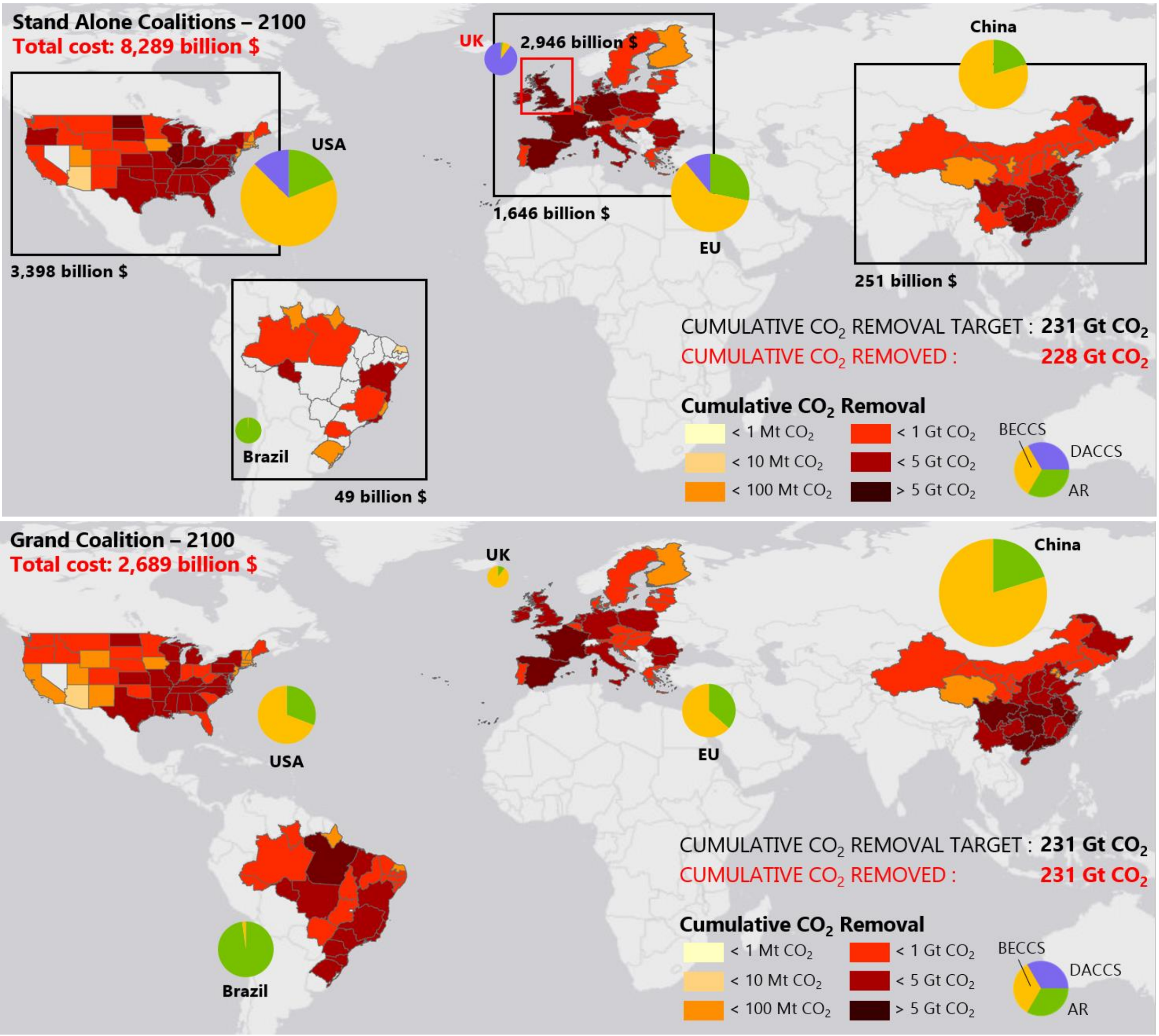

Figure 1. Cost-optimal CDR pathways by 2100 in the grand coalition (top) and in all standalone coalitions (bottom). Note that the UK can't meet its individual 2100 CDR target (by 3 Gt CO_2) in the UK standalone Coalition. With inter-regional cooperation, the Paris Agreement's 1.5C objectives are met with a combination of BECCS and AR, costing 2,689 \$ by 2100. Without inter-regional cooperation, not only the Paris Agreement's 1.5C objectives are not met, but it costs 8,289 \$ by 2100, that is 3 times, due to the deployment of DACCS in the EU, the UK and the USA, as a last-resort.

