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By **Valentina Bosetti and Massimo Tavoni**, Princeton University, FEEM and CCMC

Carlo Carraro, University of Venice, FEEM, CEPR, CESifo and CMCC

Enrica De Cian, FEEM

Romain Duval, OECD

Emanuele Massetti, FEEM and CCMC

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Keywords: Climate Policy, Climate Coalition, Game Theory, Free Riding

JEL Classification: C68, C72, D58, Q54

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Address for correspondence:

Valentina Bosetti
Fondazione Eni Enrico Mattei
Corso Magenta 63
20123 Milan
Italy
E-mail: valentina.bosetti@feem.it

THE INCENTIVES TO PARTICIPATE IN, AND THE STABILITY OF, INTERNATIONAL CLIMATE COALITIONS: A GAME-THEORETIC ANALYSIS USING THE WITCH MODEL

Valentina Bosetti, Carlo Carraro, Enrica De Cian, Romain Duval,
Emanuele Massetti and Massimo Tavoni[1]

ABSTRACT

This paper uses WITCH, an integrated assessment model with a game-theoretic structure, to explore the prospects for, and the stability of broad coalitions to achieve ambitious climate change mitigation action. Only coalitions including all large emitting regions are found to be technically able to meet a concentration stabilisation target below 550 ppm CO_2eq by 2100. Once the free-riding incentives of non-participants are taken into account, only a "grand coalition" including virtually all regions can be successful. This grand coalition is profitable as a whole, implying that all countries can gain from participation provided appropriate transfers are made across them. However, neither the grand coalition nor smaller but still environmentally significant coalitions appear to be stable. This is because the collective welfare surplus from cooperation is not found to be large enough for transfers to offset the free-riding incentives of all countries *simultaneously*. Some factors omitted from the analysis, which might improve coalition stability, include the co-benefits from mitigation action, the costless removal of fossil fuel subsidies, as well as alternative assumptions regarding countries' bargaining behaviour.

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[1] The authors are researchers at Fondazione Eni Enrico Mattei (FEEM), with the exception of Romain Duval, who is a senior economist at the OECD Economics Department. They want to express gratitude to Christine de la Maisonneuve for statistical assistance and to Susan Gascard and Irene Sinha for editorial assistance. Thanks are also due to Rob Dellink for helpful comments. The authors retain full responsibility for errors and omissions.

1. Introduction and summary of main findings

A successful international climate policy framework needs to bring the main greenhouse gas (GHG) emitting countries together into a “climate coalition” that delivers ambitious emission reductions at least cost. One potential challenge in that regard is to build a coalition that is both wide and stable. Broad-based country participation is required for any coalition to be environmentally effective. At the same time, wide coalitions may be harder to achieve, reflecting stronger incentives to ”free ride”. Against this background, this paper provides a game-theoretic analysis of four main issues:

- *The incentives for main emitting countries to participate in climate coalitions*. Such incentives ultimately depend on a wide range of economic and political factors, not all of which can be captured by model-based exercises. Bearing this caveat in mind, the analysis carried out in this paper covers two major economic drivers of participation incentives, namely the damages avoided and the abatement costs incurred both within and outside a coalition.

- *The identification of potentially effective coalitions (PECs)*, defined as those that have the potential to meet a moderately ambitious global climate change mitigation target. That target is set here as the world emission path that would be consistent with long-run stabilisation of global GHG concentration at 550 ppm CO_2eq. More ambitious targets would require larger coalitions than those identified below.

- *The internal stability of such PECs*, *i.e.* whether the welfare of each participating country is larger than the welfare it would obtain from withdrawing from the coalition and free riding on other participants’ abatement efforts.

- *The potential for improving the stability of PECs,* and for shaping the distribution of mitigation costs across countries more broadly, through international financial transfers.

The analysis is carried out using the World Induced Technological Change Hybrid (WITCH) model (Bosetti *et al.* 2007, 2009). WITCH has two major strengths in this specific context. First, it belongs to the class of so-called integrated assessment models (IAMs), *i.e.* it incorporates explicitly the gains from emission reductions in terms of avoided climate change through regional damage functions that feed climate change back into the economy. Also, WITCH has a game-theoretic structure, *i.e.* the 12 model regions and/or coalitions of regions behave strategically with respect to all major economic decision variables – not least emission abatement levels – by playing a non-cooperative Nash game. Therefore, when deciding whether or not to cooperate on GHG emission control, countries take into account how their decisions affect all other countries, and whether these countries will cooperate or remain outside the coalition.

Following a presentation of WITCH’s game-theoretic framework in Section 2, Section 3 assesses the basic individual incentives for countries to participate in coalitions. Given the uncertainties involved in predicting and valuing the future damages and risks from climate change, the analysis is performed under four alternative combinations of damage and discount rate assumptions. A low-damage case is based on the damage assessment in Nordhaus and Boyer (2000), while a high-damage case incorporates the more recent, upward revisions made for instance by Hanemann (2008) or Stern (2007). A low-discounting case assumes a (pure) utility discount rate of 0.1%, in line with Stern (2007), while a high-discounting case takes the 3% value used in Nordhaus (2007). The main findings are:

- As a general rule, developing countries are expected to incur larger damages from climate change than their developed counterparts. Within the group of developing countries, African countries appear to be more exposed than India and, to an even greater extent, China. Within the group of developed countries, Western Europe would suffer greater damage than the United States, which in turn would be more vulnerable than the OECD Asia-Pacific countries and Canada. Russia would be least affected by climate change.

- Abatement costs under a single world carbon price scenario are also larger in developing countries than in their developed counterparts, due to their higher energy/carbon intensity. Fossil fuel producers such as Middle East countries and Russia incur the largest costs, reflecting their very high energy/carbon intensity and the fall in world fossil fuel prices. Within the group of developed regions, Western Europe and Japan-Korea would face smaller costs than the United States, also due to lower energy/carbon intensity.

- Taking into account both damages and abatement costs, Russia, Middle East countries and China appear to have lower incentives to participate in a coalition than most other countries, *ceteris paribus*. In particular, a robust positive correlation is found between abatement costs and the magnitude of free-riding incentives, as measured by the welfare gain from withdrawing from a "grand coalition" consisting of all countries.

Section 4 brings together the incentive effects associated with damages and abatement costs to analyse coalition formation and stability. The starting point is that a hypothetical world social planner that fully internalises environmental externalities would take ambitious mitigation action, at least stabilising GHG concentration below 550 ppm CO_2eq by 2100 in the high-damage/low-discounting case. By contrast, in the absence of coordinated action, a fully non-cooperative "business-as-usual" (BAU) scenario prevails, little abatement is undertaken, and global welfare is significantly lower. There is therefore a strong need for building broad climate coalitions, and their analysis yields the following results:

- Among all politically relevant climate coalitions, defined here to include at least all industrialised countries, only few are PECs at the 2100 horizon. This means that only few coalitions could meet the illustrative 550 ppm CO_2eq target by 2100 even if they were able to reduce their own emissions to zero, while the emissions of non-participating regions continued along their BAU path. These few PECs include both China and India, along with most other world regions. Even by 2050, all PECs need to include both China and India, unless all other developing regions offset the non-participation of one of these two countries.

- Given that being a PEC is a necessary, but not sufficient condition to meet the target in the analysis undertaken here, in practice coalitions will need to include virtually all world regions in the course of this century. In fact, when account is made for the economic unfeasibility of zero emissions, and for the free-riding incentives of non-participating regions, only a very broad international coalition excluding no region other than Africa can achieve the target by 2100.

- Cost-benefit analysis suggests that only the grand coalition finds it optimal *as a whole* to stabilise overall GHG concentration below 550 ppm CO_2eq in the high-damage/low-discounting case. Smaller PECs, including the grand coalition excluding Africa, achieve less ambitious targets. This is because they do not fully internalise the global environmental externality, and allow a larger number of (non-participating) countries to free ride.

- Although the grand coalition can, and *as a whole* has an incentive to achieve the target, it does not appear to be internally stable. Most regions gain more from non-participation than from participation to the grand coalition. The same conclusion holds for all other, smaller PECs.

- Neither the grand coalition nor any other PEC is *potentially* internally stable either, *i.e.* no set of international financial transfers can be found that would offset the free-riding incentives of *all* participating countries *simultaneously*. This is because the overall welfare gain from any PEC relative to the non-cooperative outcome is not large enough to give each country/region its free-riding pay off. After compensating all losers in the coalition, the remaining coalition surplus is too small to offset free-riding incentives.

Although no set of transfers is found to address the free-riding incentives of *all* countries *simultaneously*, there is little doubt that transfers can improve the prospects for broad-based participation in international mitigation action. In practice, one powerful way to implement such transfers is through the allocation of emission reduction commitments across countries. For instance, allocation rules could be designed to shift some of the costs of action away from developing countries, which in general have larger free-riding incentives than their developed counterparts. Illustrative allocation rules under a global emission trading scheme (ETS) are explored in Section 5, with the following results:

- The cross-country distribution of mitigation costs varies drastically across alternative allocation rules, reflecting the wide variance in the sign and magnitude of each region's net permit imports. By 2050, developing regions are projected to gain significantly (relative to BAU) from rules that would grant allowances in inverse proportion to each region's contribution to past cumulative emissions, or from rules that would cover their projected BAU emissions. To a lesser extent, and with greater variance across countries, they would also benefit from allocation of allowances in inverse proportion to emissions per capita, or emissions per unit of output.

- By contrast, developing regions incur sizeable losses during the first half of this century under grandfathering or full auctioning of international allowances. Russia loses under all rules except grandfathering. Overall, given the heterogeneity of outcomes across alternative rules, these could in principle be combined to achieve any particular distribution of mitigation costs.

It should be acknowledged that the main findings on coalition stability are subject to a number of limitations. Although the results are reasonably robust to the alternative damage and discounting assumptions, there are also wide uncertainties surrounding more distant climate impacts (beyond the 2100 horizon considered here), future emission trends, and the cross-country distribution of damages and risks. Also, the analysis focuses on immediate, irreversible and self-enforcing participation to mitigation action, thereby abstracting from other possible bargaining options including *e.g.* delayed participation, renegotiation, sanctions or joint negotiation in multiple areas (*e.g.* linking climate and international trade negotiations).[2] Furthermore, the co-benefits from mitigation action, *e.g.* in terms of human health, energy security or biodiversity, are not taken into account. Previous OECD analysis indeed suggests that such co-benefits are large, although the participation incentives they provide are not straightforward (Bollen *et al.*, 2009; Burniaux *et al.*, 2008). Finally, removal of fossil fuel subsidies is also omitted from the analysis. Insofar as phasing out subsidies would bring an economic gain and lower the carbon intensity of a number of (mainly developing) countries, incentives to participate in international mitigation action could improve (for an analysis of the economic gains and world emission impacts of fossil fuel subsidy removal, see Burniaux *et al.,* 2009) .

Another important feature of the analysis is the assumption that even if a country benefits from an international coalition relative to a BAU scenario, it will always prefer to free-ride if that option is even more profitable. While this merely reflects the underlying assumption that each individual country

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[2] However, these limitations have little impact on the analysis of PECs, which is the main cornerstone of the paper's analysis of feasible and effective coalitions. Therefore, most conclusions are quite robust to changes in bargaining options.

maximises its own welfare, current international redistributive policies, such as official development aid, point instead to some degree of altruism. For instance, with a loss of a few per cent in the discounted value of their consumption levels, industrialised countries are estimated to stabilise the grand coalition in the high-damage/low-discounting case, *i.e.* market-based transfers of such magnitude would be large enough to fully compensate other (mainly developing) regions for their free-riding incentives.

2. Analysing climate coalitions in WITCH

WITCH is a dynamic optimal growth general equilibrium model with a reasonably detailed (bottom up") representation of the energy sector, thus belonging to a new class of hybrid (both "top-down" and "bottom-up") models. It is a global model, divided into 12 macro-regions. It is also an integrated assessment model (IAM), featuring a reduced form climate module (MAGICC), and a climate change damage function that provides the climate feedback on the economic system. Compared with earlier versions (Bosetti *et al.,* 2007), the version of the model used in this paper incorporates non-CO2 gases and forestry emissions, and also includes two "backstop" technologies that require dedicated R&D investments to become economically competitive (see Annex 1 for details). In addition to the full integration of a detailed representation of the energy sector into a macro model of the world economy, distinguishing features of the WITCH model are:

- *Endogenous technical change*. Advances in carbon mitigation technologies are described by both diffusion and innovation processes. "Learning by doing" (LbD) and "Learning by researching" (R&D) processes are explicitly modelled and enable to identify the "optimal"[3] public investment strategies in technologies and R&D in response to given climate policies. Some international technology spillovers are also modelled.

- *Game-theoretic set up*. The model can produce two different solutions: a co-operative one that is globally optimal (global central planner) and a decentralised, non-cooperative one that is strategically optimal for each given region (Nash equilibrium). As a result, externalities due to global public goods (GHG concentration, international knowledge spillovers, exhaustible resources, *etc.*) and the related free-riding incentives can be accounted for, and the optimal policy response (world GHG emission reduction policy, world R&D policy) be explored. A typical output of the model is an "optimal" carbon price path and the associated portfolio of investments in energy technologies and R&D under a given environmental target.

WITCH's game-theoretic framework allows detailed analysis of the incentives to join, and the stability of, international climate coalitions. In order to exist, coalitions must be both *profitable* and *stable*. A coalition is said to be *profitable* if signatory countries (coalition members) have a higher welfare than in a scenario where the coalition is not formed. This is a necessary, but not sufficient condition for the coalition to be formed. A second requirement concerns *stability*. A coalition is said to be *stable* if it is *internally* and *externally* stable. A coalition is *internally stable* if signatory countries do not have the incentive to defect and to behave non-cooperatively when other coalition members cooperate. A coalition is *externally stable* if there is no incentive to enlarge the coalition by including non-signatory countries. Finally, a coalition may be *potentially internally stable* if it can be turned into a stable coalition through a set of self-financed – *i.e.* not greater than the coalitions surplus – financial transfers across participating regions.

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[3] Insofar as the solution concept adopted in the model is the Nash equilibrium, "optimality" should not be interpreted as a first-best outcome but simply as a second-best outcome resulting from strategic optimisation by each individual world region.

As discussed in the survey of coalition theory presented in Annex 2, different assumptions regarding the structure and the rules of the game can lead to a wide range of possible outcomes, in terms of the equilibrium characteristics and stability of coalitions. Important issues in that context include *inter alia* (for a detailed analysis, see Carraro and Marchiori, 2003):

- *The timing of the decisions announced by players (simultaneous versus sequential game).* Coalitions can be formed in a setting in which each player announces simultaneously his/her optimal choice (simultaneous game), or they can be built in a sequential process in which each player makes his/her announcement following a pre-determined order (sequential game).

- *The norms that govern coalition membership*. In *open membership* games, each country is free to join or leave the coalition without any need to seek the permission of other coalition members. Also, each player that wants to be part of the coalition cannot be refused membership. Freedom of entry does not apply instead to the case of *exclusive membership* games, for which participation to a coalition is conditional on approval from all coalition members. Exit without permission remains an option for coalition members in this class of games as well. In *coalition unanimity* games, the formation and the existence of the coalition are conditional on the unanimous participation of all coalition members. If one of them decides to abandon the coalition to behave as a singleton, the coalition collapses and all players behave as singletons.

- *The behaviour of non signatories.* The reaction function of singletons outside the coalition may be *orthogonal*, in which case they do not have incentives to expand their negative externality (raise their GHG emissions) as a reaction to the effort of coalition members. If instead the best response of non-cooperating singletons is *non-orthogonal*, *i.e.* if it implies an increase in (the optimal level of) their individual emissions, the environmental benefits of cooperation are reduced.

- *How players build their conjectures on their counterparts' responses to their optimal strategy*. In the *Nash conjecture* case, players' decisions are taken by assuming the other player's choices as given. Equilibrium decisions in such games are the best response strategies to the other players' decisions. Another approach to expectation formation assumes that each player forms *rational conjectures* on the consequences of their choice on other players' actions, *i.e.* on the coalition structure that would result from his defection.

- *The possibility and the devices available to enlarge coalitions*. Two major ideas have been discussed in the literature to enhance coalition stability. The first concerns the possibility of expanding coalitions by means of side payments, *transfers*, between players of the game. The second concerns the possibility of reducing free-riding incentives through *issue linkage*, *i.e.* by coupling the global public good treaty with a treaty that allows the possibility of enjoying access to a *club* or *quasi-club* good (*e.g.* a treaty to liberalise international trade among signatory parties).

- *Whether bargaining over the rules of the game is allowed for*. The wide array of possibilities from which players can choose the rules of the game raises the question of how players agree on a particular set of rules. In particular, the literature has explored the process of adoption of a *minimum participation rule*, which consists in determining the minimum number of signatories for the agreement to become effective.

The WITCH model analysis assumes a non-cooperative, simultaneous, open membership, Nash game with non-orthogonal free-riding, and allows for the possibility of international transfers – but not issue linkage – to enlarge climate coalitions. In essence, the framework considers immediate, irreversible and self-enforcing participation to climate change mitigation action, and abstracts from other possible bargaining options including *e.g.* delayed participation, renegotiation, sanctions or joint negotiation in multiple areas (*e.g.* climate and international trade). Sequential games with continuous renegotiations, coalition unanimity (or at least minimum participation rules), rational conjectures and/or orthogonal free-riding are alternative features of the game which might favour greater stability of large coalitions. However, it is not always clear under what conditions it is possible to construct international agreements in which these rules of the game can apply (see Annex 2).

