UNIVERSITAT
ROVIRA I VIRGILI
DEPARTAMENT D'ECONOMIA

CENTRE DE RECERCA EN ECONOMIA INDUSTRIAL I ECONOMIA PÚBLICA

WORKING PAPERS

Col·lecció "DOCUMENTS DE TREBALL DEL DEPARTAMENT D'ECONOMIA - CREIP"

The global carbon budget:a conflicting claims problem

José Manuel Giménez
Jordi Teixidó
Cori Vilella

Document de treball n.15- 2014

DEPARTAMENT D'ECONOMIA – CREIP
Facultat d'Economia i Empresa

UNIVERSITAT
ROVIRA I VIRGILI
DEPARTAMENT D'ECONOMIA

CREIP
CENTRE DE RECERCA EN ECONOMIA INDUSTRIAL I ECONOMIA PÚBLICA

Edita:

Departament d'Economia
www.fcee.urv.es/departaments/economia/public_html/index.html
Universitat Rovira i Virgili
Facultat d'Economia i Empresa
Avgda. de la Universitat, 1
43204 Reus
Tel.: +34 977 759 811
Fax: +34 977 300 661
Email: sde@urv.cat

CREIP
www.urv.cat/creip
Universitat Rovira i Virgili
Departament d'Economia
Avgda. de la Universitat, 1
43204 Reus
Tel.: +34 977 558 936
Email: creip@urv.cat

Adreçar comentaris al Departament d'Economia / CREIP

Dipòsit Legal: T - 1119 - 2014

ISSN edició en paper: 1576 - 3382
ISSN edició electrònica: 1988 - 0820

DEPARTAMENT D'ECONOMIA – CREIP
Facultat d'Economia i Empresa

The global carbon budget: a conflicting claims problem

José-Manuel Giménez-Gómez[a], Jordi Teixidó-Figueras[a] and Cori Vilella[b]

[a] *Universitat Rovira i Virgili, Departament d'Economia and CREIP, Av.Universitat 1, 43204 Reus, Spain. (josemanuel.gimenez@urv.cat, jordijosep.teixido@urv.cat)*
[b] *Universitat Rovira i Virgili, Dep. de Gestió d'Empreses, CREIP, Av.Universitat 1, 43204 Reus, Spain. (e-mail: cori.vilella@urv.cat)*

Abstract

Despite global environmental governance has traditionally couched global warming in terms of annual CO_2 emissions (a flow), global mean temperature is actually determined by cumulative CO_2 emissions in the atmosphere (a stock). Thanks to advances of scientific community, nowadays it is possible to quantify the "global carbon budget", that is, the amount of available cumulative CO_2 emissions before crossing the 2^oC threshold (Meinshausen et al., 2009). The current approach proposes to analyze the allocation of such global carbon budget among countries as a classical conflicting claims problem (O'Neill, 1982). Based on some appealing principles, it is proposed an efficient and sustainable allocation of the available carbon budget from 2000 to 2050 taking into account different environmental risk scenarios.

Keywords: Carbon budget, Conflicting claims problem, Distribution, Climate change
JEL classification: C79, D71, D74, H41, H87, Q50, Q54, Q58

1. Introduction

In order to avoid climate change derived from the increase of the global mean temperature, the international community has repeatedly tried to achieve environmental agreements to reduce CO_2 concentration in the atmosphere (UNFCC in 1992, Kyoto 1997, Copenhagen 2009). Nonetheless, CO_2 concentration in the atmosphere has continuously increased jointly with the global mean temperature. According to the fifth assessment report of IPCC (IPCC, 2013), in an overwhelming consensus of the international scientific community, warming of the climate system is unequivocal, and such a fact might involve damaging effects and potentially irreversible impacts on ecosystems with profound implications for human societies. In accordance to climate models, most countries have adopted as a guardrail not exceeding the limit of 2^oC relative to pre-industrial levels in order to avoid abrupt climate changes. In this sense, global environmental governance has traditionally tackled global warming in terms of *annual* CO_2 emissions, although what ultimately determines global temperature raise is *cumulative* CO_2 emissions, in short CO_2 concentration in the atmosphere (Perman et al., 2003; Meinshausen et al., 2009; Canadell et al., 2007; Stern, 2007; IPCC, 2013). The first legally binding international agreement aimed at avoiding climate change, the Kyoto protocol in 1997, achieved the commitment of 38 developed countries to reduce annual CO_2 emissions in a -5% towards 1990 levels whereas the rest of the world did not have any reduction target (including USA and China). Although the annual CO_2 emissions of the 38 reduced in -12% from 1990 to 2011 (thanks to economies in transition mainly), the rest of the countries increased theirs in 94% in the same period (IEA, 2000, page 16). As a result, annual emissions increased by 49% compared to 1990 levels. However, what really matters to prevent global temperature from rising is that CO_2 concentration increased 11% in that period: climate change is a "stock" environmental problem rather than a "flow" environmental problem (Perman et al., 2003). Hence, the raise in the CO_2 flow (annual emissions) prevents such concentration from decrease, but a decrease in annual CO_2 flow neither guarantee the decrease of atmospheric CO_2 stock: it depends on how much flow is reduced in relation to natural processes of carbon cycle, and how long they keep emitting low.