Without inter-regional cooperation (the standalone coalitions scenario), the Paris Agreement's 1.5°C objectives are missed by 3 Gt CO_2 by 2100, despite the deployment of DACCS (14%), alongside BECCS (65%) and AR (22%). This is because of the UK, wherein the deployment of AR is limited by suitable and available land, and the deployment of BECCS and DACCS is limited by available CO_2 storage capacity. In our subsequent game theoretic analysis, we will translate the fact that the UK fails to deliver its individual 2100 CDR target by a virtually infinite standalone cost. Importantly, as all regions aim to deliver their fair share of the Paris Agreement's CDR objectives, without inter-regional cooperation the deployment of CDR is less cost-efficient than in the grand coalition, *i.e.* lead by individual CDR targets rather than the cost-optimal combination of bio-geophysical and socio-economic factors. Particularly, as the EU, the UK and the USA are historically the greatest polluters, they have the greatest CDR targets. Owing to a combination of limited land availability (EU, UK, USA), CO_2 storage capacity (EU, UK), and limited AR potential (EU, UK, USA), they must deploy DACCS as a last-resort solution, thereby increasing significantly the overall cost by 3, in comparison to the grand coalition, i.*e.* the standalone coalitions cost overall 8,289 billion $, that is (levelized) $36/t CO_2.

Table 1: Overview of 2100 CO_2 removals and costs in the grand coalition and in all standalone coalitions.

	Brazil	**China**	**EU**	**UK**	**USA**	**Total**
CDR ($GtCO_2$)						
Standalone coalitions	7	56	64	15[a]	87	228
Grand coalition	43	98	41	2	47	231
Cost of CDR (billion $)						
Standalone coalitions	48	251	1,646	2,946[a]	3,398	8,289
Grand coalition	-[b]	-[b]	-[b]	-[b]	-[b]	2,689

[a] The UK doesn't meet its individual 2100 CDR target in its standalone coalition.

[b] In the grand coalition, the cost allocated to each region depends from the chosen allocation. These are presented in the next sections.

3.2 Financial transfers towards China and Brazil: insights from the Shapley value

The previous section shows that international cooperation leads to a substantial cost reduction in reaching CDR targets but does not address the question of sharing the costs of such cooperation. The Shapley value is commonly used for gain and cost-sharing problems because it assigns each player its average marginal contribution, which can be seen as a justification for fairness in itself. Additionally, the Shapley value always exists, is unique and can be easily calculated. Table 2 shows how costs could be apportioned using the Shapley value method.

Brazil and China must get a negative cost (*i.e.*, a net profit) for cooperation to succeed. Brazil gets a profit that 18 times higher than its original cost, while China's profit represent 3 times its original costs. In the line of Hubert and Ikonnikova (2011) and Morbee (2014), we can interpret these profits as bargaining power. Both Brazil and China have large potential for CDR, low CDR costs, and smaller historical responsibility in climate change (see Section 3.1.). Next, the UK seems to benefit from the highest relative cost reduction. However, knowing that the UK is unable to reach its CDR target alone, its high cost reduction is rather explained by high standalone cost than by bargaining power.

Table 2: CO_2 removal cost and gain from cooperation per region under the Shapley value approach

	Brazil	**China**	**EU**	**UK**	**USA**	**Total**
Allocated cost (billion $)	-819	-567	1,115	932	2,027	2,689
Relative cost reduction[a]	1,788 %	326 %	32 %	68 %	40 %	5,601

[a] The cost reduction induced by cooperation for a region i is defined as the difference between the cost x_i allocated to region $\{i\}$ under the Shapley value approach and the cost $C(\{i\})$ faced by the region $\{i\}$ in the standalone scenario. The relative cost reduction is hence: $\frac{C(\{i\})-x_i}{C(\{i\})}$

3.3 Selecting a cost allocation method: insights from a game theoretic perspective

The Shapley value is regarded as a convenient method for sharing costs, there is no guarantee that the Shapley value is in the core of the game, *i.e.*, that no subgroup of emitters has an incentive to disband from the grand coalition. We consider the four cost allocations as proposed in Section 2.3.: the Shapley value, the nucleolus, the nucleolus per capita, and the disruptive nucleolus (Figure 2).