When checking for stability and profitability of coalitions, the solution concepts that are implemented in WITCH are well rooted in the theoretical literature. The model is solved as a one-shot meta-game, with a first stage in which countries decide on their participation and coalitions are formed, and a second stage in which countries choose their optimal emission levels. In the second stage, coalition members maximise aggregate joint welfare, whereas non participants behave as singletons and maximise individual welfare. Equilibrium is found employing the so-called γ-characteristic function approach (Chander and Tulkens, 1997), *i.e.* with WITCH the unique Nash equilibrium is computed in which coalition members jointly play their best response to non-coalition members, who adopt individually their best-reply strategies.

3. Assessing the basic drivers of individual country incentives to participate in international climate coalitions

At the individual country level, the basic drivers of the incentives to participate in an international climate change mitigation policy agreement include *inter alia* the expected impacts of climate change, the influence of distant impacts on current policy decisions (*i.e.* the discount rate), and the costs of mitigation policies. This Section describes how each of these three drivers are captured in the WITCH model analysis undertaken in this paper, and how participation incentives vary across the main world regions as a result.

3.1. Climate change impacts in WITCH

Adequate knowledge of climate change impacts is a prerequisite for well-informed climate change mitigation policies. Alternative assumptions regarding such impacts can lead to profoundly different policy insights, in terms of the outcome of cost-benefit analyses and the incentives for individual regions to participate in climate coalitions. At the same time, assigning monetary values to climate change damages is particularly challenging, reflecting the uncertainty surrounding the magnitude of long-term global warming, the uncertainty and multi-dimensional nature of impacts (market impacts, non-market impacts, catastrophic risks), and the difficulty to aggregate them across different types of impacts, countries and time.

Annex 3 describes how existing IAMs capture the impacts from climate change through so-called climate change damage functions. It also surveys the estimates used as a background for the calibration and the construction of WITCH's damage functions. One conclusion is that reliable economic analyses of climate change policies cannot be based exclusively on damage estimates that date back to the 1990s, as these may significantly under-estimate damages and risks, especially in non-market areas. As a consequence, two alternative damage scenarios are considered here: *i)* a low damage scenario, embedded in the basic version of the WITCH model, which in turn is based on the damage assessment provided by Nordhaus and Boyer (2000); *ii)* a high damage scenario, which incorporates more recent, higher damage estimates as suggested for instance by Hanemann (2008) or Stern (2007).

The climate change damage function used in the basic version of the WITCH model includes a reduced-form relationship between temperature and gross world product which follows closely Nordhaus and Boyer

(2000), both in the functional form and in the parameter values. Climate change damage drives a wedge between net and gross output:

$$YN_{n,t} = \frac{1}{1+\theta_{1n} \cdot T_t + \theta_{2n} T_t^2} \cdot YG_{n,t} \quad , \qquad (1)$$

where n and t are country and time indices, and YN, YG and T denote respectively net output, gross output and temperature. The resulting pattern of regional damages also follows Nordhaus and Boyer (2000), with higher estimated losses in developing countries, in particular South Asia (including India) and Sub-Saharan Africa (Figure 1). These two regions are expected to lose the most from climate change, especially because of higher damages in agriculture and the increase of vector-born diseases (Sub-Saharan Africa) and because of catastrophic climate impacts (South Asia including India). Damage estimates for agriculture, coastal settlements and catastrophic climate impacts are significant in Western Europe, resulting in higher damages than in other developed regions. In China, Eastern EU countries, non-EU Eastern European countries (including Russia), Japan-Korea, climate change up to 2.5°C would bring small benefits, essentially because of a reduction in energy demand for heating purposes (non-EU Eastern European countries including Russia) or positive effects on agricultural productivity (China).

Recent evidence suggests that climate change impacts will probably be higher than previously thought. However, going from physical impacts to economic losses (or benefits) expressed in monetary terms, for a number of regions, is a complex process which requires several steps of estimation, aggregation and extrapolation. As a consequence, it is difficult to infer a precise damage function, even using the latest estimates reviewed in Annex 3. For example, while Hanemann (2008) estimates that damages may be four times as higher as in Nordhaus and Boyer (2000), this applies only to the United States. Nonetheless, in order to account for the new, albeit partial, evidence of higher climate damages, the WITCH model analysis undertaken here also considers an alternative, higher damage function. That function may be seen as defining an upper bound that accounts for most of the wide and uncertain range of estimates proposed by the literature. Figure 2 illustrates the time profile of climate change damages that can be extrapolated from the IPCC ranges reported in UNFCCC (2007), together with the low and high damage functions in the WITCH model. The WITCH high damage function follows UNFCCC data quite closely until a 1.5°C rise in global temperature, and increases more sharply beyond, moving closer to – but remaining lower than –Stern's (2007) estimates. In the high damage function, global climate damages are about twice as large as in the low damage one.

3.2. Discount rate assumptions

Another element is crucial when analyzing the inter-temporal effects of climate change damages, namely the social discount rate and, in particular, the pure rate of time preference. There is a longstanding controversy regarding the choice of the latter (Weitzman, 2001). Consistent with a long line of economists (*e.g.* Ramsey, 1928; Harrod, 1948; Solow, 1974), Stern (2007) argues on ethical grounds for a near-zero value, while others dismiss this assumption on the grounds that it is inconsistent with actual individual behaviour (*e.g.* Nordhaus, 2007; Weitzman, 2007).

Aggregate discounted impacts are vastly increased if greater weight is assigned to the far future, when damages are expected to be higher. Combining about hundred estimates from 27 studies to form a probability distribution for the marginal cost of carbon, Tol (2005) finds that the median value of the social cost of carbon – an estimate of the marginal impact caused by one additional ton of carbon – increases from $US7 to 39 per ton of carbon when the pure rate of time preference declines from 3% to 0%, *i.e.* when it declines from the value used in Nordhaus' DICE/RICE model to that used in the Stern Review.

Therefore, in order to take into account the existing debate on the choice of the social discount rate, the WITCH model analysis is performed here under two different assumptions regarding the pure rate of time preference, namely 3% and Stern's 0.1% assumption.[4] Overall, in order to account for uncertainty regarding both damages and inter-temporal preferences, the climate coalition analysis carried out below will consider four cases, each of them characterised by a different combination of damage and discount factor assumptions:

- High damage, low discount rate.
- High damage, high discount rate.
- Low damage, low discount rate.
- Low damage, high discount rate.

3.3. Abatement costs

The incentives to participate in climate coalitions will also be shaped by mitigation policy costs. One determinant of these costs is the shape of the aggregate marginal abatement cost curve (MAC), which is a reduced-form relationship between the cost of abating an extra unit of emissions and cumulative abatement. In WITCH, mitigation costs are reflected into the investment and consumption patterns, and the way these complement and substitute in the production function and consumption budget. They also depend on technological change, which is endogenous. Nonetheless, it is possible to compute and compare MACs across countries by running a range of global carbon tax scenarios. The carbon tax pins down the marginal abatement cost and total abatement over the simulation horizon. By repeating this exercise for a wide set of carbon taxes, it is possible to draw a relationship between marginal abatement costs and cumulative emissions abatement for the 12 regions of the model.[5] In order to focus only on abatement costs, all damages from climate change are excluded from this exercise. Figure 3 reports the marginal abatement costs as a function of relative abatement with respect to baseline. WITCH's MACs show the usual convex relation due to increasing marginal abatement costs. A $US100 tax per ton of CO_2eq achieves a cumulative CO2 abatement between 53% and 73%, depending on the region. China and the United States have relatively lower/flatter marginal abatement curves, compared with other regions. MACs tend to become steep in all regions beyond a tax of $US150 per ton of CO_2eq.

MACs, together with other factors such as the overall carbon intensity of the economy – which also partly determines the shape of the MAC – and whether it produces fossil fuels, determine overall mitigation costs at the country level. Looking at these costs, measured in terms of the discounted consumption loss from alternative world carbon tax scenarios, developing countries are found to incur larger losses than their developed counterparts, due to their higher energy/carbon intensity (Figure 4). Fossil fuel producers such as the Middle East and non-EU Eastern European countries (including Russia) are the biggest losers, reflecting their very high energy/carbon intensity and the fall in world fossil fuel prices. Within the group of developed regions, Western Europe and Japan-Korea would face smaller costs than the United States despite steeper MACs, reflecting their lower energy/carbon intensity.

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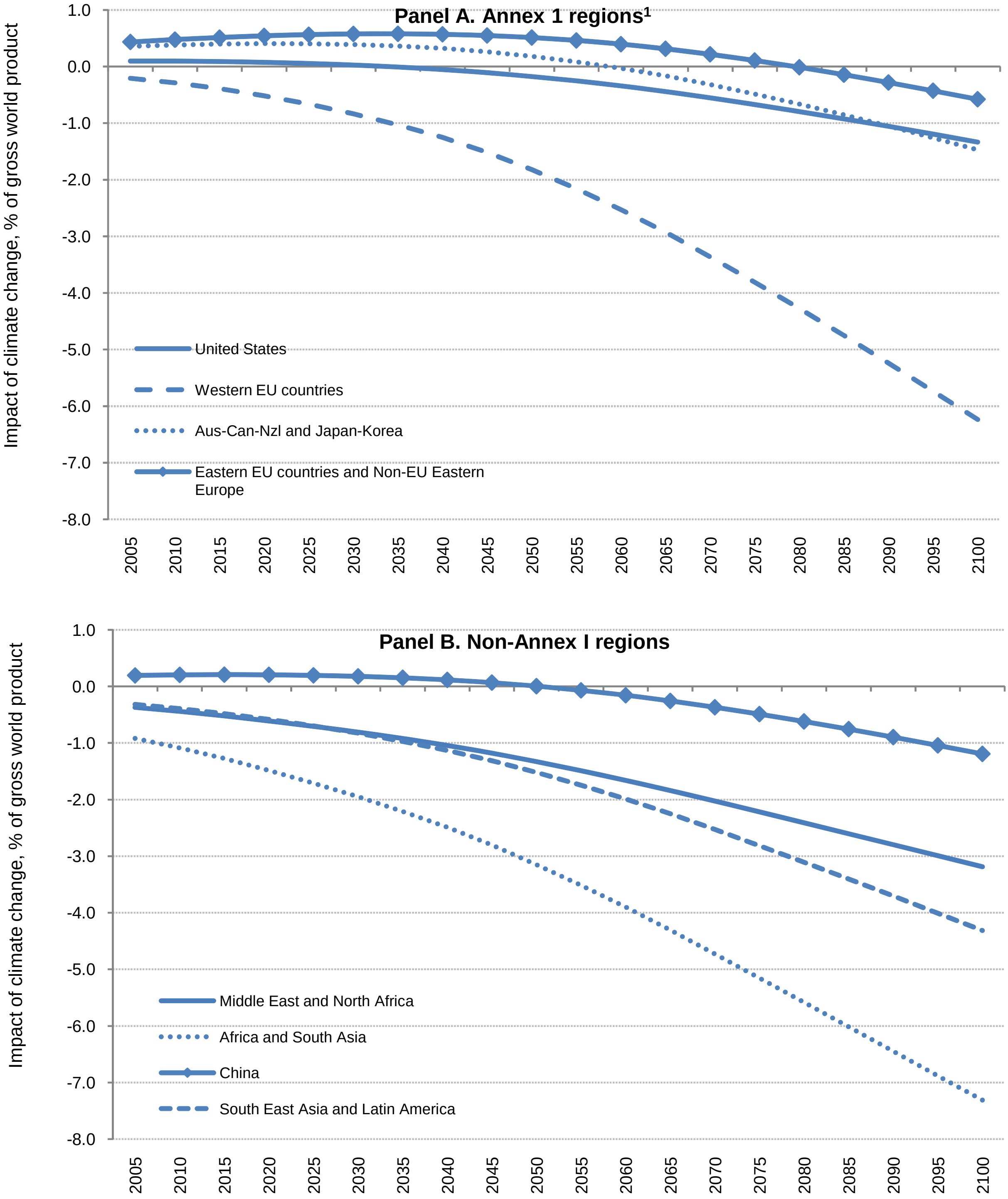
[4] Following Weitzman (2001), the pure rate of time preference is also assumed to be time-declining.

[5] Each carbon tax path considered is not constant, but instead is assumed to grow over time at the rate at which marginal abatement costs grow in the cooperative solution of the model.

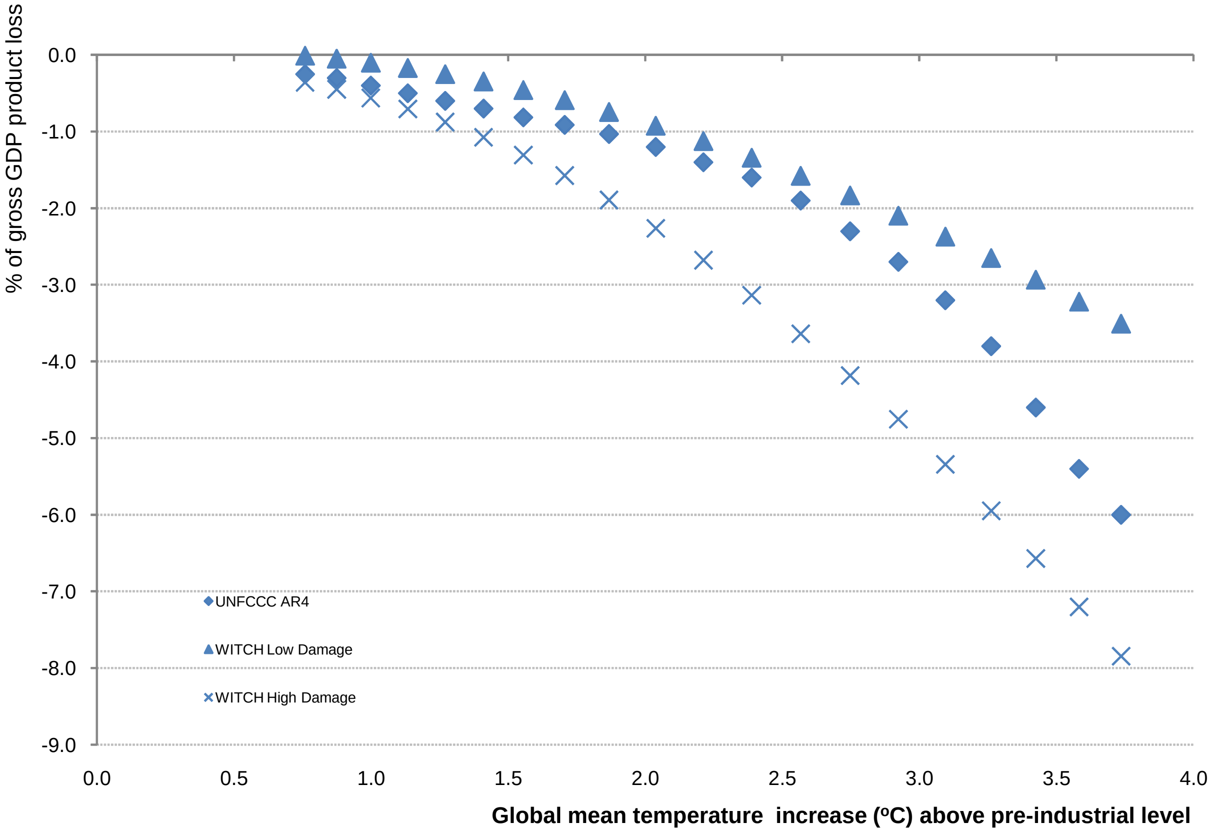
Figure 1. Regional damage functions in the basic version of the WITCH model



1. Korea is grouped with Japan, but is not an Annex I country.

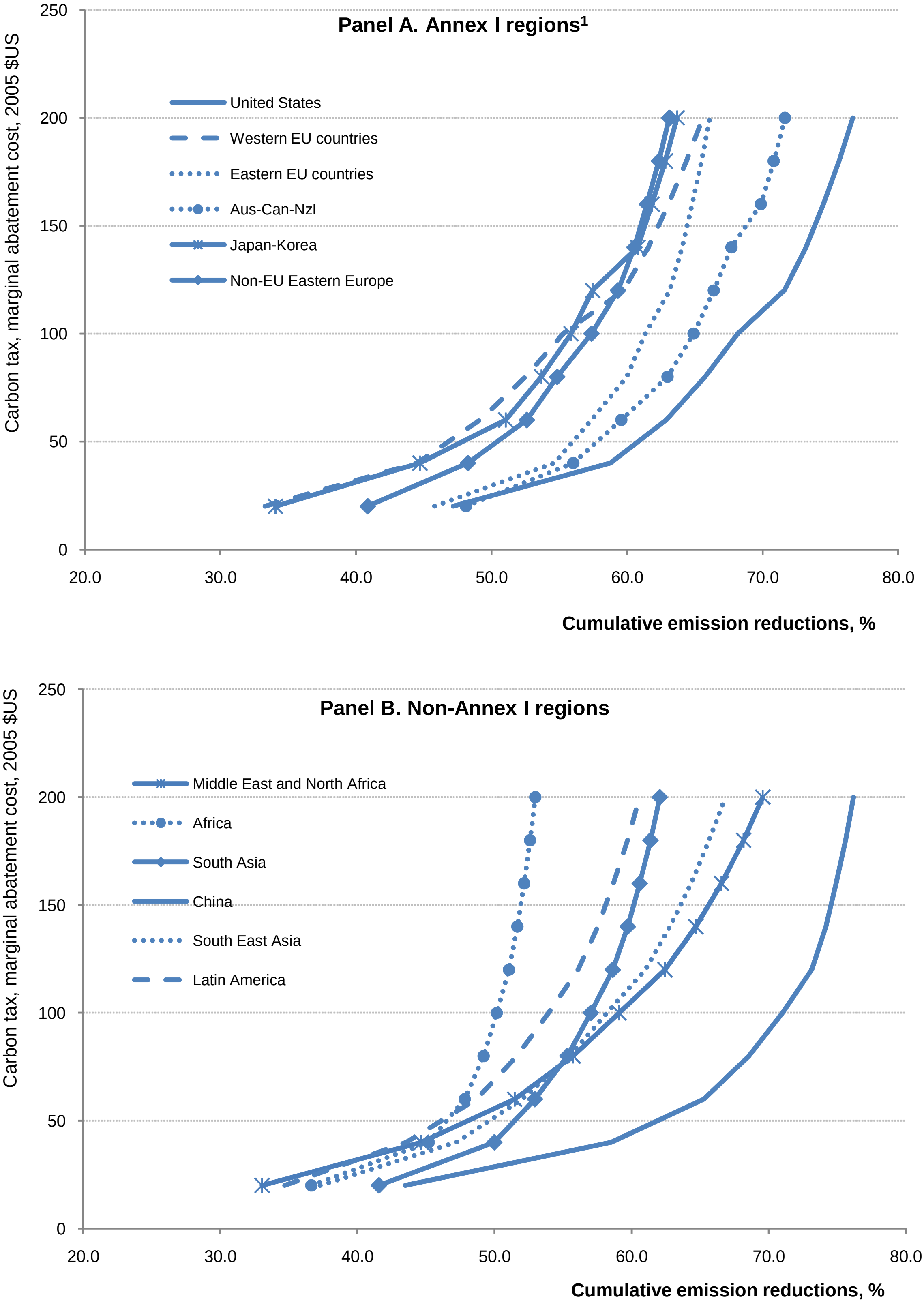
Source: WITCH model simulations.