Thanks to many resources devoted to climatic research, currently, it is possible to estimate the total amount of CO_2 that can be accumulated to the atmosphere in a given period of time and still have some chance to avoid exceeding the 2^oC limit: this is known as the carbon budget. United Kingdom Government (Climate Change Act, 2008) uses carbon budgeting to 2050 (with four sub-period budgets) to monitor their carbon footprint. They claim that carbon budgeting is a more consistent target with limiting global temperature raise. Besides British carbon budgeting is consistent with EU Emission Trading Scheme. In fact, IPCC has quantified for the first time the global carbon budget in his last fifth assessment report (IPCC 2013). From this, we propose using available cumulative CO_2 emissions (carbon budget) as a basis for international climate change negotiations rather than traditional targets based on the reduction of annual CO_2 emissions. Subsequently, climate change problem becomes a distribution problem: a global carbon budget which needs to be distributed among countries.

Therefore, we are facing a situation where different agents (countries or groups) claim (scarce) resources (the carbon budget), such that there is not enough to honor the aggregate claim. Situations like this are known as conflicting claims problems (O'Neill, 1982). Typically, an example is how should the money in a bank be distributed among its creditors. Another illustrative example is the fishing quotas reduction, in which the agent's claim can be understood as the previous captures, and the estate is the new (lower) level of joint captures (Iñarra and Prellezo, 2008). Similar examples may be the milk quotas distribution among the EU members;[1] or how a university distributes the budget among departments (the resources are distributed proportionally to the number of professors, students, subjects, etc., but a minimal (fixed) amount is allocated to each department regardless of size).

The current approach, and this is our main contribution, proposes a conflicting claims problem treatment of the greatest and more challenging conflicting claims situation humanity has ever faced: how the available carbon budget has to be distributed among a set of agents who jointly claim more stock than what is actually available. We use the widely accepted Meinshausen et al. (2009) probabilistic model to quantify global carbon bud-

[1] Quotas were introduced in 1984. Each member state was given a reference quantity which was then allocated to individual producers. The initial quotas were not sufficiently restrictive as to remedy the surplus situation and so the quotas were cut in the late 1980s and early 1990s. Quotas will end on April 1, 2015.

gets for the period 2000-2050, in order to allocate among parties the available cumulative emissions (until 2050) instead of annual emissions, since, in contrast to flow perspective, it guarantees CO_2 stabilization below the limit of 2^oC associated to a risk probability.

It is discussed that stock-based negotiations might be not only more efficient but also more appealing for current not committing countries engagement (Non-Annex I). The conflicting claims problems literature has provided different ways (rules) to solve this problem. Furthermore, behind all of the proposed rules, a set of appealing properties (principles) is considered. Consequently, our results assess (i) different rules to distribute the global carbon budget; (ii) different desirable principles that may be required in a climate change context to the proposed rules. Finally, as a result of this analysis, we conclude that the Talmud rule (a division rule that takes its name from the ancient document of the Jewish religion) is the one that satisfies all the required principles.

The most closed work to ours is found in Llavador et al. (2013). They model a intergenerational North-South world where a sustainable concentration path has already been agreed *a priori* between both regions and from there, the authors allocate CO_2 emissions in terms of growth rates of North and South. Our approach, in contrast, claims on the idea of dealing with CO_2 allocations as a conflicting claims problem; as a way to improve consistency of global climate change policies (stock vs flow) and as a normative basis to tackle international climate change negotiations.

The paper is organized as follows. Section 2 presents the problem of carbon budget and global warming. Section 3 defines the CO_2 associated conflicting claims problems. Section 4 present different possible ways of distributing carbon budget whereas section 5 propose how should they be distributed in terms of general and widely accepted principles of fairness. Finally, in Section 6 we discuss our final remarks.

2. The problem of carbon budget

CO_2 is naturally present in the Earth and self-regulated by the carbon cycle, i.e. the natural circulation of CO_2 among oceans, plants, animals, soil and atmosphere. The presence of CO_2 in the atmosphere yields a retention of heat that actually has allowed the necessary temperature level to different life forms emerged and developed through millenniums (the Holocene). However, human activities, due to the combustion of fossil fuels, have been overloading the atmosphere with greenhouse gasses (GHG), being CO_2 the primary gas emitted. Particularly, global average atmospheric CO_2 has raised from 280*ppmv* (parts per million by volume[2]) at the beginning of industrial revolution to 396*ppmv* in 2013 (according to NOAA's Manua Loa Observatory), reaching the highest CO_2 concentration in the last 650.000 years (Canadell et al., 2007) In doing so, the carbon cycle suffers critical alterations by not only increasing the concentration of CO_2 in the atmosphere, but also by affecting natural sinks' capacity of removing part of that CO_2. Consequently, the mean global temperature has increased: global warming. Specifically, the global temperature has already risen 0.78^oC since pre-industrial times (IPCC, 2013).

[2]The relative abundance of CO_2 in the atmosphere is usually discussed in terms of ppmv: it is the ratio of carbon dioxide molecules to all of the other molecules in the atmosphere. Most of the environmental policy actors considers a target achieving a stabilization at 350ppm of CO_2

According to analytical and political arguments, there is a growing convergence towards consider the 2^oC guardrail as a planetary boundary, beyond which a non-linear abrupt change in the climate system is highly probable (Rockstrom et al., 2009). identified as planetary boundary (Rockstrom et al., 2009) beyond which a non-linear abrupt change in the climate system is highly probable. International community, through the UN Framework Convention for Climate Change (UNFCCC 1992), has adopted such benchmark and proposed global policies in order to stabilize the greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system, what in practical terms requires the reduction of current CO_2 concentration. Nonetheless, it fails. The concentration of GHG emissions and, particularly, of CO_2 has not stopped increasing. Whereas some countries have actually reduced their annual CO_2 emissions in the last years, other ones have increased theirs. Therefore, since what matters is the concentration in the atmosphere, nothing is earned if global emissions continue growing. Even if world annual emissions reduce, that would not guarantee atmospheric CO_2 concentration does. It would depend on the level they are reduced to, and on the carbon cycle functions responses (ocean and land sink capacity). Therefore, avoiding climate change requires global cooperation; a planetary response to reduce CO_2 concentration in the atmosphere.