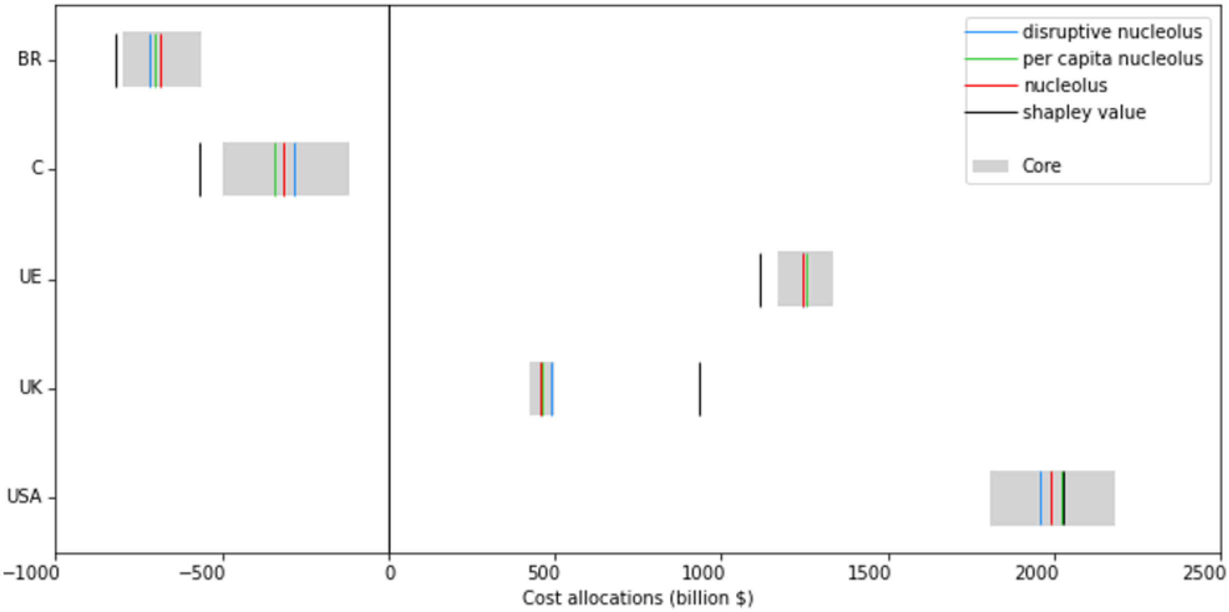

Figure 2: Cost allocations compatible with international cooperation

We notice that the Shapley value is outside of the core the game, and that the cost allocations methods favor regions differently. In particular, the disruptive nucleolus seems to favor the USA and disfavor China, while the per capita nucleolus does the contrary. Conceivably, such a situation could lead to some power struggles between China and the USA for the choice of the cost allocation method. The fairness of the chosen solution concept is therefore critical to ensure the successful cooperation. The literature on cooperative games proposes many axioms and properties to guide the solution concept choice [36]. We focus here on two approaches to fairness: mutual acceptability [31] and on monotonicity.

A cost allocation is mutually acceptable is no subgroup of emitters has an incentive to disband from the grand coalition. A minimal condition for a cost allocation to be mutually acceptable is therefore belonging to the core: any imputation outside the core can, by definition, be blocked by a coalition that faces a lower cost by disbanding. As introduced in Section 2.3., Gately (1974) proposes a measure of mutual acceptability by defining the propensity to disrupt. The disruptive nucleolus is directly built upon that concept: it minimizes the largest propensity to disrupt – and hence, the mutual acceptability – across coalitions. It does not, however, verify the conditions of monotonicity [42]. Monotonicity implies that a region's cost allocation should not decrease when its CDR targets increases. On the other hand, if costs turn out to be higher than expected then the shares of the costs allocated to the different regions should not decrease. The Shapley value and per capita nucleolus verify that property, but the nucleolus and disruptive nucleolus do not. Table 2 compares all solution concepts used in this study in terms of mutual acceptability and monotonicity.

Table 2: Mutual acceptability and monotonicity of the solution concepts

	Shapley value	**Nucleolus**	**Per capita nucleolus**	**Disruptive nucleolus**
Belongs to the core of the game	No	Yes	Yes	Yes
Largest propensity to disrupt	/	68	60	35
Associated coalition		*B, C, EU, US*	*B, C, EU, US*	*B, C, EU, US*
Second largest prop. to disrupt	/	5	6	5
Associated coalition		*B, C, UK, US*	*C, EU, US*	*C, EU, US*
Verifies monotonicity	Yes	No	Yes	No

The only solution concept that both verifies monotonicity and belongs to the core is the per capita nucleolus. Its largest propensity to disrupt can be interpreted as follows: under the per capita nucleolus cost allocation, the cost reduction achieved by the UK compared is 60 times higher than the cost reduction achieved by the coalition formed by Brazil, China, the EU and the USA. Under the disruptive nucleolus, the largest propensity to disrupt is almost 42 % smaller. That said, the propension to disrupt of the coalition formed by Brazil, China, the EU and the USA is high under both solution concepts. The second largest propensity to disrupt is much closer. Hence, it seems reasonable to select the per capita nucleolus method in the present case study.