Figure 2. **A higher damage function in WITCH**



Sources: UNFCCC (2007), *Investments and Financial Flows to Address Climate Change*; WITCH model simulations.

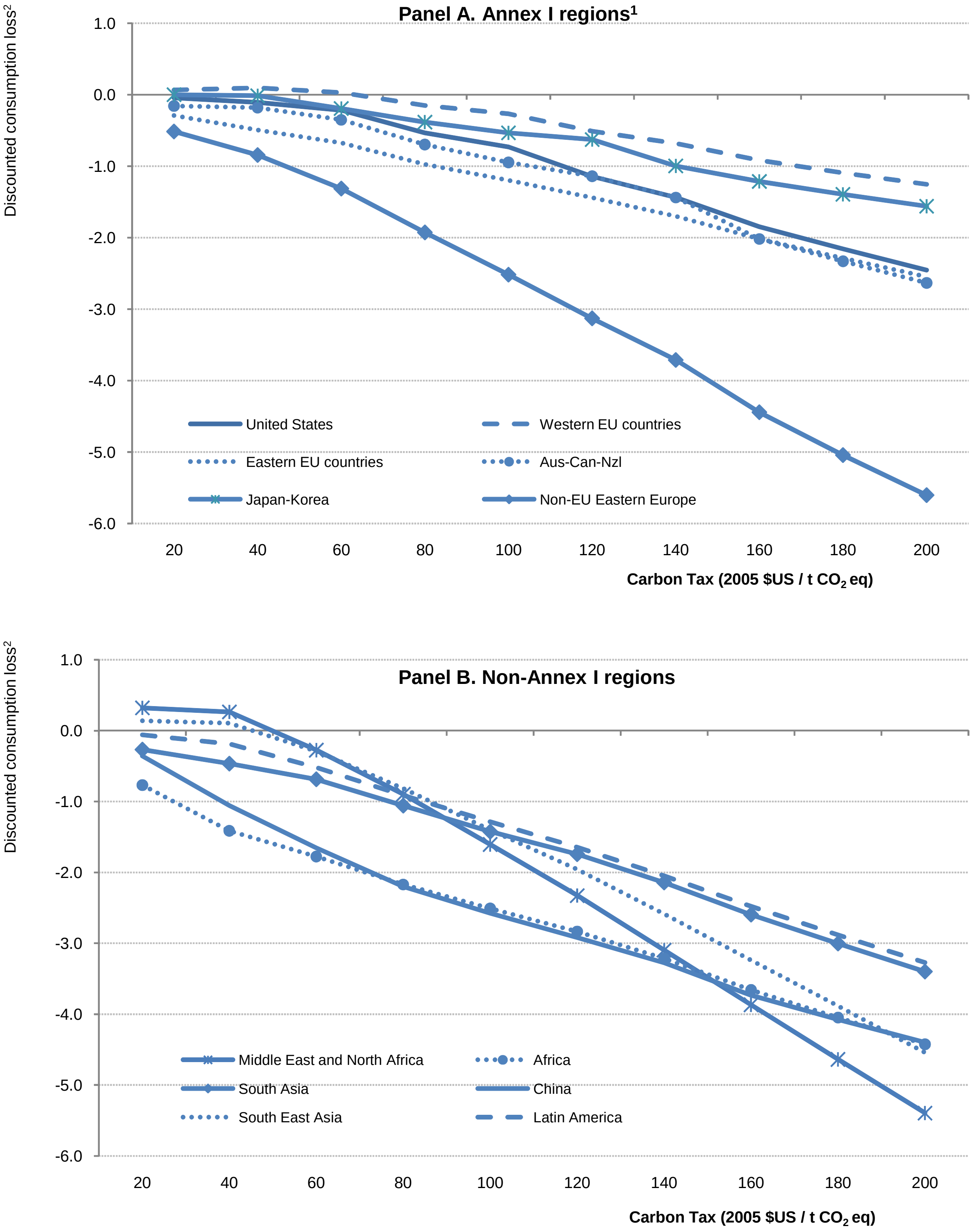
Figure 3. **Marginal abatement cost curves (all GHGs included)**



1. Korea is grouped with Japan, but is not an Annex I country.

Source: WITCH model simulations.

Figure 4. **Discounted regional abatement costs under a range of world carbon tax scenarios**



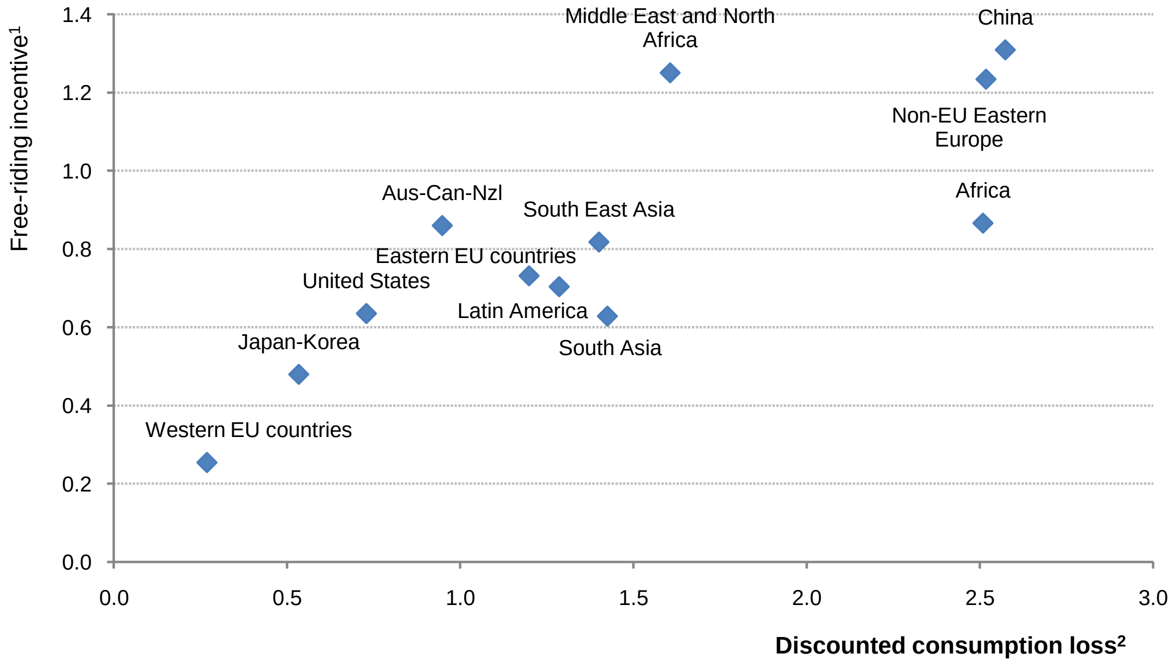
1. Korea is grouped with Japan in the WITCH model, but is not an Annex I country.

2. Cumulative consumption gap relative to baseline in present value terms over 2015-2100, using a 3% annual discount rate.

Source: WITCH model simulations.

The larger a region's mitigation costs under a global carbon tax, the smaller its incentives to participate in a climate coalition, *ceteris paribus*. One possible measure of free-riding incentives that will be introduced and discussed below is the difference (in %) between a region's welfare (defined as the discounted sum of the logarithm of future domestic per-capita consumption) if it free rides on a world coalition of acting countries, and its welfare if it participates in that coalition. As Figure 5 shows, there is a strong positive relationship between that synthetic indicator of free-riding incentives and the overall consumption loss induced by a given world carbon tax – set here at $US100 per ton of CO_2eq. This is because climate coalitions are assumed to implement an efficient climate policy, *i.e.* to equalise marginal abatement costs across all participating regions.[6] As a result, countries that face larger costs from a given world carbon price can expect to gain less from joining an international coalition, and therefore have larger incentives to defect, *ceteris paribus*.

Figure 5. **Mitigation policy costs and free-riding incentives**



1. The free-riding incentive is computed as the difference in % between a region's intertemporal welfare if it withdraws from a world coalition of acting countries (the so-called "grand-coalition", see Section 3), and its intertemporal welfare if it participates in the world coalition. A 0.1% annual pure rate of time preference is used to compute the present value of welfare.

2. Cumulative consumption gap relative to baseline in present value terms over 2015-2100, using a 3% annual discount rate.

Source: WITCH model simulations.

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[6] This is a consequence of using so-called Negishi weights to aggregate welfare.

4. Analysing coalition formation and stability

4.1. Fully cooperative versus non-cooperative outcomes

A natural first step towards analysing coalition formation and stability is to determine the optimal abatement policy that would be implemented by a "grand coalition" of world regions that fully internalises the environmental externality due to GHG emissions.[7] When the fully cooperative solution is implemented, a world social planner maximizes the aggregate welfare of the so-called *grand coalition* of world regions. This aggregate welfare is defined as the weighted sum of regional welfare functions, using the standard Negishi weights which ensure that the coalition equalises marginal abatement costs worldwide.

By contrast, in the non-cooperative set-up, each of the 12 regions is assumed to choose the optimal path of a set of choice variables (investments in physical capital, in different energy technologies, in R&D, *etc.*) so as to maximize its own social welfare function. In this framework, each region takes its decisions individually, given the action of the other players. The outcome of this non-cooperative game is an open loop Nash equilibrium, which also constitutes WITCH's BAU scenario. In this scenario, little abatement is undertaken since individual regions do not internalise the negative externality they impose on other regions, taking only into account the domestic ancillary benefits of their climate policy.

Figure 6 shows the implications of the two solution concepts for global GHG emissions in the high-damage/low-discounting scenario. In the non cooperative case, world emissions grow throughout the century because each individual region alone has little incentive to reduce them. If instead countries gather in a grand coalition climate, environmental externalities are fully internalised, and emissions are reduced drastically, consistent with long-run stabilisation of overall GHG concentration at about 550 ppm CO_2eq. The difference in outcomes between the cooperative and non-cooperative cases is a powerful illustration of the well-known "tragedy of the commons". Emissions under any coalition will fall between their levels in the non-cooperative and cooperative cases.

In both the non-cooperative and cooperative cases, the optimal emission path depends on the damage and discount rate assumptions. However, sensitivity to underlying assumptions is far greater in the cooperative case (Figure 7). In the non-cooperative case, neither damage nor discount rate assumptions have a major impact on emissions, reflecting the fundamental inability of individual regions to internalise the environmental externality (Figure 7, Panel A). It is also the case that a higher discount rate implies not only a higher weight on future damages – which should favour emission reductions – but also a higher consumption path – which leads to higher emissions. The relative strength of these two offsetting factors determines the net effect on emissions. In the cooperative setting, instead, lower discounting and/or higher damages have a sizeable impact on emission abatement (Figure 7, Panel B). The high-damage/low-discounting and low-damage/high-discounting define the upper and lower bounds for future emissions.

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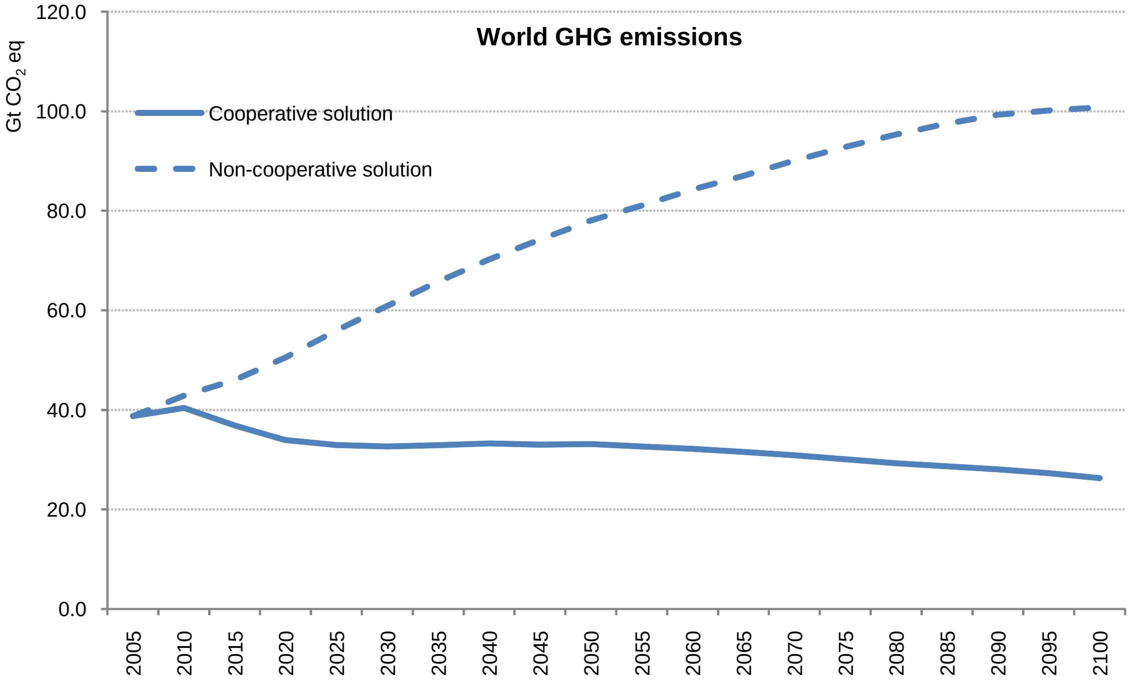
[7] The WITCH model incorporates other economic externalities related to the use of natural resources and to the production and diffusion of knowledge and experience. However, this paper analyses the incentive to form climate coalitions, independently from linkages with other issues. In that context, it is assumed that countries decide whether or not to cooperate on the environmental externality only. Cooperation on technological externalities and on the use of natural resources is not considered.

Figure 6. **Cooperative and non-cooperative solutions of the WITCH model, high-damage/low-discounting rate case**



Source: WITCH model simulations.

4.2. Potentially effective coalitions (PECs)

Given the regional disaggregation in WITCH, coalitions can be of any size between 1 and 12 regions, implying 4 095 possible coalition structures – even assuming a single climate treaty, *i.e.* that only one coalition can form in each coalition structure. In practice, however, only a small subset of these 4 095 coalition structures is politically relevant and has the potential to be environmentally effective. Against this background, the strategy followed in this paper is to narrow down the list of coalitions to be explored by discarding two types of coalitions: *i)* those that are politically irrelevant, which here are assumed to be all coalitions that do not include all high-income countries (United States; European Union; Japan and Korea; Australia, Canada and New Zealand); *ii)* those that do not have the potential to stabilise overall GHG concentration at a level of 550 ppm CO_2eq. Since meeting more stringent targets would require larger coalitions than the PECs identified below, the latter should be seen as minimum coalitions sizes needed to meet any target equal to or below 550 ppm CO2eq.