A growing number of scientific papers have shown that global temperature is closely related to CO_2 emissions released over a period of time (cumulative emissions) rather than the timing of those emissions (Canadell et al. 2007, Meinshausen et al. 2009, Rockstrom et al. 2009, IPCC 2013). So that, climate change is a CO_2 stock problem rather than a CO_2 flow problem (Perman et al., 2003). However, since CO_2 stock control is out of policy makers' influence, they have been proposed limits on the rate of emissions flow, such as Kyoto protocol. But, dealing with flows does not guarantee the solution to the problem, as the limited success of existing attempts of reaching global commitments shows, so humanity faces a public good dilemma and requires further cooperation (Vasconcelos et al., 2013, Beccherle and Tirole, 2011, Finus and Pintassilgo, 2013). Given the causality of economic growth on CO_2 emissions[3] , international income inequality plays a critical role in this scene: rich countries are responsible of the bulk of historical cumulative emissions, whereas developing countries feel punished for others' sins and reclaim their right to achieve greater income.

3. The CO_2 conflicting claims problem

Dealing directly with CO_2 stock rather than the traditional CO_2 flow of international commitments leads us to analyze what actually needs to be solved: the sharing of the global carbon budget. Accordingly, Meinshausen et al. (2009), considering the main uncertainties in climate projection models, provide a comprehensive probabilistic model by which a CO_2 emissions budget can be quantified and associated to the probability of exceeding the 2^oC guardrail in the period 2000-2050. So that, their model allows to estimate how much CO_2 can be emitted before crossing the 2^oC. One of their most highlighted results is that limiting world cumulative CO_2 over 2000-2050 at $1000Gt$ CO_2

[3]see Raupach et al. (2007), Dinda (2004), Azomahou et al. (2006), York et al. (2003)

would yield a 25% probability of exceeding the guardrail, whereas $1440Gt$ CO_2 would yield a 50% probability. From this point of view, countries will need to share those $1000Gt$ or $1440Gt$ CO_2 and administrate their assigned carbon budget along the referred time period by adapting their CO_2 flows. Moreover, this procedure gives additional information to governments, as they know how much further they can safely emit and benefit from a better pricing of every CO_2 ton.

The current approach analyzes the carbon budget problem as a CO_2 stock problem from a conflicting claims point of view. A conflicting claims problem is a particular case of distribution problem, in which the amount to divide, the global carbon budget (hereinafter, the carbon budget), is not enough to satisfy all the agents' claims. This model describes the situation faced by a court that has to distribute the net worth of a bankrupt firm among its creditors. But, it also corresponds with cost-sharing, taxation, or rationing problems. The formal analysis of situations like these, which originates in a seminal paper by O'Neill (1982), shows that a vast number of well-behaved solutions have been defined for solving claims problems.[4]

Consider a set of agents $N = \{1, 2, ..., n\}$ and amount $E \in \mathbb{R}_+$ of an infinite divisible resource, the **endowment**, that has to be allocated among them. Each agent has a **claim**, $c_i \in \mathbb{R}_+$ on it. Let $c \equiv (c_i)_{i \in N}$ be the claims vector.

A **claims problem** is a pair (E, c) with $\sum_{i=1}^{n} c_i > E$. Without loss of generality, we will order the agents according to their claims, $c_1 \leq c_2 \leq \ldots \leq c_n$, and we will denote by $\mathcal{B}$ the set of all claims problems.

The endowment is determined by the amount of available anthropogenic cumulative CO_2 that prevent global temperature from exceeding the 2^oC: our carbon budget taken from Meinshausen et al. (2009). Specifically, we consider three different carbon budgets for the period 2000-2050: (a) $1440Gt$ CO_2 which corresponds to a 50% probability of crossing the 2^oC threshold; (b) $1000Gt$ CO_2 which corresponds to a 25% probability; and (c) $745Gt$ CO_2 as a budget where, according to current knowledge, the probability of exceeding the 2^oC is 0. Budgets (a) and (b) are considered sensible for both scientific community and policy makers (Rockstrom et al, 2009) as they have been managed in both worlds. Budget (c), in contrast, is considered to allow us for a risk zero scenario.

To define agents' claims, we adopt a future pathway of cumulative CO_2 projected by the IPCC Special Report Emissions Scenarios (SRES)[5]. Specifically, we will consider the A1FI IPPCC scenario as our framework scenario from where predicted cumulative emissions by 2050 are assumed to be their conflicting claims. The A1FI scenario predicts that a whole world cumulative emissions will amount $2736Gt$ CO_2 by 2050 (beyond any of the carbon budgets considered). This accumulated CO_2 emissions are a product of the very scenario's storyline, which projects a world tending to globalization, with a rapid economic growth and global population peaks at 2050. There is a rapid introduction of

[4]The reader is referred to Moulin (2002) and Thomson (2003, 2013) as surveys of this literature.