3.4 The cost of cooperation

We assumed in the previous subsection that coordination may be organized at no cost, resulting in a complete redistribution of gains. Conceivably, some additional cost occurs from the cooperation process, for example for Monitoring, Reporting and Verifying carbon removal credits. In this section, we evaluate how high the coordination cost can be for cooperation to be successful.

Let us assume that the coordination cost is calculated as a percentage of total costs. Note ω the percentage allocated to coordination costs. For cooperation to be successful, ω must be such that a mutually acceptable sharing of costs remains feasible. Hence, the core of the game must remain non-empty. We therefore solve the following linear program to find the maximum acceptable share of cost allocated to coordination $\bar{\omega}$:

$$\bar{\omega} = \max_{x,\omega} \omega$$

$$\text{s.t.} \quad \sum_{i \in N} x_i = C(N) * (1 + \omega)$$

$$\sum_{i \in S} x_i \leq C(S) \qquad \forall S \subset N, |S| = 1$$

$$\sum_{i \in S} x_i \leq C(S) \; * (1 + \omega) \qquad \forall S \subset N, |S| \neq 1$$

$$\omega \geq 0$$

We find that for up to 41% of total costs, the regions of our case study prefer to cooperate than to stand alone. The gains from cooperation will hence likely be large enough to cover the cost of coordination, at least in the case of CDR[5].

4 Concluding remarks

International cooperation is needed to ensure Carbon Dioxide Removal (CDR) levels compatible with the Paris Agreement. However, the conditions for the success of such cooperation has not been examined until now. We apply concepts from cooperative game theory to analyze the CDR deployment pathways from the engineering-based Modelling and Optimization of Negative Emissions Technologies (MONET) framework. Three points stand out in our analysis. First, we reiterate that international cooperation reduces the cost of deploying CDR to levels that are compliant with the Paris Agreement. Second, our case study demonstrates that considerable financial flows to Brazil from China are required for cooperation to be conceivable. Third, we show how critical it is to develop fair and mutually acceptable cost allocations for international cooperation to succeed. Finally, we discuss whether the transaction costs related to cooperation can be covered.

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[5] *As a comparison, the coordination cost under the Article 6.4. mechanism can be approximated to 7% of the value of exchanged credits. During COP26 negotiators indeed agreed that on each first issuance of Emissions Reduction Credits, 5% are to be levied for adaption and administrative expenses, and 2% are to be cancelled [50].*

Appendix A – the MONET framework

The Modelling and Optimisation of Negative Emissions Technologies (MONET) framework provides insight into the location, timing, and scope of CDR pathways that might be deployed to deliver 1.5°C consistent climate targets. The MONET framework is an explicit spatio-temporal model, comprised of two sub-frameworks: 1) the modelling framework provides whole-system analyses of a portfolio of CDR options, *e.g.* AR, BECCS or DACCS, and 2) the optimisation frameworks determines the least-cost deployment of that portfolio of CDR options in ten-year time steps between 2020 and 2100. Here, the objective function, *i.e.* the key metric to be optimized, is the discounted cumulative total net cost, *i.e.* total costs minus revenues, for any CDR pathway. This is written as follows:

$$CTNC(t) = CTC^{AR}(t) + CTNC^{BECCS}(t) + CTC^{DACCS}(t) \qquad \forall t$$

where:

$CTNC(t)$ is the cumulative total net cost of the CDR pathway until the year t ($),

$CTC^{AR}(t)$ is the cumulative total cost of AR until the year t ($),

$CTNC^{BECCS}(t)$ is the cumulative total net cost of BECCS, *i.e.* total costs of BECCS associated with the biomass supply, the BECCS plant, and the CO_2 transport and storage, minus revenues from electricity generation, until the year t ($),

and $CTC^{DACCS}(t)$ is the cumulative total cost of DACCS until the year t ($).