A coalition is assumed to be a potentially effective coalition (PEC) at a given horizon (2050 and/or 2100 below) if participating regions' lower bound emission levels, assumed here to be zero,[8] added to the BAU emissions of non-participating countries (singletons), results in stabilisation of overall GHG concentration at 550 ppm CO_2eq or below. In line with the IPCC's fourth assessment report (FAR) (IPCC, 2007) and keeping in mind existing uncertainties regarding the link between emissions and concentrations, the achievement of the 550 ppm CO_2eq long-term target requires in the short-term (in 2050) and long-term (in

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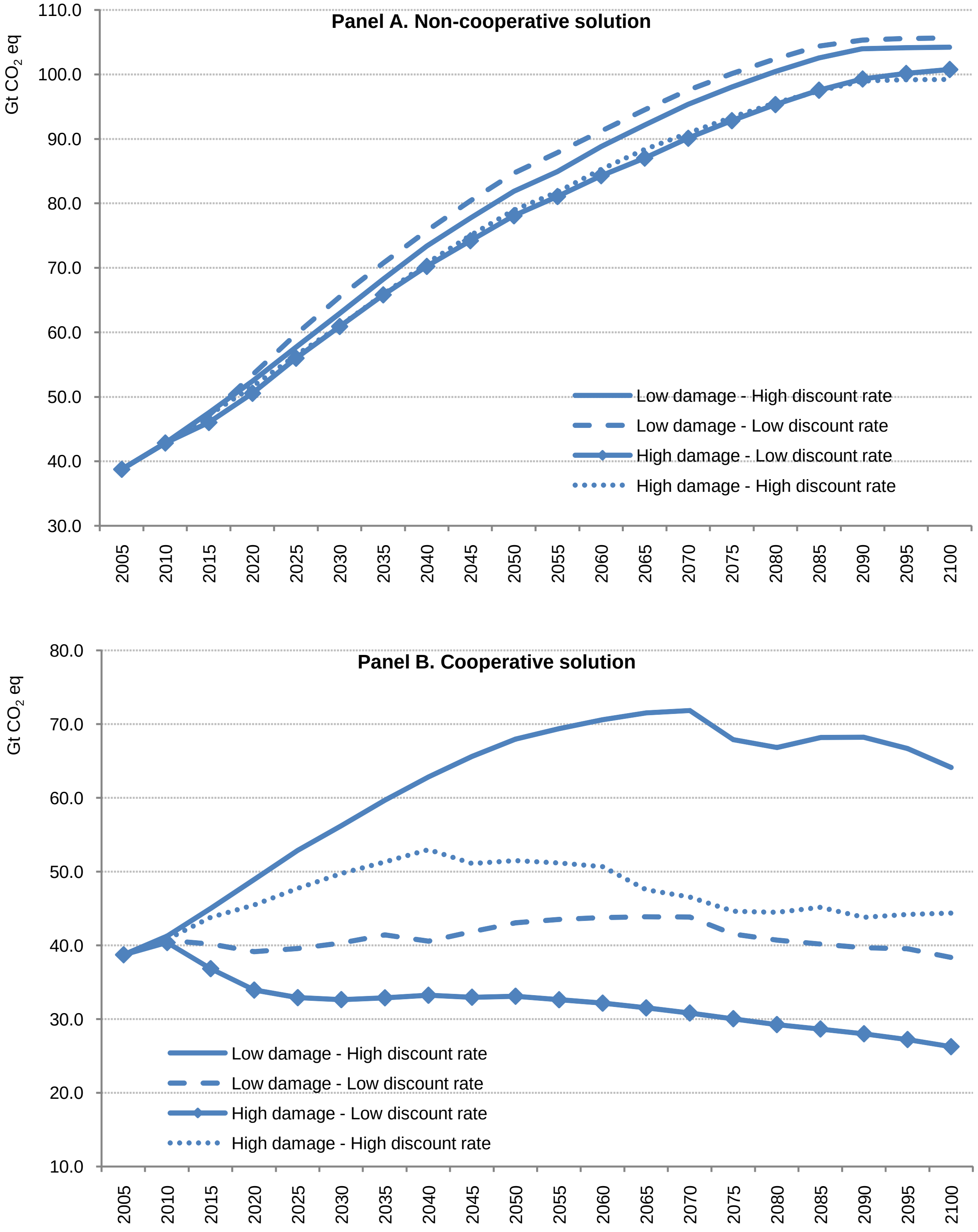
[8] Zero emissions do not strictly represent a technical lower bound since negative emissions could in principle be achieved through aforestation/reforestation.

2100) emission reduction targets of about 25% and 50% relative to 2005 levels, respectively. In practice, PECs are identified by comparing, for each coalition structure, the path of singletons' BAU emissions and the world emission path required to meet the target both in 2050 and 2100. This comparison is repeated four times for each coalition structure, corresponding to the four different non-cooperative baselines derived from alternative damage and discount rate assumptions.

The PECs identified at the 2050 and 2100 horizons are summed up in Table 1. In order to achieve a world emission path consistent with a long-run 550 ppm CO_2eq GHG concentration target, an international climate coalition should include virtually all large emitters by 2050. In particular, all (politically relevant) PECs include all industrialised countries and both China and India by 2050, unless *all* other developing regions (except Africa) reduce their emissions below BAU levels (Table 1, Panel A). A coalition consisting of industrialised countries only cannot, even potentially, meet the target at the 2050 horizon. Furthermore, only 12 coalitions are PECs at the 2100 horizon, and they include all world regions with just a few exceptions (Table 1, Panel B). Only Sub Saharan African, plus one or two additional regions among Latin America, South East Asia, Middle East-North Africa, and Non-EU Eastern Europe (including Russia), can be left out of an international coalition for the target to be attainable.

These findings are very robust for two reasons. First, they hold under each of the four possible damage and discount rate scenarios. Second, and more importantly, being a PEC is a necessary but not sufficient condition for the 550 ppm CO_2eq target to be attainable. This is due both to the likely unfeasibility of zero emissions over the foreseeable future, and to the "free-riding incentives" and carbon leakage that such a large abatement effort would generate, raising emissions in non-participating regions *above* their BAU levels. Therefore, the definition of PECs underestimates the actual emission levels of both cooperating regions and singletons, as the cost-benefit analysis run for all PECs below will illustrate. This implies that international coalitions will have to be larger than PECs in practice.

Figure 7. **Sensitivity of the cooperative and non-cooperative solutions to alternative damage and discount rate assumptions**



Source: WITCH model simulations.

Table 1. **Potentially effective coalitions (PECs) to meet a 550 ppm CO_2eq target at the 2050 and 2100 horizons**

Panel A. PECs in 2050

Must participate	May not participate
	Any combination of the following regions:
1. Developed countries[1] , Latin America , Non-EU Eastern Europe (including Russia) , South East Asia , Middle East and North Africa	Africa , South Asia (Including India) , China
2. Developed countries[1] , Non-EU Eastern Europe (including Russia) , China , Middle East and North Africa	Africa , South Asia (Including India) , South East Asia , Latin America
3. Developed countries[1] , Non-EU Eastern Europe (including Russia) , China , South East Asia	Africa , South Asia (Including India) , Latin America , Middle East and North Africa
4. Developed countries[1] , China , South East Asia , Middle East and North Africa	Africa , South Asia (Including India) , Non-EU Eastern Europe (including Russia) , Latin America
5. Developed countries[1] , Latin America , China	Africa , South Asia (Including India) , Non-EU Eastern Europe (including Russia) , Middle East and North Africa , South East Asia
6. Developed countries[1] , Latin America , South Asia (including India), South East Asia, Middle East and North Africa	Africa , China , Non-EU Eastern Europe (including Russia)
7. Developed countries[1] , Non-EU Eastern Europe (including Russia), South Asia (including India), South East Asia, Middle East and North Africa	Africa , China , Latin America
8. Developed countries[1] , Latin America , Non-EU Eastern Europe (including Russia), South Asia (including India)	Africa , China , Middle East and North Africa , South East Asia
9. Developed countries[1] , South Asia (including India), China , South East Asia	Africa , Non-EU Eastern Europe (including Russia) , Middle East and North Africa , Latin America
10. Developed countries[1] , South Asia (including India) , China , Middle East and North Africa	Africa , Non-EU Eastern Europe (including Russia) , South East Asia , Latin America
11. Developed countries[1] , South Asia (including India), China	Africa , Latin America , South East Asia , Middle East and North Africa , Non-EU Eastern Europe (including Russia)

Panel B. PECs in 2100

Must participate	May not participate
	Any combination of the following regions:
1. Developed countries[1] , Non-EU Eastern Europe (including Russia), South Asia (including India), China , South East Asia, Middle East and North Africa	Africa , Latin America
2. Developed countries[1] , Latin America , Non-EU Eastern Europe (including Russia) , South Asia (including India) , China , South East Asia	Africa , Middle East and North Africa
3. Developed countries[1] , Latin America , South Asia (including India), China , Middle East and North Africa	Africa , Non-EU Eastern Europe (including Russia) , South East Asia

Note: Each row features one type of PEC. For instance, the first row of Panel A indicates that one type of PEC includes at a minimum all regions in the left column, along with, some (or none) of the regions in the right column.

1. Developed countries include Australia-Canada-New Zealand, Japan-Korea, United States , Western EU countries and Eastern EU countries.

Source: WITCH model simulations.

4.3. Environmental effectiveness, profitability and stability of climate coalitions

Environmentally effective coalitions

While PECs have the potential to achieve the illustrative 550 ppm CO_2eq target, it may not necessarily be optimal for them to do so. Therefore, in order to explore the environmental effectiveness of PECs, cost-benefit analysis is undertaken. Concretely, for each PEC, the optimal emission path chosen by the coalition, added to the optimal path of non-participating regions (singletons), is compared with the path needed to achieve the 550 ppm CO_2eq target. This cost-benefit analysis is undertaken first under the high-damage/low-discounting case, which is most conducive to significant emission reductions by the coalition considered. If a coalition is not environmentally effective in this case, it cannot be either under lower damages and/or a higher discount rate.

Among all possible PECs, only the grand coalition is found to stabilise GHG concentration at 550 ppm CO_2eq by 2100 if optimal emission paths – computed by solving the dynamic game in a cost-benefit framework – are considered. This is illustrated in Table 2, which shows the environmental performance of 6 out of the 11 PECs, other than the grand coalition, that have the technical potential to meet the target at the 2100 horizon. For illustrative purposes, these 6 PECs are chosen to be those that do not include Sub Saharan Africa – coalitions that include Africa but exclude other, richer developing regions may also be seen as politically unrealistic. Even if only Sub Saharan Africa behaves as a singleton, the target at 2100 is no longer reached, and the intermediate 2050 term target is barely achieved. Leaving an additional region out of the coalition raises concentration significantly above the target. Two main factors explain the failure of small coalitions to achieve the 550 ppm concentration target:

- The smaller the coalition, the less it internalises the environmental externality, the larger the gap between the private (coalition's) and the social marginal benefit from emission reduction, and the smaller the emission cuts achieved (Figure 8). However, there is univocal cut relationship between coalition size, coalition marginal damage and emission reductions, because damages are not evenly distributed among world regions. The presence of regions facing larger damages from climate change increases coalition marginal damage and the magnitude of emission cuts, *ceteris paribus* (Figure 9).

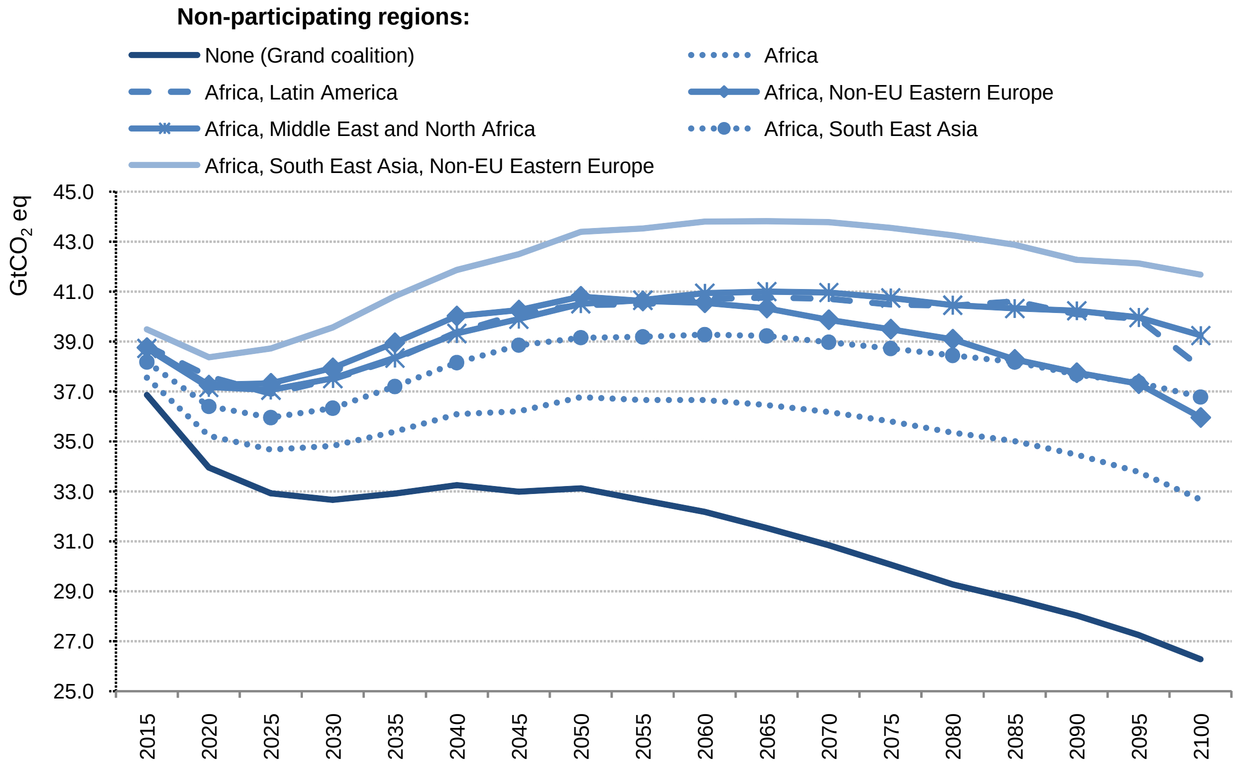
- The smaller the coalition, the larger the number of regions that can set their emissions freely and free-ride on the coalition's efforts.

Table 2. **Analysis of the environmental achievements of potentially effective coalitions, cost-benefit mode, high-damage/low-discounting case**

Overall GHG concentration (ppm CO_2 eq)		
	2050	2100
Non-participating regions:		
None (Grand coalition)	507	546
Africa	518	579
Africa, Latin America	532	612
Africa, Non-EU Eastern Europe	531	603
Africa, Middle East and North Africa	529	609
Africa, South East Asia	526	598
Africa, South East Asia, Non-EU Eastern Europe	529	603

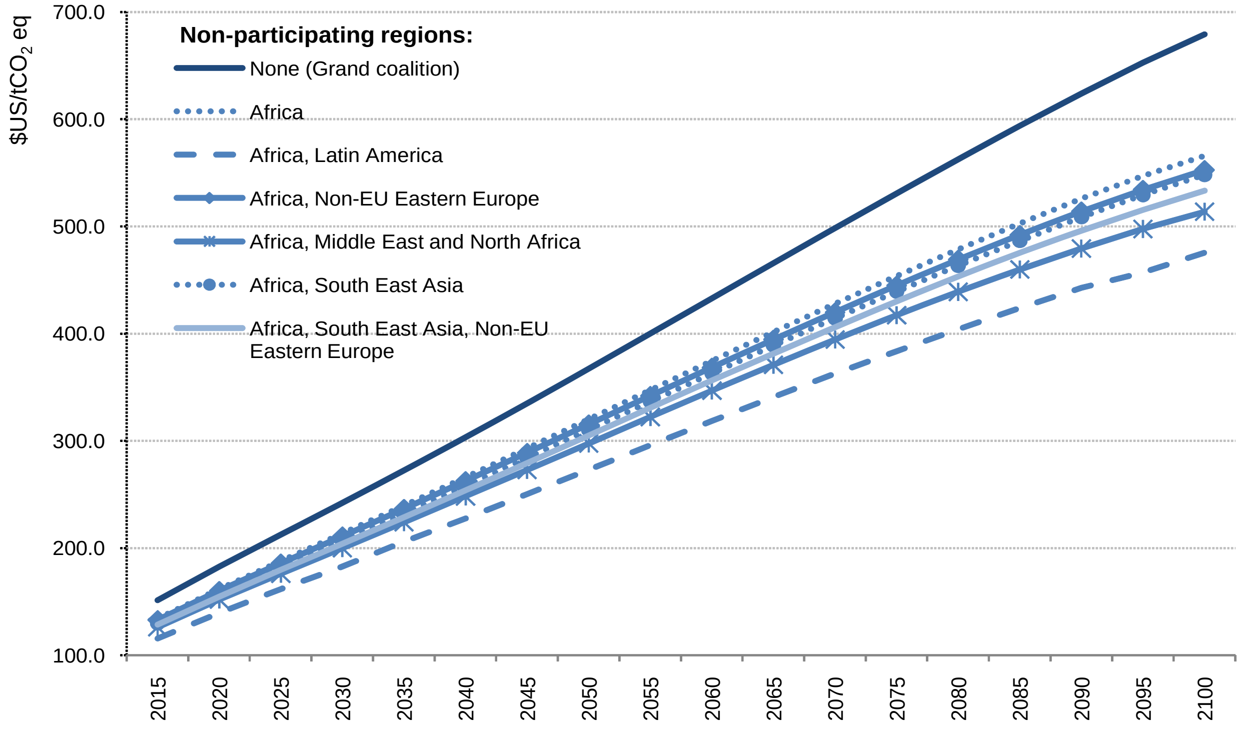
Source: WITCH model simulations.

Figure 8. **Optimal emission paths of 7 potentially effective coalitions at the 2100 horizon, cost-benefit mode**



Source: WITCH model simulations.