[5]The IPCC emissions scenarios are alternative images (up to 40) of future GHG emissions as shaped by very complex dynamic system determined by driving forces such as population trends, socio-economic development and technological change (IPCC, 2000).

new and more efficient technologies where the technological change in energy system is fuel intensive. This scenario is as feasible as any of the remaining 40 SRES scenarios, however, what matters here is that the A1FI storyline pictures a world where, because of the fuel intensive technologies (that is what FI actually means), yields the highest concentration of atmospheric CO_2 by 2050. Llavador et al. (2011)used a different IPCC scenario which in contrast describes a pathway with very low GHG concentrations because of their aims, however, given the purpose of the present analysis, it results more sensible to situate future in the worst feasible IPCC scenario, this is the Fuel Intensive Scenario, where all countries are projected to accumulate the highest atmospheric CO_2. From this perspective, both developed and developing countries' projected cumulative emissions can be seen as what countries claim as their rights to emit. In other words, the proposed claims framework pictures a world where all countries claim the maximum emission rights possible, which is seen as a sensible behavior in a context of international bargaining, especially when carbon markets frames are considered. Besides, since the SRES scenario are the projection of future GDP, population, technologies, etc, these claims can also be read as countries higher emitting necessities.

The set of claiming agents is composed by the four world SRES groups typically considered in climatic models [6]: OECD countries as 1990 (OECD90), Asia (ASIA), Africa and Latin America (ALM), countries undergoing economic changes (REF). Notice that OECD90 and REF roughly corresponds to Annex I countries of UNFCCC while ASIA and ALM roughly correspond to developing countries of no-annex I group (see IPCC (2000).

4. How global carbon budget can be distributed?

Given a conflicting claims problems, a rule associates within each problem a distribution of the endowment among the agents. A **rule** is a single valued function $\varphi : \mathcal{B} \to \mathbb{R}^n_+$ such that $0 \leq \varphi_i(E,c) \leq c_i$, for all $i \in N$ (**non-negativity** and **claim-boundedness**); and $\sum_{i=1}^{n} \varphi_i(E,c) = E$ (**efficiency**). Those rules used throughout the present approach are introduced below.[7]

The **Proportional (P)** rule recommends a distribution of the endowment which is proportional to the claims: for each $(E,c) \in \mathcal{B}$ and each $i \in N$, $P_i(E,c) \equiv \lambda c_i$, where $\lambda = \dfrac{E}{\sum_{i \in N} c_i}$.

The **Constrained equal awards (CEA)** rule (Maimonides, 12th century), proposes equal awards to all agents subject to no one receiving more than his claim: for each (E,c) $\in \mathcal{B}$ and each $i \in N$, $CEA_i(E,c) \equiv \min\{c_i, \mu\}$, where μ is such that $\sum_{i \in N} \min\{c_i, \mu\} = E$.

[6]Given the purpose of this article, the authors would have considered further decomposition of the groups used as agents, however, the only regional decomposition for future cumulative emissions is only available at IPCC (2000). Although other possibilities such as the more recent RCP-database have been considered, to the best of our knowledge non other database than SRES-IPCC decomposes cumulative emissions by groups of countries.

[7]The interested reader is referred to the survey by Thomson (2003, 2013).

The **Constrained equal losses (CEL)** rule (Maimonides, 12th century (Aumann and Maschler, 1985), chooses the awards vector at which all agents incur equal losses, subject to no one receiving a negative amount: for each $(E, c) \in \mathcal{B}$ and each $i \in N$, $CEL_i(E, c) \equiv \max\{0, c_i - \mu\}$, where μ is such that $\sum_{i \in N} \max\{0, c_i - \mu\} = E$.

The **Talmud (T)** rule (Aumann and Maschler, 1985) proposes to apply the constrained equal awards rule, if the endowment is not enough to satisfy the half-sum of the claims. Otherwise, each agent receives the half of her claim and the constrained equal losses rule is applied to distribute the remaining endowment: for each $(E, c) \in \mathcal{B}$, and each $i \in N$, $T_i(E, c) \equiv CEA_i(E, c/2)$ if $E \leq C/2$; or $T_i(E, c) \equiv c_i/2 + CEL_i(E - C/2, c/2)$, otherwise.

With the aim of ensuring some awards to each agent, the following rules are proposed. The first rule is a combination of the proportional rule and the constrained equal awards that gathers the idea of sustainability (Herrero and Villar, 2002).[8] This rule, as pointed by Giménez-Gómez and Peris (2014) is commonly used for sharing the milk quotas among EU countries, or the seats in the Spanish Parliament and the United States House of Representatives.

The **α-minimal (α-min)** rule (Giménez-Gómez and Peris, 2014) assigns the minimal claim to each agent; then it distributes the remaining estate $E' = E - nc_1$ in a proportional way among the agents with respect to the remaining claims: for each $(E, c) \in \mathcal{B}$ and each $i \in N$, recommends: if $c_1 > E/n$ then α-$\min_i(E, c) = E/n$ and if $c_1 < E/n$ then α-$\min_i(E, c) = c_1 + P(E - nc_1, c - c_1)$.

Finally, we also consider the average rule as a natural way to compromise between the CEA and CEL, two of the most opposite views to adjudicate claims (the former the more egalitarian and the latter the least one).
The **Average (Av)** rule is the average between the constrained equal awards and the constrained equal looses rules: for each $(E, c) \in \mathcal{B}$, $Av(E, c) = \frac{CEA(E,c)+CEL(E,c)}{2}$.