The cost optimization is subject to a variety of constraints, including: CDR targets that are specified globally or regionally, sustainability limits (land and biomass supply availability, maximum water stress) that are imposed, CDR deployment rates (build and ramping rates and operating lifetimes) that are specified, and geological CO_2 storage limits that are imposed. The MONET framework, developed initially for BECCS, then adapted for AR and DACCS as well, has been presented previously [13,15]. Table A-1 provides a short description of the main constraints of the model. Further details can be found in [15]

Table A-1 Main constraints of the MONET framework

	Description of the constraint	**Key elements**
CDR targets	Cumulative CDR targets for each region over the 2020-2100 period	Targets are based on responsibility-based burden-sharing principle. See Table 1.
CDR deployment rates	Deployment rates reflect the maximum speed at which each CDR method can deploy.	*Project lifetime:* - BECCS/DACCS: 30 years - AR: unlimited *Maximum deployment at global scale:* - BECCS/DACCS: 16.8 $MtCO_2$/yr - AR: 8.5 Mha/yr,

Sustainability and land availability	Both AR and BECCS require to grow biomass, which is limited by the availability of land and water. Biomass grown for BECCS can stem from dedicated-energy crops or agricultural residues.	- AR is limited by the availability of ecologically viable areas with a potential for reforestation. - Dedicated-energy crops for BECCS are grown on marginal agricultural land. - Agricultural residues consist of wheat straw collected from harvested wheat areas - Bio-energy production for BECCS is limited to areas with low water stress
Geological CO_2 storage availability	BECCS and DACCS store CO_2 into geological reservoirs, situated in the vicinity (*i.e.*, 100km) of the BECCS and DAC plant, respectively.	- Brazil: 0.95 Gt CO_2 [43] - China: 3,106 Gt CO_2 [44,45] - EU-27: 102 Gt CO_2 [46,47] - UK: 78 Gt CO_2 [48] - USA: 8,533Gt CO_2 [49]

Appendix B – Discount rate and biomass trade scenarios

This appendix assesses the impact of two assumptions in our study: the discount rate (3% in our study), and the impossibility to trade biomass between regions outside of a coalition. We test two discount rates: 3% and 7%, as advised by the U.S. Federal guidance in Circular A-4 by the Office of Management and Budget. Concerning biomass trade, we assumed "No biomass trade" in our previous analysis: no inter-regional trading of resources is permitted if countries decide not to cooperate (standalone scenario). In that case, regions must the Paris Agreement individually, based on their respective responsibilities for climate change, and entirely domestically by using exclusively indigenous resources. This appendix also includes a "Biomass trade" scenarios: if regions decide not to cooperate in reaching their CDR targets, they can still trade resources. Such assumption seems more realistic: international biomass trade can occur even in the absence of a framework for exchanging carbon removal credits. However, the "Biomass trade" assumption is not compatible with the assumption of transferrable utility necessary to develop the cooperative game theory approach in Section 2.3.. The cost faced by a coalition S is computed by running the MONET framework for each coalition individually, hence the competition for biomass resources – that should normally occur if biomass trade is allowed – is not reflected.

The most remarkable difference from our basis scenario (top left on Figure B-1), is that in the other cases there exist cost allocations in the core where China is allocated a slightly positive cost. However, the Shapley value – which can be interpreted as the bargaining power of each region – drives the cost allocation to a net profit for China. Brazil can only be allocated a net profit in all cases. The lower total costs in the 7% discount rate scenarios are due to a smaller importance given to future costs. Overall, the cost sharing schemes under discount rate and biomass trade scenarios remain largely similar.