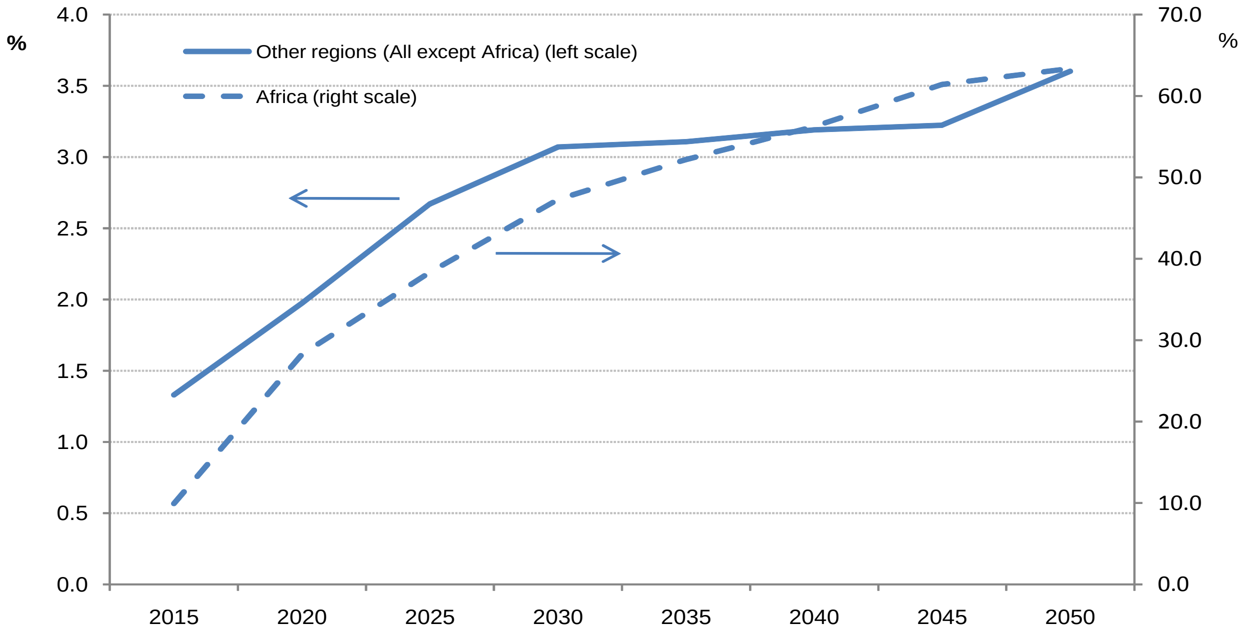
Figure 9. **Marginal damage from climate change for 7 potentially effective coalitions at the 2100 horizon, cost-benefit mode**



Source: WITCH model simulations.

These two forces undermining the achievement of the environmental target can be illustrated by looking at a coalition structure under which only Sub Saharan Africa does not participate and behaves as a singleton (Figure 10). First, compared with the grand coalition, a coalition that leaves out Sub Saharan Africa achieves significantly lower abatement effort, because the non-internalisation of the large damages incurred by that region lowers the marginal damage in the coalition. Second, the emissions of Sub Saharan Africa itself increase dramatically when it behaves as a singleton. However, it is worth noting that Sub Saharan Africa emits less when free-riding on a grand coalition than under a fully non-cooperative scenario, due to negative carbon leakage. In WITCH two forms of leakage are modeled. First, the abatement efforts of participating countries reduce the demand for, and therefore the world price of fossil fuels, thereby raising demand in non-participating countries. Second, in addition to such positive leakage, a "negative leakage" stemming from the higher R&D investments and faster emergence of carbon-free backstop technologies when some countries take action is modeled. Depending on the stringency of the target and the characteristics of the free riding country, one or the other leakage effect might prevail.

Figure 10. **An illustration of free-riding incentives: the case of Africa]**
Difference in GHG emissions between the grand coalition without Africa and the grand coalition, %



Source: WITCH model simulations.

Profitability, stability and the role of transfers

International climate coalitions need not only to be environmentally effective, but also to be formed in the first place through an international agreement. In the game-theoretic framework of this paper, a coalition can only exist if it is profitable and stable, or at least potentially stable:

- A coalition is profitable if the overall welfare of the coalition is larger than the sum of its members' welfare in the fully non-cooperative (BAU) scenario:

$$\sum_{i \in PEC} W_i(PEC) \geq \sum_{i \in PEC} W_i(Nash)$$

where $Wi(PEC)$ is the welfare of region i under the PEC considered, and $Wi(Nash)$ is the welfare of region i in the fully non-cooperative Nash equilibrium.

- A coalition is stable if the welfare of each participating region is larger or equal to the welfare it would obtain from staying out of the coalition and free riding on participants' abatement efforts:

  $$\forall i \in PEC, W_i(PEC) \geq W_i(PEC \setminus i)$$

- A coalition is Potentially Internally Stable (PIS) if there is a transfer scheme that gives each member its free-riding pay-off and shares the remaining surplus according to any redistribution rule:

  $$\sum_{i \in PEC} W_i(PEC) - \sum_{i \in PEC} W_i(PEC \setminus i) \leq surplus$$

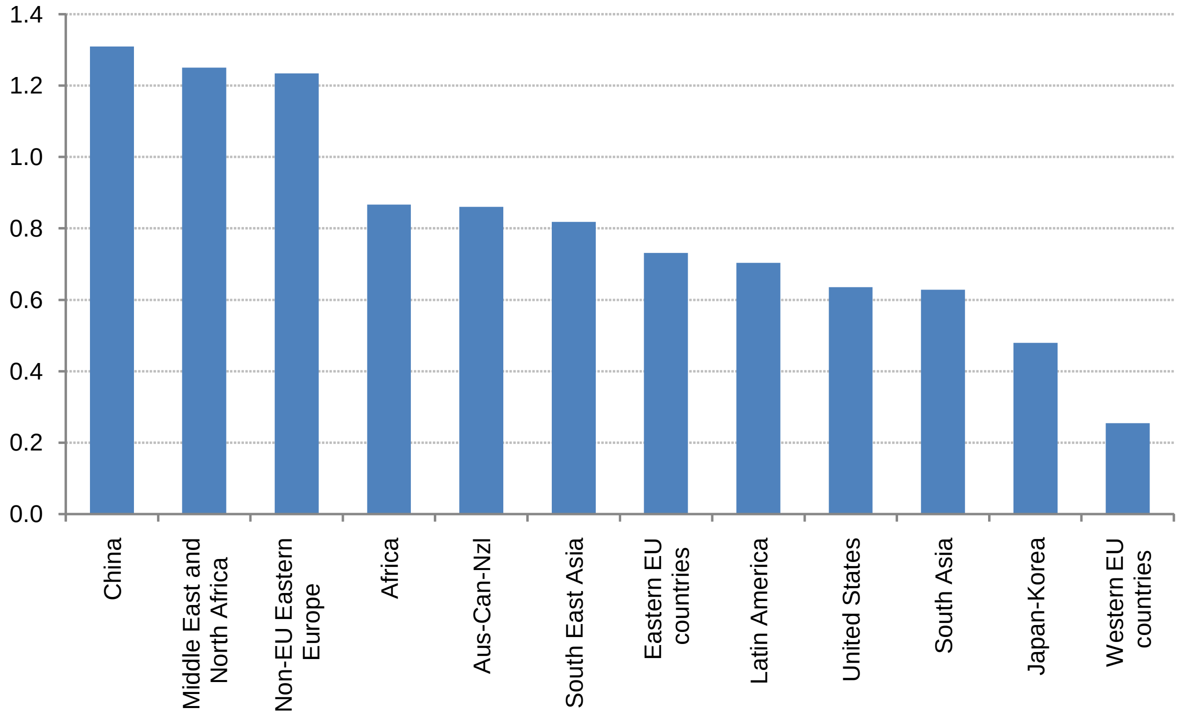
Although only the Grand Coalition is found to be environmentally effective, profitability and stability are assessed for all other, non effective PECs. As would be expected, all coalitions are found to be profitable. Environmental cooperation allows internalising externalities, and thereby increases collective welfare. Given that all PECs yield an aggregate welfare gain, there is always room for the countries that benefit most from participation to compensate the losers, so that everyone gains relative to a fully non-cooperative (BAU) scenario. Under the grand coalition for instance, developed countries gain while developing countries and non-EU Eastern European countries lose, but transfers from the former to the latter group of countries can deliver a gain to every participant. In the absence of transfers, China loses because it is more carbon intensive than most other regions, and therefore incurs larger costs from a single carbon price, *ceteris paribus* (see Section 3.3). Non-EU Eastern European countries are the major losers, being both carbon intensive economies and fossil fuel producers, and gaining less from cooperation than other regions in terms of avoided damages.

However, none of the PECs is internally or even potentially stable. This implies that in all coalition structures that can potentially achieve the 550 ppm CO_2eq target by 2100, there are always countries/regions that have an incentive to free-ride. This is because the overall welfare gain from the coalition relative to the non-cooperative outcome is not large enough to find a set of transfers that would give each country/region its free-riding pay off. Having compensated all losers in the coalition to achieve profitability, the remaining surplus is too small to offset free-riding incentives. Under the grand coalition for instance, the free-riding incentive of Sub Saharan Africa alone is found to outweigh the residual surplus. This conclusion holds even in the high-damage/low discounting scenario, and *a fortiori* under all other discount rate and climate damage assumptions.

Figure 11 shows the ranking of free-riding incentives across regions, based on the difference in (inter-temporal) welfare per capita between free riding on and participating in the grand coalition. China, the Middle East-North Africa region and non-EU Eastern European countries are estimated to have the largest per capita incentive to free ride. By contrast, developed countries have the lowest free-riding incentives, with the exception of the Australia-Canada-New Zealand region.

Figure 11. Estimated ranking of free-riding incentives across regions

Difference in welfare per capita[1] between free-riding on and participating in the grand coalition, in %



1. Average population over the period 2005-2100 is used to compute (discounted) welfare per capita.

Source: WITCH model simulations.

These findings are subject to a number of limitations:

- Even though some sensitivity analysis has been carried out to assess the robustness of the main results, it should be acknowledged that the model-based analysis relies on strong assumptions. In particular, there are wide uncertainties in practice surrounding future emission trends,[9] the market and non-market impacts from climate change, the likelihood and effect of catastrophic risks, and the cross-country distribution of these damages and risks.

- Furthermore, the analysis focuses on immediate, irreversible and self-enforcing participation to mitigation action, thereby abstracting from other possible bargaining options including *e.g.* delayed participation, renegotiation, sanctions or joint negotiation in multiple areas (*e.g.* linking climate and international trade negotiations. If feasible, these alternative bargaining options which might yield different results (see Annex 2). For instance, a major emitting country may have greater participation incentives than found here if it expects its withdrawal to prevent the formation of *any* coalition.

- The co-benefits from mitigation action, *e.g.* in terms of human health, energy security or biodiversity, are not taken into account. Previous OECD analysis indeed suggests that such

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[9] For instance, projected world BAU emission growth is somewhat higher in WITCH than in the OECD model ENV-Linkages as featured in Burniaux *et al.* (2008) (100% versus 85% over the period 2005-50).

co-benefits are large, although the participation incentives they provide are dampened by the fact that some of these co-benefits could be reaped through direct policy action – in particular, local air pollution might be reduced at a lower cost through direct policy action than through reductions in GHG emissions (Bollen *et al.* 2009; Burniaux *et al.* 2008).

- Removal of fossil fuel subsidies, one of the few policies to yield potentially both climate and economic benefits, is also omitted from the analysis. Insofar as phasing out subsidies would bring an economic gain and lower the carbon intensity of a number of (mainly developing) countries, incentives to participate in international mitigation action could improve.

Another potential limitation of the analysis is to assume that even if a country benefits from an international coalition relative to a BAU scenario, it will always prefer to free-ride if that option is even more profitable. While this assumption merely derives from individual welfare maximisation, current international redistributive policies such as official development aid point instead to some degree of altruism. Against this background, there might be a possibility for some countries to sign an agreement even if they could in principle gain more from free riding on other countries' abatement efforts. This is explored here by computing the cost for developed countries of using additional resources (additional to the coalition surplus) to stabilise the grand coalition, *i.e.* to give each other region its free-riding pay off. These calculations show that with a 3% loss in the discounted value of their consumption levels, industrialised countries could stabilise the grand coalition in the high-damage/low-discounting case, *i.e.* all other participating regions could be fully compensated for their free-riding incentives through financial transfers, thereby bringing them into an agreement.

5. Cost-effective analysis of climate coalitions

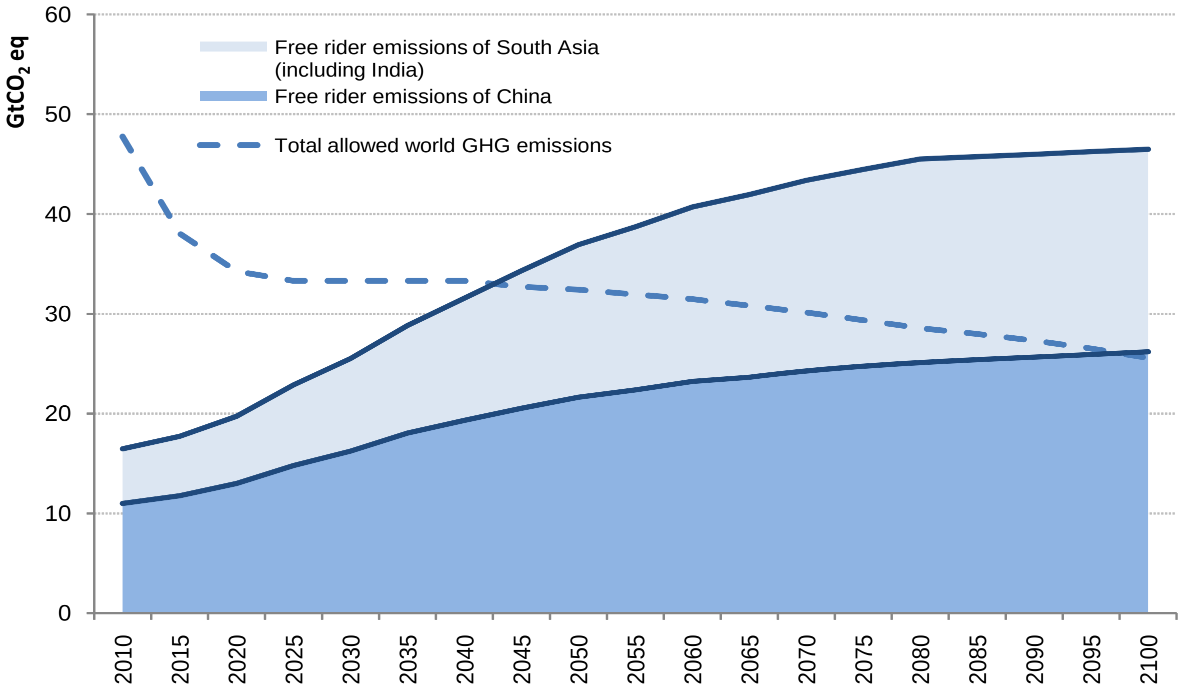
The previous sections have explored incentives to participate in, and the stability of, international climate coalitions. Here, a different approach is taken. The formation of a coalition is taken as given, and participating regions are assumed to set up an ETS, with a total amount of allowances consistent with the illustrative 550 ppm CO_2eq target. On this basis, two issues are explored: *i)* whether it would be economically – and not just technically – feasible for any of the PECs identified previously to reach the 550 ppm CO_2eq target, and if so at what cost; *ii)* how the cost of meeting the target could be distributed across participating countries through the allocation of emission reduction commitments, in a way that improves the prospects for broad-based participation. In both cases, the analysis implies running the WITCH model in cost-effective rather than cost-benefit mode. In a cost-effective mode, the emission path chosen by each region or coalition does no longer result from the optimal balance of cost and benefits associated with emission control. Rather, the coalition is committed to meet the global concentration target, regardless of the cost and the free-riding behaviour of non-participating countries.

5.1. Economically feasible coalitions

The economic feasibility analysis shows among the 12 PECs (including the grand coalition) that have the technical potential to meet the 550 ppm CO_2eq target at the 2100 horizon, only the grand coalition and the grand coalition minus Sub Saharan Africa can effectively do so. All the other PECs can meet the target in 2050 but not in 2100. Although the discussion below focuses on the high-damage/low-discounting case, this result is robust to alternative damage and discounting assumptions. The difficulty for smaller coalitions to achieve the target by 2100 is driven by two factors: *i)* as the coalition of acting countries shrinks, the burden of achieving a global concentration target falls on a smaller number of participants, implying larger and costlier cuts for each of them; *ii)* the smaller the number of participants, the larger the number of free-riding countries, and the higher their total emissions.

In order to understand why the 550 ppm CO_2eq target quickly becomes unattainable unless virtually all regions – with the exception of Africa – participate in the coalition, it is sufficient to look at the simulated behaviour of free-riders. For instance, Figure 12 provides an illuminating comparison between the maximum amount of emissions allowed to meet the target at the world level and the free-rider emissions of China and India. These free-rider emissions are those that would prevail in a scenario where mitigation action is taken by a coalition that excludes the region considered and Sub Saharan Africa.[10] If they free ride along with Sub Saharan Africa, China and India (South Asia) quickly absorb most of allowed global emissions. By mid-century, their emissions together account for total world emissions consistent with the 550 ppm CO_2eq target. As a consequence, cooperating countries are required to reduce their emissions to zero by mid-century, and eventually to deliver negative emissions. This makes it impossible for a coalition that excludes both China and India to meet the target. To a lesser extent, the same argument holds if other developing regions are allowed to free ride, in particular Latin America and the Middle East.

Figure 12. **Comparison between total world emissions allowed to meet a 550 ppm CO_2eq target and the free-rider emissions of China and India**



Source: WITCH model simulations.