Scenario A1G: Claim REF=300.36; Claim ALM=618.78; Claim OECD90=768.47; Claim ASIA=1048.57												
Budgets	1440 (50%)				1000 (25%)				745 (0%)			
Rules	REF	ALM	OECD90	ASIA	REF	ALM	OECD90	ASIA	REF	ALM	OECD90	ASIA
P	158,07	325,65	404,43	551,84	109,77	226,15	280,86	383,22	81,78	168,48	209,24	285,5
CEA	300,36	379,88	379,88	379,88	250	250	250	250	186,25	186,25	186,25	186,25
CEL	0	286,84	436,53	716,63	0	140,17	289,86	569,96	0	55,17	204,86	484,96
T	150,18	309,39	384,24	596,2	150,18	283,27	283,27	283,27	150,18	198,27	198,27	198,27
$\alpha-\min$	300,36	349,86	373,12	416,66	250	250	250	250	186,25	186,25	186,25	186,25
AV	150,18	333,36	408,21	548,26	125	195,09	269,93	409,98	93,13	120,71	195,56	335,61

Table 1: **Cumulative CO_2 emissions allocations.** The rules are computed for the different carbon budgets (cumulative G_t CO_2 emissions by 2050). Numbers in brackets show the probability of exceeding 2^oC (Meinshausen et al., 2009). Columns provide the allocations recommended by each of the four considered groups. Rows show the allocations recommended by each rule for each group.

Table 1 summarizes the comparison among the proposed rules and the three different considered carbon budgets. Note that, as we mentioned, we consider four agents (groups)

[8] A claim c_i is said to be sustainable in (E, c) if $\sum_{j=1}^{n} \min\{c_i, c_j\} \leq E$.

and the proposed CO_2 allocations as emitting right in a 50 years period. Accordingly, P divides the carbon budget proportionally to each group's claim. The CEA proposes an egalitarian distribution of the cumulative CO_2 emissions (for instance, with $E = 1000$ G_t CO_2), such that no group can cumulate more that its claim (with $E = 1440$ G_t CO_2, REF has honored its total claim). In fact, REF countries, which are the lowest claimers (despite doing their best to emit as we are in the worst feasible SRES scenario), will always prefer CEA as it is the one that, regardless the carbon budget, allocates more emissions to them.

On the contrary, the CEL recommends an egalitarian distribution of the incurred losses (the part of the aggregate cumulative CO_2 emissions not satisfied, i.e., $\sum_{i=1}^{n} c_i - E$, given that no-one can emit a negative amount (that is, a group cannot reduce the carbon budget). The $ASIA$ countries, as the largest claimers, will always lobby in favor of CEL rule for the same reason as REF countries prefer CEA. Furthermore, $OECD$ countries, the most developed SRES region, will vote for CEL in most of the cases (either $E = 1440$ $GtCO_2$ or $E = 1000$ $GtCO_2$).

T is a mixture of both. It takes the middle of the aggregate claims as a reference point. If the half of the total needs of cumulative CO_2 emissions is lower than the carbon budget, then the CEA is applied; whereas, each region receives half of its expected emissions and the amount recommended by CEL, otherwise. The ALM countries, among which, the most poor countries are counted, will choose this rule whenever the carbon budget is lower than 1440 $Gt\ CO_2$.

The last two proposed rules ensures a minimal amount of emissions to each region. Specifically, $\alpha-$min shares the budget in an egalitarian way, except in the case that the expected cumulative CO_2 emissions of the smallest groups are so small in relative terms ($E = 1440$), in which case this region is totally honoured. Finally, AV proposes the average between CEA and CEL recommendations.

According to all showed results, Non-Annex I (roughly, Africa and Latin America, in ALM and $ASIA$ groups) countries always obtain a higher CO_2 budget than Annex I countries ($OECD90$ and REF groups). On the one hand, this is coherent with the Kyoto's protocol output: only Annex I countries committed to reduce their annual CO_2 emissions whereas Non-Annex I did not commit as a claim of their developing necessities. On the other hand, it looks sensible since Annex I countries are less carbon intensive economies (more efficient), so they have lower CO_2 capabilities. Furthermore, this in turn might foster economic convergence since Annex I countries might be interested in acquiring Non-annex I emitting rights. On balance, the "stock-based commitment" by Non-Annex I countries becomes at least as feasible as their previous "no-commitment in flow-based negotiations". This, jointly with the greater global warming concern, might make agent's commitment more appealing.

Finally, as developed in the next section, we use the conflicting claims approach to focus the discussion about climate change global governance on the "sensible" principles behind the rules, rather than on quantitative allocations of cumulative CO_2 emissions. This approach is consistent with the "veil of uncertainty" concept, by which climate change agreements are more feasible when participants do not know its distributional consequences (Finus and Pintassilgo, 2013). For instance, all countries might agree that the ranking of their emissions allocations should be coherent with the ranking of their initial claims.

Furthermore, as the intensive future emissions scenario has been used, all countries appear to claim the maximum amount of cumulative CO_2 emissions given their projected populations or GDP: satisfying all agents will not prevent climate system from global warming. Hence, what is really up for discussion is to what extent countries are willing to accept looses over their initial proposed claims, so that different bargaining powers will play an important role in international negotiations. A fact that enforces the idea that allocations should be defend via principles or appealing properties that all the involved groups may exogenously accept, independently of the numerical result.