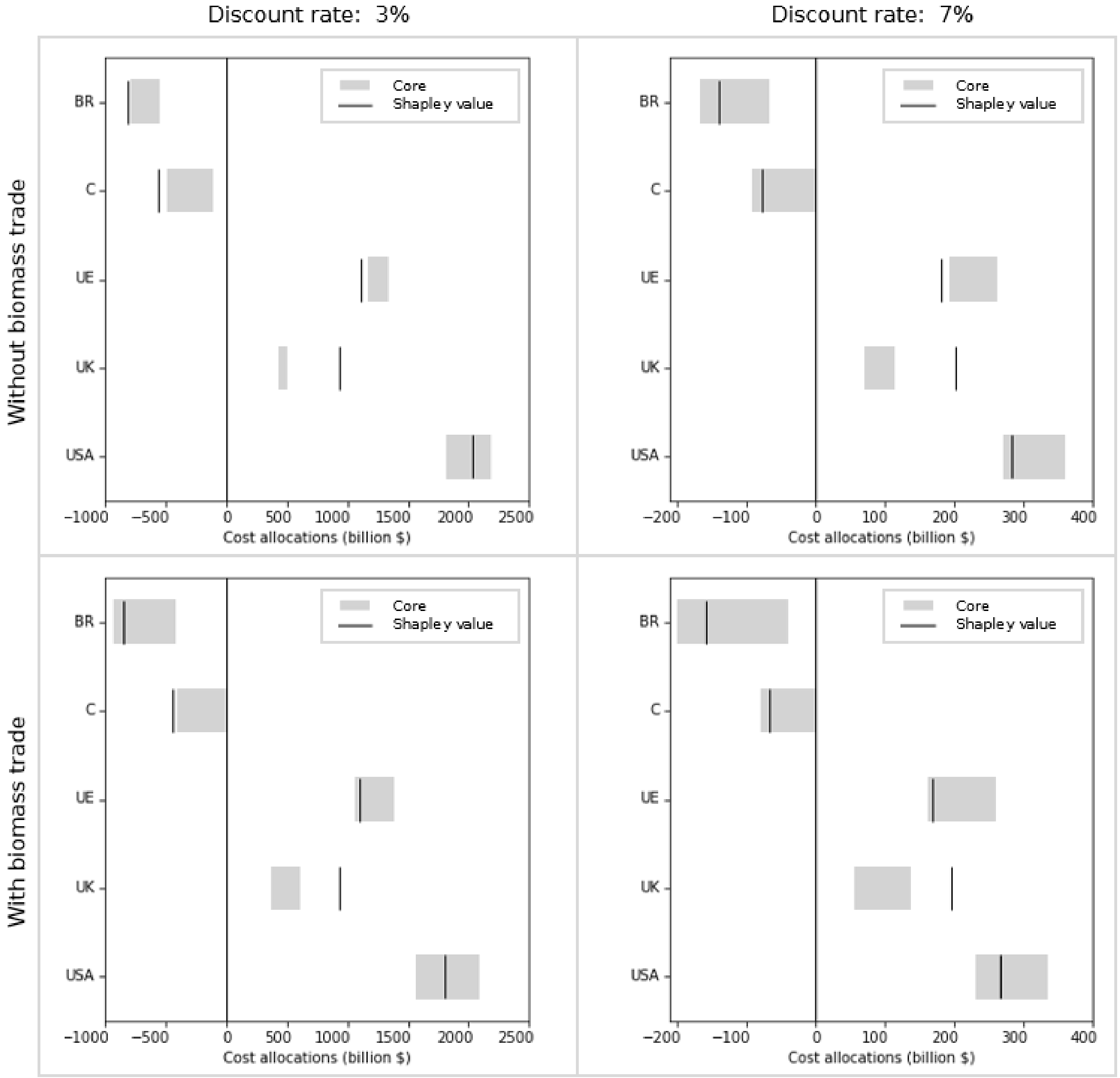

Figure B-1: Cost allocations under two discount rate scenarios (3% and 7%), and in two biomass trade scenarios. When standing alone without biomass trade, regions can only use their domestic resources. When standing alone with biomass trade, regions can import biomass but can only use domestic CO_2 storage.

References

[1] IPCC. (2022) Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Internet]. Shukla PR, Skea J, Slade R, Al Khourdajie A, van Diemen R, McCollum D, et al., editors. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926

[2] Pathak, M., Slade, R., Shukla, P.R., Skea, J., Pichs-Madruga, R. and Ürge-Vorsatz, D. (2022) Technical Summary. In: Shukla PR, Skea J, Slade R, Al Khourdajie A, van

Diemen R, McCollum D, et al., editors. *Climate Change 2022: Mitigation of Climate Change Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press.

[3] Canadell, J.G. and Raupach, M.R. (2008) Managing forests for climate change mitigation. *Science*, American Association for the Advancement of Science. **320**, 1456–7.

[4] Gough, C. and Upham, P. (2011) Biomass energy with carbon capture and storage (BECCS or Bio-CCS). *Greenhouse Gases: Science and Technology*, **1**, 324–34.

[5] Keith, D.W., Holmes, G., Angelo, D.S. and Heidel, K. (2018) A process for capturing CO2 from the atmosphere. *Joule*, Elsevier. **2**, 1573–94.

[6] Minx, J.C., Lamb, W.F., Callaghan, M.W., Fuss, S., Hilaire, J., Creutzig, F. et al. (2018) Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters*, **13**.