For the two PECs that are economically effective at the 2100 horizon (grand coalition with and without Africa), the costs of meeting the 550 ppm CO_2eq target are estimated to be low in the high-damage/low-discounting case, compared with most of the existing literature – including earlier WITCH model estimates, see *e.g.* Bosetti *et al.* (2008). The high-damage assumption implies large income and consumption gains (avoided damages) from mitigation action. These gains reduce the net cost of action relative to BAU, and in fact generate increasingly large net gains starting from mid-century (Figure 13). Also, the version of the WITCH model used throughout this paper incorporates the emergence of two

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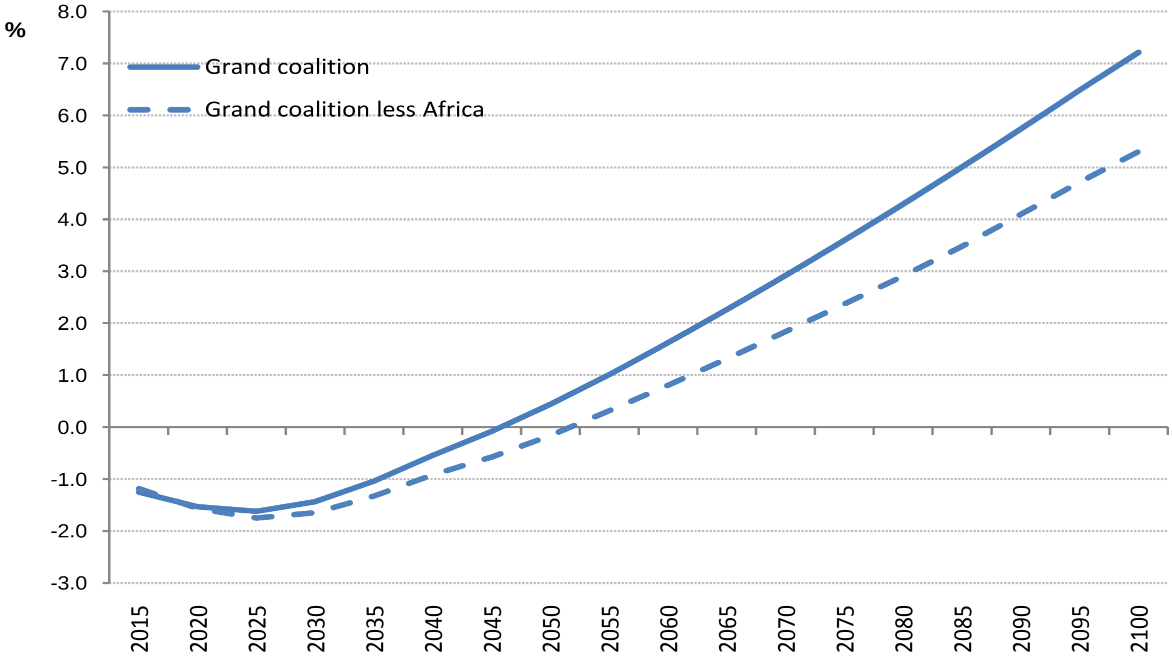
[10] These model simulations assume that cooperating countries operate in cost-effective mode while non-cooperative countries behave as singletons, *i.e.* they set their emissions at their optimal free-riding levels.

backstop technologies *via* dedicated R&D investments, which tend to reduce mitigation costs as time passes (see Annex 1, and Bosetti *et al.*, 2009).[11]

Figure 13. **Costs of meeting a 550 ppm CO_2eq target at the 2100 horizon, grand coalition with or without Sub Saharan Africa, high-damage/low-discounting case**

Difference in consumption levels relative to BAU scenario, in %



Note: Negative (positive) figures indicate costs (gains).

Source: WITCH model simulations.

While 11 PECs other than the grand coalition can meet the 550 ppm CO_2eq target at the 2050 horizon, the costs incurred by smaller PECs – those that exclude two or even three regions – are much higher than those incurred by the grand coalition. This is illustrated in Figure 14 for the 6 PECs (out of 11) that do not include Sub Saharan Africa. For instance, the consumption loss relative to BAU reaches over 8% in 2050 under a coalition excluding Africa, South East Asia and non-EU Eastern European countries (including Russia), versus almost zero under the grand coalition (Panel A). Carbon prices mirror this sensitivity of economic costs to coalition size, reaching over $US2 000 in 2050 for the smallest PEC (Panel B). The implication from this analysis is that free riding by just one or two regions – even smaller than China and India, both of which are included in all PECs – makes it much costlier for other countries to meet an environmentally effective climate target.

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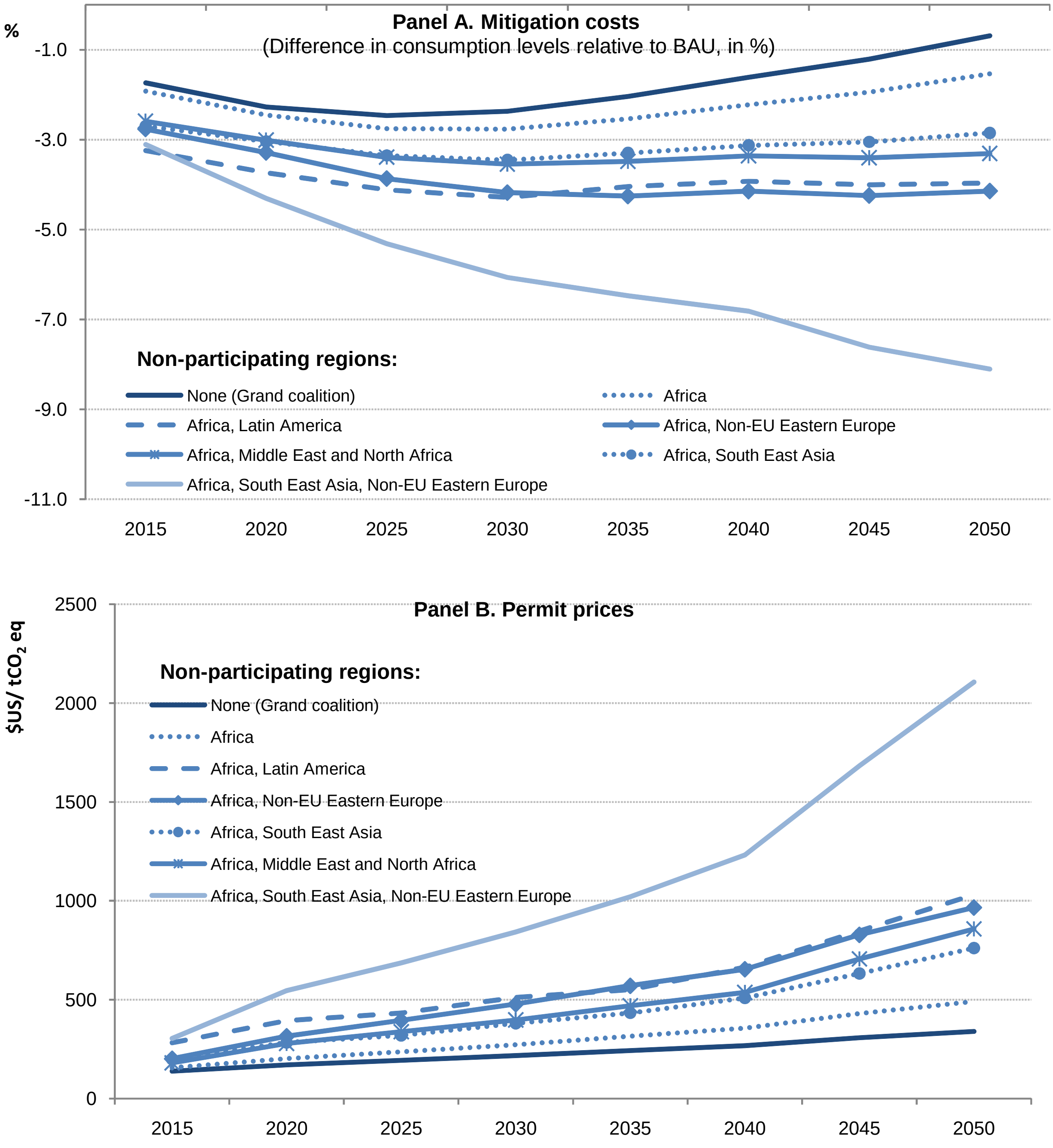
[11] Costs are also somewhat lower than under a similar cost-effective 550 ppm CO_2eq scenario with breakthrough technologies explored in other recent work using the WITCH model (Bosetti *et al.,* 2009). This reflects the fact that non-CO_2 GHGs and forestry emissions have now been incorporated in the WITCH model (see Annex 2). Also, the high-damage rather than low-damage case is considered here, which further reduces net mitigation costs.

Figure 14. **Costs of meeting a 550 ppm CO_2eq target and associated carbon prices for 7 potentially effective coalitions at the 2050 horizon, high-damage/low-discounting case**



Note: In Panel A, negative (positive) figures indicate costs (gains).
Source: WITCH model simulations.

5.2. Allocation rules and the distribution of mitigation costs across countries

Although the analysis in Section 4 highlighted the difficulty to design a set of international transfers that ensures the stability of an environmentally effective coalition, there is little doubt that transfers can improve the prospects for broad-based participation in international action against climate change. In practice, one powerful way to implement such transfers is through the allocation of emission reduction commitments across countries, under any agreed global target. Allocation rules create a disconnection between who takes action – ensuring mitigation action takes place wherever it is least cost – and who pays for that action. They could therefore be designed to shift at least some of the burden away from developing countries, which in general have larger free-riding incentives than their developed counterparts.

To explore how the gains from participation in a world agreement could vary across alternative rules, the illustrative 550 ppm CO_2eq scenario is run in cost-effective mode under six simple rules: *i)* full permit auctioning (equivalent to a world carbon tax); *ii)* grandfathering, under which emission rights are allocated based on each country's share of global emissions in 2005; *iii)* a per capita rule, under which the same amount of allowances is granted to every human being; *iv)* an ability-to-pay rule that allocates allowances every year to each human being in inverse proportion to its GDP per capita ratio *vis-à-vis* the world average;[12] *v)* a "historical responsibility" rule that grants allowances to each region in inverse proportion to its contribution (in per cent) to cumulative world CO_2 emissions over the period 1900-2004 (Figure 15);[13] and, *vi)* a "BAU" rule under which the amount of allowances allocated to non-Annex I regions covers their projected BAU emissions, close to what would happen under a well-functioning crediting mechanism with generous baselines. The latter rule implies that Annex I regions set their cap at whatever level is required to meet the 550 ppm CO_2eq target – implying a negative emission level objective by 2035, given the fast projected BAU emission growth in most developing countries.[14]

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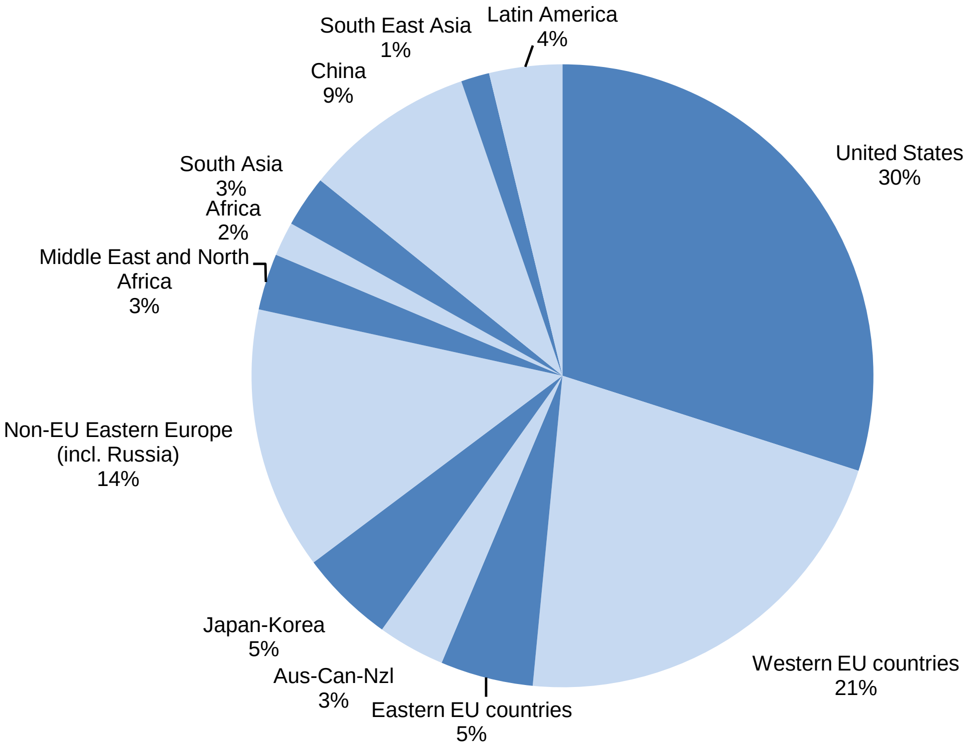
[12] There is not straightforward way to implement an ability-to-pay rule in practice. Here, this is achieved in three steps. In a first step, the amount Xi of world allowances that each region i would receive if allocation was proportional to the ratio of GDP per capita to the world average is computed as (total world allowances / world population)*(GDP per capita of region i / average world GDP per capita)*(population of region i). In a second step, the inverse (1/ Xi) of this amount is computed for each region. Unlike the sum of Xi, the sum of (1/ Xi) is not equal to total world emissions. Therefore, in a third step, a normalisation is applied, *i.e.* each region's share (in %) of total world allowances is computed as (1/ Xi)/[Σi(1/ Xi)].

[13] This also requires a "normalisation" along the lines of that used for the ability-to-pay rule.

[14] The overall Annex I cap is assumed to be then allocated across Annex I regions on a per-capita basis.

Figure 15. **Contribution of each world region to cumulative world emissions over 1900-2004]**

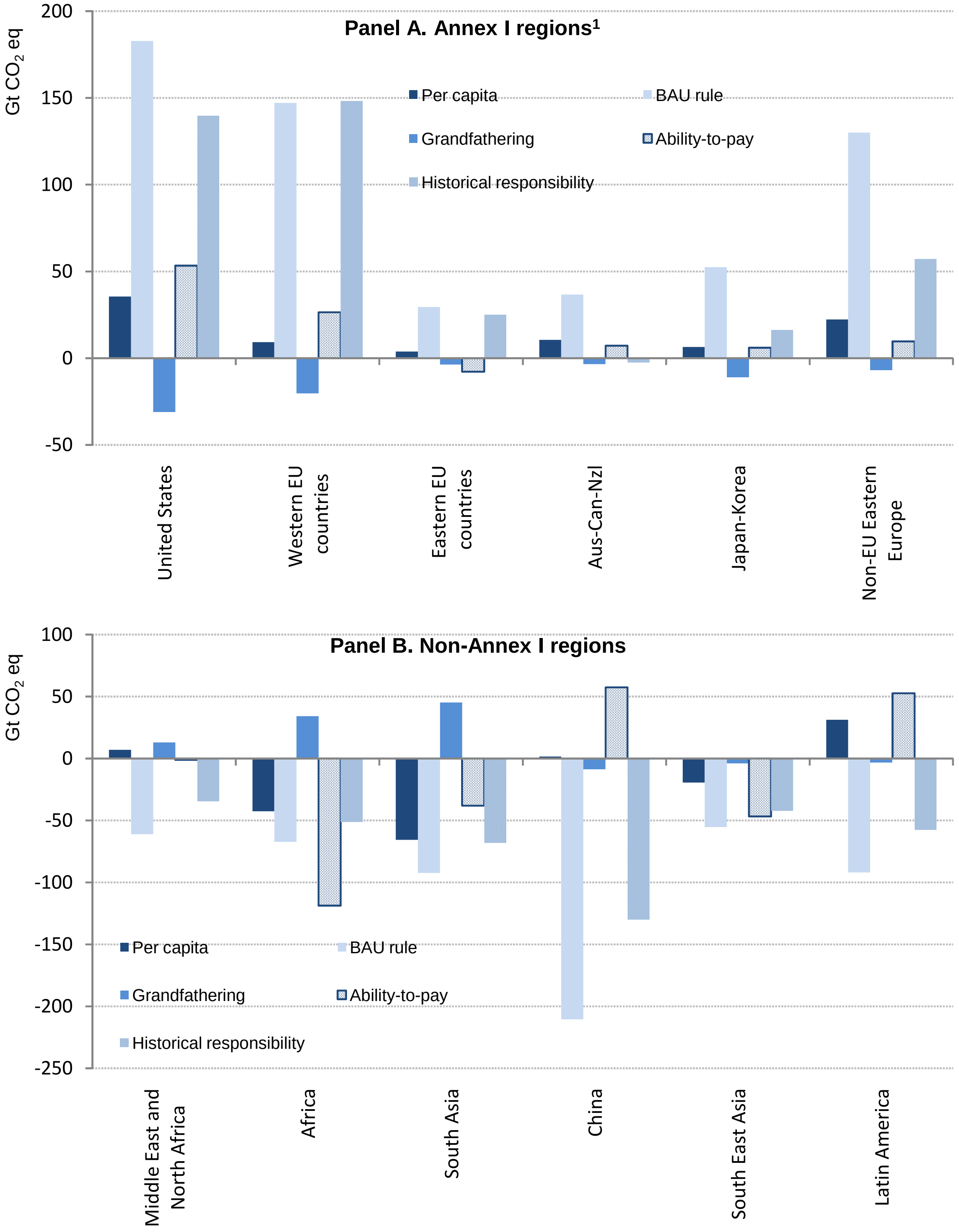


1. Excluding emissions from Land Use, Land-Use Change and Forestry.
Source: World Resources Institute (WRI).

The costs and gains from international mitigation action are found to vary drastically across alternative allocation rules for each world region, even though overall costs at the world level are roughly unchanged and – as already noted – fairly low. This reflects the wide variance in the sign and magnitude of regions' net permit imports (Figure 16). By 2050, developed regions are projected to lose significantly under the historical responsibility and – even more so – "BAU" allocation rules, but to gain under grandfathering and full auctioning (Figure 17). Non-EU Eastern Europe (including Russia) loses under all rules except grandfathering. This is because it is highly carbon-intensive, produces fossil fuels and faces limited damage from climate change.