5. How global carbon budget should be distributed?

Note that the rules proposed in the literature about conflicting claims problems follows a well-behaved purpose, which reflects the idea that the considered rules might fulfill some principles of fairness, or appealing properties behind the allocations. In that sense, we introduce the principles that we consider relevant for the distribution of the carbon budget between the set of countries asking for their ability to pollute in terms of their expected cumulative emissions.

Equal treatment of equals implies that agents with equal claims should receive the same awards: for each $(E, c) \in \mathcal{B}$, and each $\{i, j\} \subseteq N$, if $c_i = c_j$, then $\varphi_i(E, c) = \varphi_j(E, c)$.

Anonymity states that the awards received by an agent, should depend only on her claim, and not on her identity: for each $(E, c) \in \mathcal{B}$, each $\pi \in \Pi^N$, and each $i \in N$, $\varphi_{\pi(i)}(E, (c_{\pi(i)})_{i \in N}) = \varphi_i(E, c)$, where Π^N is the class of all the permutations of N.

Order preservation (Aumann and Maschler, 1985) requires respecting the ordering of the claims, i.e., if agent $i's$ claim is at least as large as agent $j's$ claim, she should receive and lose at least as much as agent j does, respectively: for each $(E, c) \in \mathcal{B}$, and each $i, j \in N$, such that $c_i \geq c_j$, then $\varphi_i(E, c) \geq \varphi_j(E, c)$, and $c_i - \varphi_i(E, c) \geq c_j - \varphi_j(E, c)$.

Claims truncation invariance (Dagan and Volij, 1993) says that truncating claims at the endowment should not affect the recommended award vector: for each $(E, c) \in \mathcal{B}$, and each $i \in N$, $\varphi_i(E, c) = \varphi_i(E, \min\{c_i, E\}_{i \in N})$.

Self-duality (Aumann and Maschler, 1985) implies that the problem of dividing “what is available ”or “what is missing ”should give the same awards: for each $(E, c) \in \mathcal{B}$ and each $i \in N$, $\varphi_i(E, c) = c_i - \varphi_i(\sum_{i \in N} c_i - E, c)$.

Midpoint property (Aumann and Maschler, 1985) says that if the amount to divide is half of all the claims, then every agent should receive half of her claim: for each $(E, c) \in \mathcal{B}$ and each $i \in N$, if $E = C/2$ then $\varphi_i(E, c) = c_i/2$.

Table 2 shows which of these desirable properties are satisfied by the considered rules.

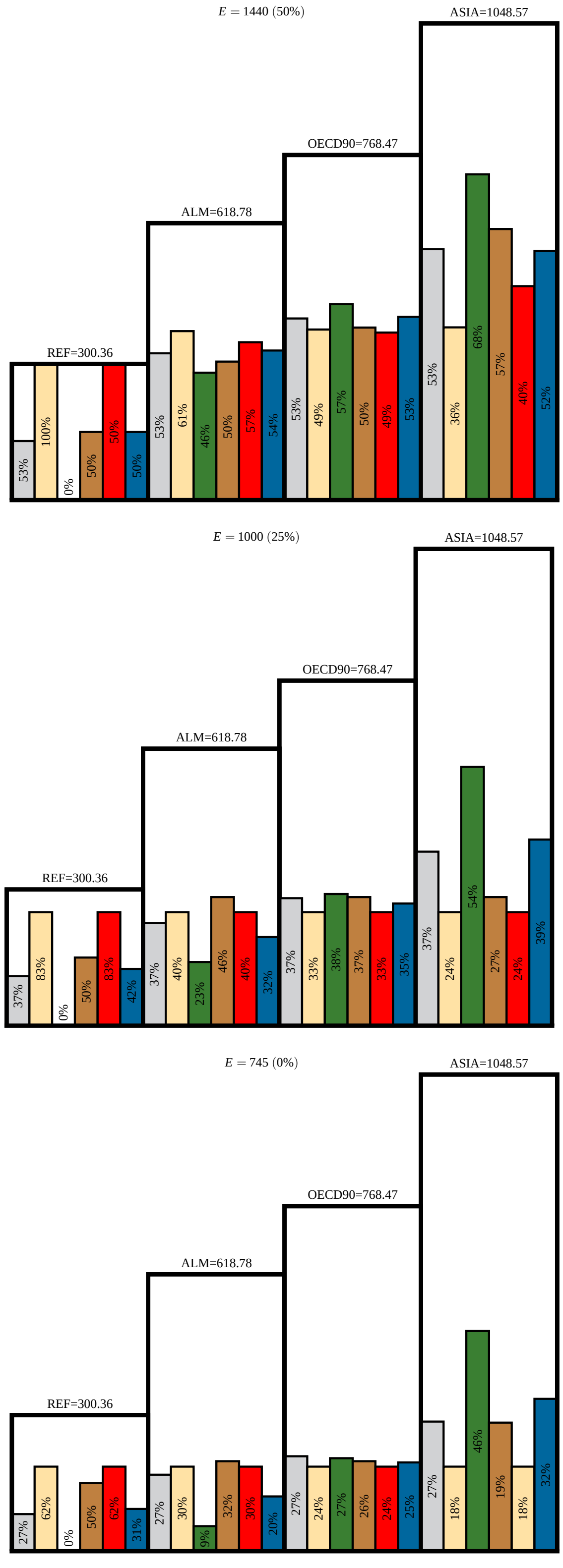

Figure 1: **Vessels representation of each agent's honoured claims.** The three figures show with vessels how the claims are satisfied by each of the proposed rules in each of the three considered scenarios ($E = 1440$; $E = 1000$; $E = 745$, respectively). The white vessels (the widest ones) represents each agent's claim. The narrower vessels show the amount of cumulative CO_2 recommended by each of the introduced rules: the P (grey), CEA (yellow), CEL (green), T (brown), AP (light green), $\alpha-$min (red), and AV (blue) rules. The percentages indicate the relative amount of the claims satisfied by each rule.