[7] Huppmann, D., Rogelj, J., Kriegler, E., Krey, V. and Riahi, K. (2018) A new scenario resource for integrated 1.5°C research. *Nature Climate Change*, Nature Research. **8**, 1027–30.

[8] Rogelj, J., Popp, A., Calvin, K. V, Luderer, G., Emmerling, J., Gernaat, D. et al. (2018) Scenarios towards limiting global mean temperature increase below 1.5 C. *Nature Climate Change*, Nature Publishing Group. **8**, 325–32.

[9] IEA. (2021) Global Energy Review: CO2 Emissions in 2021 [Internet].

[10] Heck, V., Gerten, D., Lucht, W. and Popp, A. (2018) Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nature Climate Change*, Nature Publishing Group. **8**, 151–5.

[11] Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B. et al. (2016) Biophysical and economic limits to negative CO2 emissions. *Nature Climate Change*, **6**, 42–50.

[12] Fuss, S., Lamb, W.F., Callaghan, M.W., Hilaire, J., Creutzig, F., Amann, T. et al. (2018) Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, **13**, 63002.

[13] Fajardy, M., Chiquier, S. and Mac Dowell, N. (2018) Investigating the BECCS resource nexus. *Energy and Environmental Science*, **11**, 3408–30.

[14] Fajardy, M. and Mac Dowell, N. (2020) Recognizing the Value of Collaboration in Delivering Carbon Dioxide Removal. *One Earth*, **3**, 214–25.

[15] Chiquier, S., Fajardy, M. and Macdowell, N. (2022) CO2 removal and 1.5°C: what, when, where, and how? [Internet]. ArXiv.

[16] Stua, M., Nolden, C. and Coulon, M. (2022) Resources , Conservation & Recycling Climate clubs embedded in Article 6 of the Paris Agreement. *Resources, Conservation & Recycling*, Elsevier B.V. **180**, 106178. https://doi.org/10.1016/j.resconrec.2022.106178

[17] Carraro, C. and Siniscalco, D. (1998) International institutions and environmental policy: international environmental agreements: incentives and political economy. *European Economic Review*, Elsevier. **42**, 561–72.

[18] Botteon, M. and Carraro, C. (1997) Environmental coalitions with heterogeneous countries: Burden-sharing and carbon leakage. *Fondazione Eni Enrico Mattei Working*

Paper,.

[19] Wu, J. and Thill, J.-C. (2018) Climate change coalition formation and equilibrium strategies in mitigation games in the post-Kyoto Era. *International Environmental Agreements: Politics, Law and Economics*, Springer. **18**, 573–98.

[20] Luqman, M., Soytas, U., Peng, S. and Huang, S. (2019) Sharing the costs and benefits of climate change mitigation via Shapley value. *Environmental Science and Pollution Research*, Springer. **26**, 33157–68.

[21] World Bank. (2022) World Development Indicators [Internet].

[22] Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V. et al. (2018) Mitigation pathways compatible with 1.5 C in the context of sustainable development [Internet]. Press. Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J, Shukla PR, et al., editors. Glob. Warm. 1.5°C. An IPCC Spec. Rep. impacts Glob. Warm. 1.5°C above pre-industrial levels Relat. Glob. Greenh. gas Emiss. pathways, Context Strength. Glob. response to Threat Clim. Chang. Press.

[23] Fuhrman, J., McJeon, H., Doney, S.C., Shobe, W. and Clarens, A.F. (2019) From zero to hero?: why integrated assessment modeling of negative emissions technologies is hard and how we can do better. *Frontiers in Climate*, Frontiers Media SA. **1**, 11.

[24] Raupach, M.R., Davis, S.J., Peters, G.P., Andrew, R.M., Canadell, J.G., Ciais, P. et al. (2014) Sharing a quota on cumulative carbon emissions. *Nature Climate Change*, Nature Publishing Group. **4**, 873–9.

[25] Gütschow, J., Jeffery, M.L., Gieseke, R., Gebel, R., Stevens, D., Krapp, M. et al. (2016) The PRIMAP-hist national historical emissions time series. *Earth System Science Data*, Copernicus GmbH. **8**, 571–603.

[26] Gütschow, J., Günther, A. and Pflüger, M. (2021) The PRIMAP-hist national historical emissions time series (1750–2019) v2. 3, Zenodo [data set].

[27] Ringius, L., Torvanger, A. and Underdal, A. (2002) Burden sharing and fairness principles in international climate policy. *International Environmental Agreements*, Springer. **2**, 1–22.