Figure 16. **Cumulative net imports of emission permits up to 2100 under the grand coalition, 550 ppm CO_2eq target, cost-effective mode]**

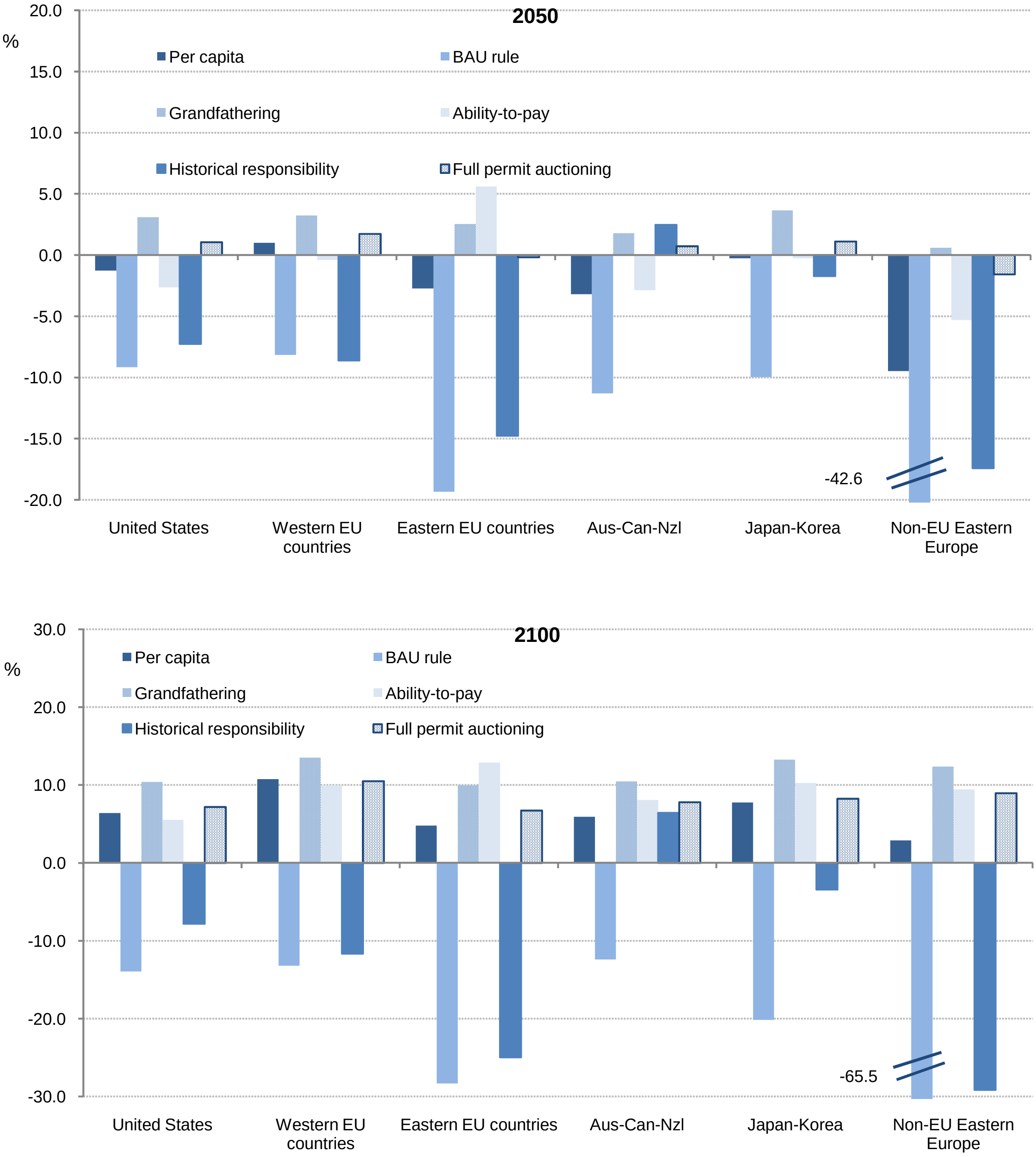
High-damage/low-discounting case



1. Korea is grouped with Japan, but is not an Annex I country.

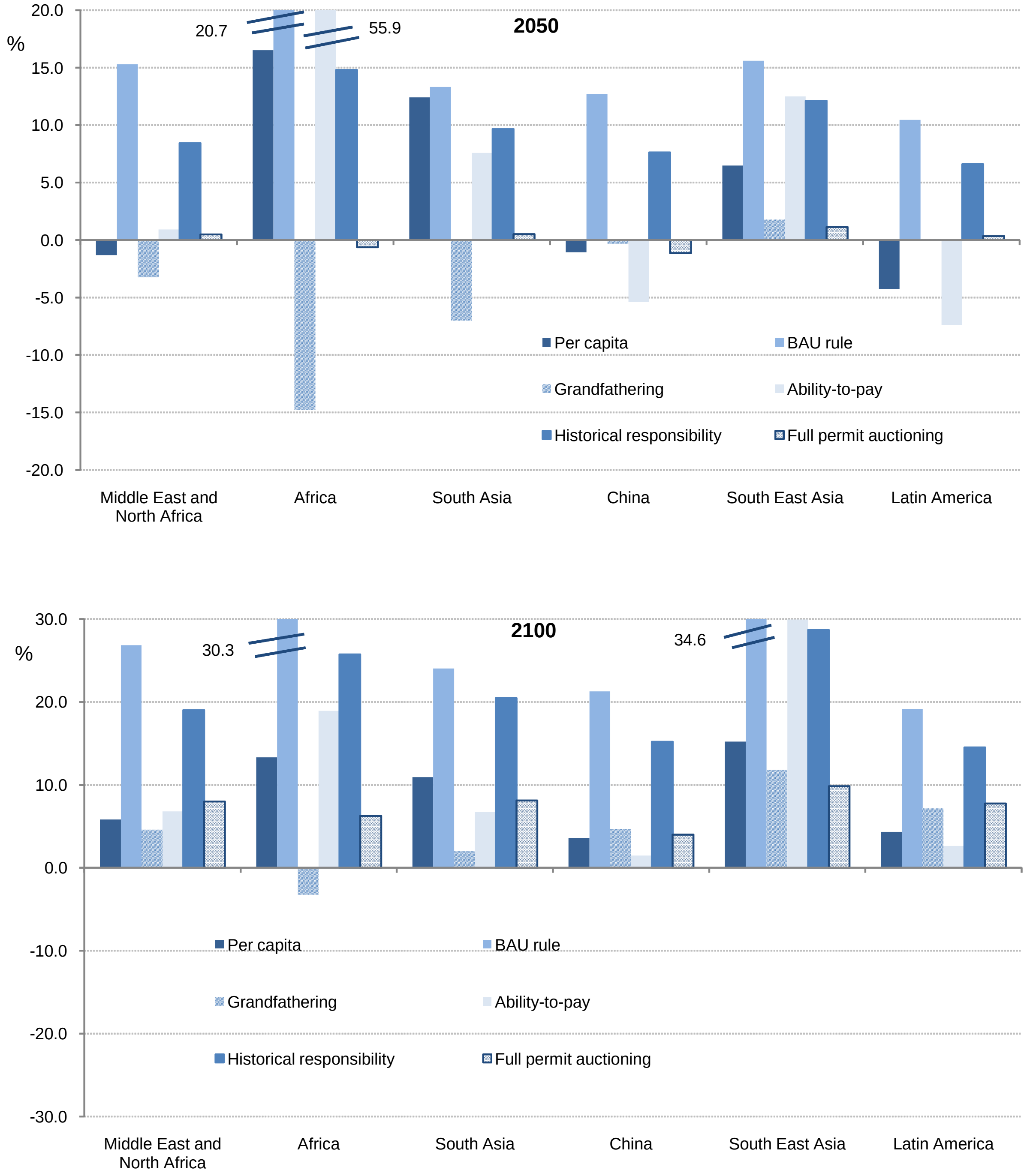
Source: WITCH model simulations.

Figure 17. **The impact of permit allocation rules on the costs of mitigation action, Annex I regions**
Difference in consumption levels relative to BAU, high-damage/low discounting rate



Note: Negative (positive) figures indicate costs (gains).
Source: WITCH model simulations.

Figure 18. **The impact of permit allocation rules on the costs of mitigation action, non-Annex I regions**
Difference in consumption levels relative to BAU, high-damage/low discounting rate



Note: Negative (positive) figures indicate costs (gains).
Source: WITCH model simulations.

Conversely, developing countries gain most from "BAU" and (to a lesser extent) historical responsibility allocation rules, with the exception of Africa which benefits most from an ability-to-pay rule, due to low income-per capita levels (Figure 18). An equal-per-capita rule benefits South Asia (including India) but not China, reflecting faster projected demographic growth and lower carbon intensity in the former region. Overall, given the heterogeneity of outcomes across alternative scenarios, there may be room for achieving any given set of transfers – and therefore any given distribution of mitigation costs across countries – through a combination of the simple allocation rules considered here.

On average, developing regions gain more than their developed counterparts, reflecting larger benefits from avoided climate change, especially in the high-damage case considered here. Avoided damages influence the distribution of policy costs especially during the second half of the century, when they become significant. By 2100, all regions benefit from the mitigation action of a grand coalition regardless of the allocation rule, with the exception of developed countries and non-EU Eastern Europe under the historical responsibility and "BAU" rules, which become increasingly stringent over time.[15]

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[15] However, it should be stressed again that countries might gain from an international agreement but still not have sufficient incentives to participate if the gain from free-riding is larger.

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ANNEX 1. THE WITCH MODEL: NEW FEATURES

Full details on the WITCH model can be found in Bosetti *et al.* (2007). This annex provides an update on the most recent features of the WITCH model as used for this project. This latest version of WITCH, henceforth referred to as WITCH08, incorporates more recent data and revised estimates for future projections of the main exogenous drivers. The base calibration year has been set at 2005, for which economic, energy and environmental variables data are now available. For the purpose of this study, the regional aggregation of countries in the model has also been changed in a way that puts more emphasis on political relevance in the context of climate coalition analysis than on similarities in the energy sector.

New regional aggregation and updated economic assumptions

The regional aggregation of WITCH06 was based on geographic, economic and technological vicinity. In some cases, similarities in terms of the structure of the energy sector were considered, and countries were grouped together to reproduce regional aggregates with homogenous energy demand and supply. However, this led to some unconventional matches from an international policy standpoint. In order to address this shortcoming, the WITCH06 regions CAJANZ (Canada, Japan, New Zealand), KOSAU (Australia, South Africa, Korea) and SSA (Sub-Saharan Africa without South Africa) have been changed into AUCANZ (Australia, Canada, New Zealand), JPNKOR (Korea, Japan) and SSA (Sub‑Saharan Africa, South Africa) in WITCH08. The model has been re-calibrated to accommodate for the new regional aggregation. The new baseline has been tested to match relevant observed patterns in WITCH08. Other regional aggregates have remained unchanged, so that the 12 regions of the WITCH08 model are now:

- United States (USA)
- Western EU countries (WEURO)
- Eastern EU countries (EEURO)
- Japan and Korea (JPNKOR)
- Australia, Canada and New Zealand (AUCANZ)
- Non-EU Eastern European countries, including Russia (TE)
- Latin America, Mexico and Caribbean (LAM)
- Middle East and North Africa (MENA)
- South Asia, including India (SASIA)
- China, including Taiwan (CHINA)
- Sub‑Saharan Africa and South Africa (SSA)
- South East Asia (EASIA)

The model's base year has been updated to 2005, and the most recent UN population projections are used for the period up to 2050.[16] For the period 2050 to 2100, updated data are not available, and less recent, longer term UN projections are used instead.[17] The differences in the two datasets are smoothed by

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[16] See http://unstats.un.org/unsd/cdb/cdb_simple_data_extract.asp?strSearch=&srID=13660&from=simple.

[17] United Nations (2004), *World Population to 2300*, Report No. ST/ESA/SER.A/236, Department of Economic and Social Affairs, Population Division, New York.

extrapolating population levels (at 5-year intervals) beyond 2050 using average projected growth rates over 2050-2100. Similar techniques are used to project population trends beyond 2100. Population in 2005 equals roughly 6.5 billion, and peaks in 2070 at almost 9.6 billion, slightly decreasing thereafter to reach 9.1 in 2100.

The GDP data for the new base year are from the World Bank Development Indicators 2007, and are reported in 2005 $US, using market exchange rates (MERs),. Global gross world product in 2050 is projected to be 3.9 times higher than 2005 levels. This is somewhat higher than the 3.5-fold increase in detailed recent long-run OECD projections (Duval and de la Maisonneuve, 2009). World growth rates start at around 4% per year, declining to 2.5% per year around mid-century. This comes along with substantial income convergence across countries, although per capita differences remain substantial.

The prices of fossil fuels and exhaustible resources have been revised upwards, factoring in the sharp increases in market prices between 2002 and 2005. Base year prices have been calibrated following Enerdata, IEA WEO2007 and EIA AEO2008. The 2005 international prices for exhaustible resources are set at $US55 per barrel for oil, or roughly $US8 per GJ, $US7.14 per GJ for natural gas, and $US60 per ton for coal, equivalent to $US2 per GJ.

Non-CO_2 emissions

WITCH06 only considered explicitly industrial CO_2 emissions, while other non-CO_2 gases, together with aerosols, entered the model in an exogenous and aggregated manner, as a single radiative forcing component. WITCH08 takes a step forward and specifies non-CO_2 gases, modelling explicitly emissions of CH_4, N_2O, SLF (short-lived fluorinated gases, *i.e.* HFCs with lifetimes under 100 years) and LLF (long-lived fluorinated, *i.e.* HFCs with long lifetime, PFCs, and SF6). SO_2 aerosols, which have a cooling effect on temperature, are also identified.

Since most of these gases are determined by agricultural practices, the modelling relies on estimates for reference emissions, and a top-down approach for mitigation supply curves. For the baseline projections of non-CO_2 GHGs, EPA regional estimates are used.[18] The regional estimates and projections are available until 2020 only. Beyond that horizon, growth rates for each gas are taken from the IIASA-MESSAGE-B2 scenario,[19] which underlying assumptions similar to WITCH's. SO_2 emissions are taken from MERGE v.5[20] and MESSAGE B2. Given the very large uncertainty associated with aerosols, they are translated directly into the temperature effect (cooling), so that only the radiative forcing deriving from GHGs is reported in this paper. In any case, sulphates are expected to be gradually phased out over the next decades, so that the two radiative forcing measures would eventually converge to similar values.

The equations translating non-CO_2 emissions into radiative forcing are taken from MERGE v.5. The global warming potential methodology is employed, and figures for global warming potential and the base year stocks of the various GHGs are taken from IPCC's FAR, Working Group I. The simplified equation translating CO_2 concentrations into radiative forcing has been modified from WITCH06, and is now in line with IPCC.[21]

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[18] EPA Report 430-R-06-003, June 2006. the report is available from:
http://www.epa.gov/climatechange/economics/mitigation.html

[19] Available at http://www.iiasa.ac.at/web-apps/ggi/GgiDb/dsd?Action=htmlpage&page=regions

[20] http://www.stanford.edu/group/MERGE/m5ccsp.html

[21] http://www.grida.no/climate/ipcc_tar/wg1/222.htm, Table 6.2, first row.

End-of-pipe type of abatement possibilities are introduced *via* marginal abatement curves (MACs) for non-CO_2 GHG mitigation. The MACs provided by EPA for the EMF 21 project are used,[22] aggregated for the WITCH regions. MACs are available for 11 cost categories ranging from $US10 to 200 per ton of carbon. Zero or negative cost abatement options are ruled out. MACs are static projections for 2010 and 2020, and for many regions they show very low upper values, so that even at maximum abatement, emissions would keep growing over time. Therefore exogenous technological improvements are introduced. For the highest cost category only ($US200 per ton of carbon), a technical progress factor is assumed that reaches 2 in 2050 and the upper bound of 3 in 2075. However, an upper bound to the amount of emissions which can be abated is set, assuming that no more than 90% of each gas emissions can be mitigated. Such a framework allows to keep non-CO_2 GHG emissions somewhat stable in a stringent mitigation scenario (530 ppm CO_2eq) in the first half of the century, before some gradual decline subsequently. This path is similar to what is found in the CCSP report,[23] as well as in MESSAGE stabilisation scenarios. Nonetheless, the very little evidence on technology improvements potential in non-CO_2 GHG sectors indicates that sensitivity analysis needs to be performed to verify the impact on policy costs. Figure A1.1 shows the projected contributions of each of the model's regions to CO_2 and non-CO_2 emissions by 2050 in a BAU scenario. Some regions that account for a small share of CO_2 emissions account for a much larger share of non-CO_2 emissions, such as Africa, Latin America and South Asia (including India). Developing countries, the Middle East and non-EU Eastern European countries account for the bulk of non-CO2 emissions.