Properties	P	CEA	CEL	T	α-min	Av
Equal treatment of equals	Yes	Yes	Yes	Yes	Yes	Yes
Anonymity	Yes	Yes	Yes	Yes	Yes	Yes
Order preservation	Yes	Yes	Yes	Yes	Yes	Yes
Claims truncation invariance	No	Yes	No	Yes	No	No
Self-duality	Yes	No	No	Yes	No	Yes
Midpoint property	Yes	No	No	Yes	No	Yes

Table 2: **Principles and rules.** Each column corresponds with a rule, whereas each row with the proposed principle.

Note that some of the principles come directly from the own definition of a rule. The rule satisfies non-negativity and claim-boundedness, therefore it assigns a non-negative amount to each group and no-one receives more than its expected cumulative CO_2 emissions. Any rule also satisfies efficiency, that is, ensures the total distribution of the carbon budget among the groups of countries.

As shown in Table 2, the first three additional desirable properties are basic, so they are satisfied by all the considered rules. The first one, equal treatment of equals, says that two or more countries with equal projected cumulative emissions or, as suggested above, let's say equal emitting necessities, should receive the same operative carbon budget each. The second requirement, anonymity, is that the emissions allowed to a country should depend only on their stated emitting necessities (projected emissions), and not on its particular identity. The third one, order preservation, asserts that a country with a greater emitting necessities should not receive a smaller allocation.

Claims truncation invariance refers to the upper bound for emitting quotas; it says that those claims that are over the global carbon budget should not be rewarded. Hence, according to this principle, the rule should not depend on that part of the claim that is greater than the total amount to divide. In order to see what this property implies in our conflicting claims problem we can analyze the proposed rules in Table 1 in two different cases: first, note that when the budget is 1000 G_t CO_2, we are supposing that $ASIA$ reduces its claim from $1048,57$ G_t CO_2 to 1000 G_t CO_2. Under this assumption we obtain a table similar to Table 1 where roughly speaking we observe that there are no any big changes, but all the groups increase a little their allocations except $ASIA$ that decreases the amount that receives for all the rules except for CEA, T and $\alpha-$min. As we can see in Table 2, CEA and T satisfy this property, so the amount each county receives should not change if we reduce the claim. However, in general $\alpha-$min does not satisfy it (see Giménez-Gómez and Peris, 2014).[9]

Second, also note that when the carbon budget is 745 G_t CO_2, the claims of $OECD90$ and $ASIA$ are now truncated to 745 G_t CO_2. In this case, when we apply the rules we are obtaining similar variations than in the above case, though all changes vary in a little more significant way. In addition, this case also allows us to see the fulfillment of the

[9]In this case, since E/n is smaller than the smallest claim, each groups receives E/n, so the allocation does not change. Whenever E/n should be greater than the smallest claim then, $\alpha-$min varies.

property of equal treatment of equals, since under claims truncation $OECD90$ and $ASIA$ receive the same amount. Finally we observe that anonymity and order preservation are still fulfilled if the claims are truncated.

Finally, we also impose self-duality. This requirement looks at the problem from two opposite perspectives: from "'what is available"' and from "'what is missing"'. It requires both perspectives to be equivalent. Therefore, the rule should give the same either dividing the amount of emissions that are allowed or the amount of emissions that are missing. In particular, self-duality implies that if the amount of global carbon budget is equal to the half sum of the demands, each country should receive his half demand. Notice that, when this requirement is considered separately, we obtain the midpoint property, our last required principle. By applying self-duality to our conflicting claims problem and by comparing results in Table 1, with those that we would obtain by dividing looses, we may see that the CEA and the CEL would invert their roles and, therefore, those countries with greater claims, would register higher losses. Observe that for rules meeting this property, the allocations will not change.

6. Conclusions

The novelty of the current approach stems on the fact that international climate change commitments could be based on the carbon budget concept, i.e. the available cumulative CO_2 before exceeding the 2^oC limit, rather than on simply annual CO_2 emissions as done up to now with meager success. In fact, this approach has only become feasible when scientific community has been able to quantify such global carbon budget.

Such perspective allows, on the one hand, to deal with climate change in a more robust way since it involves approaching global warming as what it really is; a *stock* problem rather than a flow problem. It in turn allows approaching such a global challenge as a a well defined conflicting claims problem. On the other hand, only because of this *stock* perspective, a better pricing of this environmental service provided by the atmosphere could be provided. Indeed, every CO_2 tone will count, and the increase of CO_2 emissions in one sector will necessarily reclaim a reduction in another. Besides, this approach could be consistent with an international carbon trading systems with real economic convergence benefits.