[28] Rose, A., Stevens, B., Edmonds, J. and Wise, M. (1998) International equity and differentiation in global warming policy. *Environmental and Resource Economics*, Springer. **12**, 25–51.

[29] Pozo, C., Galán-Martín, Á., Reiner, D.M., Mac Dowell, N. and Guillén-Gosálbez, G. (2020) Equity in allocating carbon dioxide removal quotas. *Nature Climate Change*, Nature Publishing Group. **10**, 640–6.

[30] Gillies, D.B. (1953) Some theorems on n-person games. Princeton University.

[31] Gately, D. (1974) Sharing the gains from regional cooperation: A game theoretic application to planning investment in electric power. *International Economic Review*, 195–208.

[32] Schmeidler, D. (1969) The nucleolus of a characteristic function game. *SIAM Journal on Applied Mathematics*, SIAM. **17**, 1163–70.

[33] Peters, H. (2015) Game theory: A Multi-leveled approach. Springer.

[34] Kopelowitz, A. (1967) Computation of the kernels of simple games and the nucleolus of n-person games. HEBREW UNIV JERUSALEM (ISRAEL) DEPT OF MATHEMATICS.

[35] Granot, D., Granot, F. and Zhu, W.R. (1998) Characterization sets for the nucleolus. *International Journal of Game Theory*, Springer. **27**, 359–74.

[36] Boyer, M., Moreaux, M. and Truchon, M. (2006) Partage des coûts et tarification des infrastructures. *CIRANO Monographs*, Cirano.

[37] Megiddo, N. (1974) On the nonmonotonicity of the bargaining set, the kernel and the nucleolus of game. *SIAM Journal on Applied Mathematics*, SIAM. **27**, 355–8.

[38] Grotte, J.H. (1970) Computation of and Observations on the Nucleolus, the Normalized Nucleolus, and the Central Games. Cornell University, Sept.

[39] Littlechild, S.C. and Vaidya, K.G. (1976) The propensity to disrupt and the disruption nucleolus of a characteristic function game. *International Journal of Game Theory*, Springer TS - RIS M4 - Citavi. **5**, 151–61.

[40] Morbee, J. (2014) International Transport of Captured CO2: Who Can Gain and How Much? *Environmental and Resource Economics*, Springer TS - RIS T4 - Who Can Gain and How Much? M4 - Citavi. **57**, 299–322.

[41] Hubert, F. and Ikonnikova, S. (2011) Investment options and bargaining power: the Eurasian supply chain for natural gas. *The Journal of Industrial Economics*, **LIX**.

[42] Lemaire, J. (1984) An application of game theory: cost allocation. *ASTIN Bulletin: The Journal of the IAA*, Cambridge University Press. **14**, 61–81.

[43] Rockett, G.C., Ketzer, J.M.M., Ramírez, A. and Van den Broek, M. (2013) CO2 storage capacity of Campos Basin's oil fields, Brazil. *Energy Procedia*, Elsevier. **37**, 5124–33.

[44] Li, X., Wei, N., Liu, Y., Fang, Z., Dahowski, R.T. and Davidson, C.L. (2009) CO2 point emission and geological storage capacity in China. *Energy Procedia*, Elsevier. **1**, 2793–800.

[45] Dahowski, R.T., Li, X., Davidson, C.L., Wei, N. and Dooley, J.J. (2009) Regional opportunities for carbon dioxide capture and storage in China: A comprehensive CO2 storage cost curve and analysis of the potential for large scale carbon dioxide capture and storage in the People's Republic of China. Pacific Northwest National Lab.(PNNL), Richland, WA (United States).

[46] Vangkilde-Pedersen, T., Anthonsen, K.L., Smith, N., Kirk, K., van der Meer, B., Le Gallo, Y. et al. (2009) Assessing European capacity for geological storage of carbon dioxide–the EU GeoCapacity project. *Energy Procedia*, Elsevier. **1**, 2663–70.

[47] Poulsen, N., Holloway, S., Neele, F., Smith, N.A. and Kirk, K. (2014) CO2StoP Final Report - Assessment of CO2 storage potential in Europe,.

[48] Gammer, D. (2014) A Picture of CO2 Storage in the UK - Learnings from ETI's UKSAP and derived Projects.

[49] USDOE. (2015) Carbon Storage Atlas (5th edition).

[50] UNFCCC. (2021) Decision -/CMA.3 Rules, modalities and procedures for the mechanism established by Article 6, paragraph 4, of the Paris Agreement [Internet].