Our analysis consisted in addressing climate change concern from a conflicting claims problem approach. The central aim has been, therefore, to allocate the global carbon budget among encountered parties whose growth necessities yield a distributional conflict in terms of the available carbon budget. As a result, we show how techniques naturally emerge as a very useful and suitable tool to deal with environmental negotiations and global warming. According to our proposed set of desirable principles (see Table 2), and under a 'veil of uncertainty', the Talmud rule appears as the only proposed rule that could reach required cooperative consensus, and hence, its proposed allocations of the available cumulative CO_2 emissions should be considered as enforceable.

As a possible extensions of this work, we can analyze the same problem as a dynamic conflicting claims problem and as a cooperative game, in this case the Talmud rule coincides with the nucleolus (Schmeidler, 1969), a well known solution for cooperative games.

Acknowledgements

We would like to thank Humberto Llavador for his very useful comments. Financial support from Universitat Rovira i Virgili, CREIP, Ministerio de Ciencia e Innovación and FEDER under project ECO2011-22765 and ECO2010-18158 and Generalitat de Catalunya under project 2009SGR900 are gratefully acknowledged.

References

Aumann, R. J., Maschler, M., 1985. Game Theoretic Analysis of a bankruptcy from the Talmud. Journal of Economic Theory 36, 195–213.

Azomahou, T., Laisney, F., Van, P. N., 2006. Economic development and CO_2 emissions: A nonparametric panel approach. Journal of Public Economics 90 (67), 1347 – 1363.

Beccherle, J., Tirole, J., 2011. Regional initiatives and the cost of delaying climate change agreements. Journal of Public Economics 95 (11-12), 1339–1348.

Canadell, J. G., Le Qur, C., Raupach, M. R., Field, C. B., Buitenhuis, E. T., Ciais, P., Conway, T. J., Gillett, N. P., Houghton, R. A., Marland, G., 2007. Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proceedings of the National Academy of Sciences 104 (47), 18866–18870.

Climate Change Act, C. ., 2008. Chapter 27. The National Archives.

Dagan, N., Volij, O., 1993. The bankruptcy problem: a cooperative bargaining approach. Mathematical Social Sciences 26, 287 – 287.

Dinda, S., 2004. Environmental kuznets curve hypothesis: A survey. Ecological Economics 49 (4), 431–455.

Finus, M., Pintassilgo, P., 2013. The role of uncertainty and learning for the success of international climate agreements. Journal of Public Economics 103 (0), 29–43.

Giménez-Gómez, J.-M., Peris, J. E., 2014. A proportional approach to claims problems with a guaranteed minimum. European Journal of Operational Research 232 (1), 109–116.

Herrero, C., Villar, A., 2002. Sustainability in bankruptcy problems. Top 10 (2), 261–273.

Iñarra, E., Prellezo, R., 2008. Bankruptcy of fishing resources: The northern european anglerfish fishery. Marine Resource Economics 17, 291–307.

IEA, 2000. CO_2 Emissions From Fuel Combustion. Highlights. 2011 Edition. IEA publications, Paris, France.

IPCC, 2000. Special Report on Emissions Scenarios, nakicenovic, n. and swart Edition. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, stocker, t.f., d. qin, g.-k. plattner, m. tignor, s.k. allen, j. boschung, a. nauels, y. xia, v. bex and p.m. midgley Edition. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Llavador, H., Roemer, J. E., Silvestre, J., 2011. A dynamic analysis of human welfare in a warming planet. Journal of Public Economics 95 (1112), 1607–1620.

Llavador, H., Roemer, J. E., Silvestre, J., 2013. North-south convergence and the allocation of CO_2 emissions. Cowles Foundation Discussion Paper (No 1932).

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S. B., Frieler, K., Knutti, R., Frame, D., Allen, M., 2009. Greenhouse-gas emission targets for limiting global warming to 2^oC. Nature 458 (7242), 1158–1162.

Moulin, H., 2002. Axiomatic cost and surplus sharing. In Arrow, A. K., and Sen, K. (eds), Handbook of social choice and welfare. Vol. 1. Elsevier. North Holland, Amsterdam. pp. 289–357.

O'Neill, B., 1982. A problem of rights arbitration from the Talmud. Mathematical Social Sciences 2 (4), 345–371.

Perman, R., Ma, Y., McGilvray, J., Common, M., 2003. Natural Resource and Environmental Economics. Essex: Pearson Education.

Raupach, M. R., Marland, G., Ciais, P., Le Qur, C., Canadell, J. G., Klepper, G., Field, C. B., 2007. Global and regional drivers of accelerating CO_2 emissions. Proceedings of the National Academy of Sciences 104 (24), 10288–10293.

Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, III, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sorlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J. A., 2009. A safe operating space for humanity. Nature 461 (7263), 472–475.

Schmeidler, D., 1969. The Nucleolus of a characteristic function game. SIAM Journal of Applied Mathematics 17, 1163–1170.

Thomson, W., 2003. Axiomatic and game-theoretic analysis of bankruptcy and taxation problems: a survey. Mathematical Social Sciences 45 (3), 249–297.

Thomson, W., 2013. Axiomatic and game-theoretic analysis of bankruptcy and taxation problems: an update. mimeo.

Vasconcelos, V. V., Santos, F. C., Pacheco, J. M., 2013. A bottom-up institutional approach to cooperative governance of risky commons. Nature Climate Change 3 (September 2013), 797–801.

York, R., Rosa, E. A., Dietz, T., 2003. STIRPAT, IPAT and imPACT: analytic tools for unpacking the driving forces of environmental impacts. Ecological Economics 46 (3), 351 – 365.