Forestry

Reducing emissions from deforestation and degradation (REDD) is estimated to offer sizeable low-cost abatement potential. WITCH08 includes a new baseline projection of land use CO_2 emissions, as well as estimates of the global potential and costs for reducing emissions from deforestation, assuming that all tropical forest nations can join an emission trading system and have the capacity to implement REDD programs. These data are based on one of the leading economic models of global forests, the IIASA cluster model prepared for the U.K. Office of Climate Change as part of the recent *Eliasch Review* (2008).[24]

Technological Innovation

WITCH08 includes two backstop technologies – one in the electricity sector and the other in the non-electricity sector – that necessitate dedicated innovation investments to become competitive at market prices, even in a scenario with a climate policy. In line with the most recent literature, the costs of these backstop technologies are modelled through a so-called two-factor learning curve, in which their price declines both with investments in dedicated R&D and with technology diffusion. This improved formulation is meant to overcome the limitations of single factor experience curves,[25] providing a more structural, R&D investment led approach to the penetration of new technologies.

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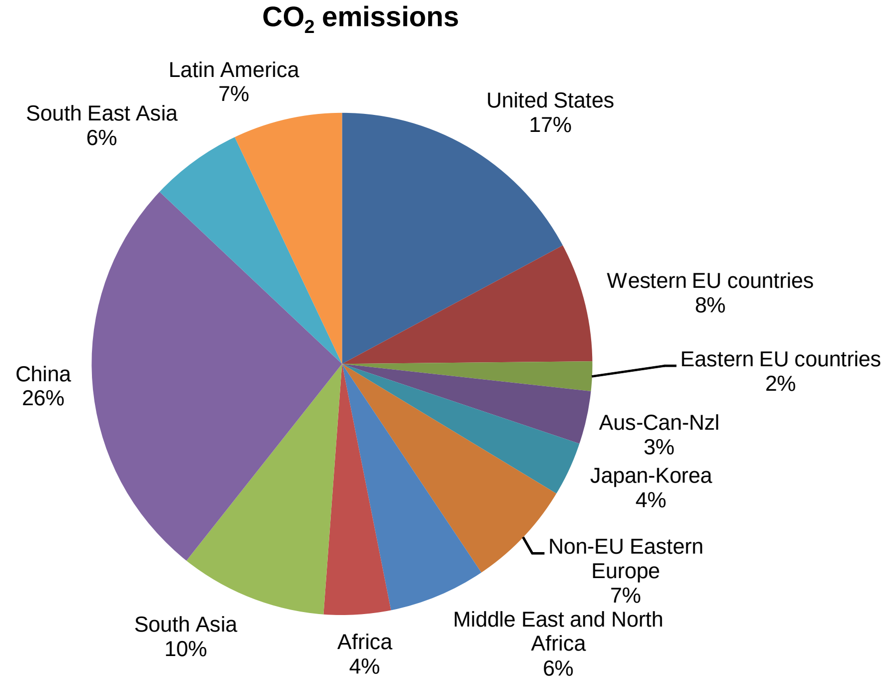
[22] http://www.stanford.edu/group/EMF/projects/projectemf21.htm

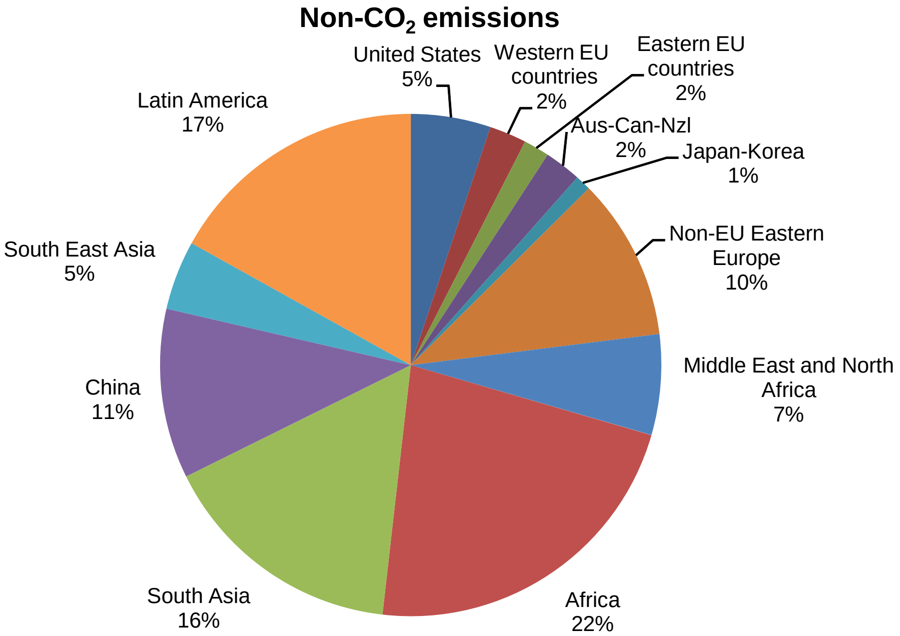
[23] http://www.climatescience.gov/Library/sap/sap2-1/finalreport/default.htm

[24] Eliasch J. (2008), Climate Change: Financing Global Forests, *The Eliasch Review*, available at http://www.occ.gov.uk/activities/eliasch.htm

[25] Nemet (2006).

Figure A1.1. **Geographical decomposition of projected CO2 and non-CO2 emissions in 2050, BAU scenario**





Source: WITCH model simulations.

More specifically, the two-factor learning curve formulation models the investment cost in a backstop technology as being driven by a learning-by-researching process and by learning by doing.[26] The former is the main driving force of cost declines before the adoption of the backstop technology, while the latter is the main driving force after adoption. The initial prices of the backstop technologies at set at arbitrarily high levels, corresponding to roughly 10 times the 2005 price of commercial equivalents ($US16 000 per kW for electric, $US 550 per bbl for non-electric). The cumulative deployment of the technology is initiated at 1 000twh and 1 000EJ respectively for the electric and non-electric backstops, an arbitrarily low value.[27] The backstop technologies are assumed to be renewable, in the sense that the fuel cost component is negligible. For power generation, it is assumed to operate at load factors comparable with those of baseload power generation.

The backstops are assumed to substitute linearly for nuclear power in the electric sector, and for oil in the non-electric one. However, once the backstop technologies become competitive as a result of dedicated R&D investment and pilot deployments, their uptake is not be immediate and complete. Instead, a transition period is assumed. An upper limit is set on the penetration of each backstop, equal to 5% of total consumption in the previous period by technologies other than the backstop, plus the electricity produced by the backstop itself.

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[26] Kouvaritakis *et al.* (2000).

[27] Kypreos (2007).

ANNEX 2. COALITION THEORY: A SELECTIVE SURVEY

Introduction to climate change control as a global public good

Long-lived GHGs have two peculiar characteristics. First, no matter where the initial source of emission is, they have the same impact on global GHG concentrations and, ultimately, temperature and the climate. Emissions from any source, anywhere in the world, yield a global negative externality. Second, long-lived GHGs remain in the atmosphere from decades to centuries. The fact that the negative effects of present emissions are delayed into the future is the source of another externality, of an inter-temporal and inter-generational nature. The presence of horizontal (among individuals at different locations, at the same time) and vertical (among individuals at the same location, at different points of time) externalities enhances the scope for strategic behaviour and calls for an analytical framework capable of dealing with these complex interactions. Game theory has thus emerged as the natural approach to study policies to counteract global climate change.

WITCH has a game theoretic structure that allows modelling the strategic interactions among players and the related free-riding incentives. The intertemporal equilibrium of the dynamic game that captures these interactions can be computed both as an open-loop non-cooperative Nash equilibrium, and as a Nash cooperative solution. In this latter case, any potential coalition structure can be implemented and analysed. WITCH is thus particularly suited to perform analysis of the incentives to participate in international climate agreements. When checking for stability and profitability of coalitions, the solution concepts that are implemented in WITCH are well rooted in the theoretical literature. The model is solved as a one-shot meta-game, with a first stage in which coalitions are formed, and a second stage in which countries choose the optimal level of emissions. In the second stage, coalition members maximise aggregate joint welfare, whereas free-riders behave as singletons and maximise individual welfare. Equilibrium is found employing the γ-characteristic function approach (Chander and Tulkens, 1997), *i.e.* with WITCH the unique Nash equilibrium is computed in which coalition members jointly play their best response to non-coalition members, who adopt individually their best-reply strategies.

The following section lays out the theoretical ground for the game structure of the WITCH model and summarises the wide set of issues explored in the existing literature on non-cooperative coalition formation.

Cooperative coalition theory

A starting point is to consider a simplified setting in which players bargain over the provision of a global public good, which here is assumed to be emission (and climate change) control. Emissions of GHG are associated with higher welfare because they allow production of useful goods and services. However, the build up of emissions in the atmosphere increases concentrations and global mean temperature with a long lasting impact on climate and negative consequences on welfare of all countries.[28] Reducing GHG emissions is assumed to be costly because new technologies have to developed and adopted. Nonetheless, lower emissions reduce concentrations and the associated negative impacts of climate change, thus increasing welfare.

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[28] We assume here for simplicity that impacts are negative. Although, as detailed in Section 3, it likely that some world regions will benefit from climate change, at least at some point in time.

A first approach to study this problem in a game theoretic set up is along the lines of the so-called *cooperative approach* to the *bargaining problem*. In this approach, interactions among countries are modelled as a one-shot simultaneous game, and lead either to full cooperation or to free-riding. If the benefits from a higher provision of the global public good are widely dispersed in space and in time, whereas costs are instead high and private as in the case of the climate problem, free-riding inevitably prevails and the global common resource is spoiled, leading to the well-known "tragedy of the commons".

However, the strategic interactions outlined in the above Prisoner's Dilemma game are rather crude and do not correspond to the observed behaviour of countries facing global externalities. The non-cooperative outcome is not the optimal outcome, and it is possible for players of the game to devise bargaining strategies that lead to higher levels of cooperation. In fact, international cooperation does exist, albeit at different degrees, on a wide range of issues of common interest. In particular, the last decades have seen the emergence of international treaties to protect global common goods. This raises the question as to why those treaties come into existence and are enforced while individual countries would in principle benefit from free-riding.

A first step towards a richer analytical framework has focused on the recurring interaction among world countries. It has been shown that, under suitable conditions, the simple repetition of the basic Prisoner's Dilemma game may lead to cooperation. A group of studies have therefore characterised outcomes in which all world countries cooperate towards the common environmental goal (Maler, 1989; Barrett, 1992). However, games structured to deliver full cooperation are as inadequate to describe the observed strategic behaviour of players as those in which free-riding incentives impede any form of cooperation. Indeed, what seems most relevant in practice is a situation in which some of the countries join a coalition and cooperate on emission reductions, whereas other countries behave as singletons and free ride on cooperating countries' emission reductions.

Non-cooperative coalition theory

The absence of any intermediate form of cooperation is indeed the most limiting characteristic of the cooperative approach to the bargaining problem. A particularly striking limit of this approach is that rational decision-makers are assumed to choose the most efficient solution regardless of the specific bargaining process followed to reach the final equilibrium (Carraro, Marchiori and Sgobbi, 2006). For example, the one-shot Prisoner's Dilemma game does not capture the fact that countries interact repeatedly, that they learn from each other's past actions, that they can commit themselves to certain decisions, and can design mechanisms to enhance cooperation and deter non compliance with international norms. The standard bargaining theory also does not capture the complex decision process through which countries agree on a set of rules that govern the bargaining process itself, and consequently shape the final outcome.

All the above issues are instead at the core of *non-cooperative coalition theory*. This modern approach to the *bargaining problem* addresses the whole process of negotiation. This leads to a characterisation of players' incentives that finally allows intermediate degrees of cooperation to emerge. The simplest case to consider is that of a simultaneous one-shot game. This game can be ideally decomposed into two stages. In the first step – the *coalition game* – countries decide whether or not to cooperate. In the second step – the *policy game* – countries choose the optimal level of carbon emissions. The decision in the first step is influenced by what countries perceive to be the optimal strategies of all other countries in the second step of the game. In this game setting, Carraro and Siniscalco (1993) have shown that partial cooperation is fully rational and can emerge as the outcome of the *non-cooperative* game. They show that the bargaining process may lead to different degrees of cooperation. If all countries form a coalition to control global emissions it is said that "*full cooperation*" is achieved; the case in which only a subset of world countries join the coalition is instead defined as "*partial cooperation*". The non-cooperative case is still a possible equilibrium of the game (see Carraro and Marchiori, 2003 for a full characterisation of all possible outcomes of the game).

Non-cooperative coalition theory has shown that countries can endogenously form coalitions in many different combinations. Indeed, most recent developments in coalition theory have focused on: *i)* the characterisation of coalitions at the equilibrium – in particular, the necessary conditions for coalitions to form and to remain stable have been explored; *ii)* the optimal size and the optimal number of coalitions under many different assumptions on the rules of the game; and, *iii)* mechanisms that can foster coalition formation and enhance their stability, among which transfers and issue linkage are the most prominent (Carraro, Eyckmans and Finus, 2006).

These three broad issues are reviewed below, starting from the characterization of the properties of *profitability* and *stability* of a coalition and using as a benchmark the one-shot, simultaneous game. In the first stage of this game, players choose whether or not to cooperate. In the second stage, they act cooperatively if they sign the agreement, or play a non-cooperative Nash game against the coalition if they find it more profitable to behave non-cooperatively.

Profitability, stability and the γ-game

Profitability and stability as necessary conditions for coalitions

For a coalition to exist, it must be both *profitable* and *stable*. A coalition is said to be *profitable* if signatory countries – the coalition members – have a higher welfare than in a scenario where the coalition is not formed. This is a necessary but not sufficient condition for the coalition to be formed. A second requirement concerns *stability*. A coalition is said to be *stable* if it is *internally* and *externally* stable. A coalition is *internally stable* if signatory countries do not have the incentive to defect and to behave non-cooperatively when other coalition members cooperate. A coalition is *externally stable* if there is no incentive to enlarge the coalition by including non-signatory countries.

Under fairly general conditions, stable coalitions have been shown to exist (Donsimoni *et al*, 1986). However, stable coalitions are generally small and might well not address satisfactorily the environmental problem, especially when they deal with a global externality as in the case of climate change (D'Aspremont *et al*, 1983; D'Aspremont and Gabszewicz, 1986; Carraro and Siniscalco, 1991; Hoel 1992). This is for two reasons: *i)* the emission reductions delivered by the coalition might be too small compared with the global discharge of the pollutant; and, *ii)* the optimal reaction of non-signatory countries to the environmental coalition might imply higher emissions – *i.e.* there might be carbon leakage – compared with a case in which no coalition is formed.

The γ-game: from characteristic functions to partition functions

The reaction of non-signatory countries plays a major role in shaping the incentives for signatory countries to remain in the coalition. In order to test for stability, it is therefore necessary to account for the strategic behaviour of countries outside the coalition. Chander and Tulkens (1997) show that in games with externalities, in order to define the set of stable coalitions that emerges as a strategic equilibrium – the *core* – of the emissions game, it is crucial that the function that describes the payoff achievable by each possible coalition of players – the *characteristic* function – reflects the actual behaviour of players which are not members of the coalition.

Describing the actual response of non-coalition members to coalition strategies is not straightforward. A simplified approach often used in the literature is to assume that players outside the coalition behave in the least favourable manner to coalition members. This "pessimistic" view is embodied in the so-called *α-characteristic function* (see Maler, 1989). However, this approach is both unrealistic and inconsistent as it does not guarantee that the choice to make the highest damage to coalition members is optimal for players that are outside the coalition.

These shortcomings of the *α-characteristic function* have motivated Chander and Tulkens (1997) to define the *γ-characteristic function*, in which countries inside the coalition assume that their non-signatory counterparts respond optimally to the equilibrium choice of the coalition. This implies that the equilibrium of the emissions game is a Nash equilibrium in which coalition members play their best response to non-coalition members, which in turn adopt individually their best reply strategies.

In the simplified setting used by Chander and Tulkens (1997), players outside the coalition find it optimal to emit more than in the non-cooperative equilibrium, but overall emissions are lower. The emergence of *γ-type* description of the bargaining games marks the shift from a characteristic functions centred analysis, in which the worth of the coalition is computed regardless of the best reply of non signatories, towards games based on *partition functions*, which assign an individual payoff to each player for each possible coalition structure.

If countries are allowed to be part of only one coalition at a time, the bargaining process can be seen as a process that leads to a particular *partition* of the whole population. This partition leads to a well defined *coalition structure* of the game. The representation of the whole coalition structure is particularly useful in games with externalities, because the payoff of each player depends on the peculiar partition of the set of players that emerges from the coalition game (Bloch, 1997; Ray and Vohra, 1999).[29] In order to check the overall desirability of each partition of the set of players, it is possible to construct a function that associates to each *coalition structure* the payoff of all coalitions, with the payoff of each coalition formed as the sum of the payoffs of all coalition members. This function is the *partition function*. The description of individual countries payoffs from cooperation can be done using *per-member partition functions*, which assign to each country the payoff which corresponds to the *coalition structure* to which it belongs.

In general, a non-cooperative game of coalition formation can be modelled as a two-stage game. In the first stage, players decide non-cooperatively whether or not to join a coalition, given the adopted burden-sharing rule. In the second stage, agents set their policy/decision variables by maximising their welfare function, given the decision taken in the first stage and the adopted burden-sharing rule (Carraro, Marchiori and Sgobbi, 2006). The standard assumption is that coalition members act as a single player maximising the aggregate payoff to their coalition, but behave non-cooperatively towards outsiders. Equilibrium coalition structures are then determined by applying the concept of internal and external stability and welfare is measured using partition functions (Barrett 1994, 1997; Carraro and Siniscalco, 1993; Hoel, 1992; Hoel and Schneider, 1997; Rubio and Ulph, 2001).

Equilibrium coalitions structures and the rules of the game

There is a wide range of factors that influence the bargaining process among negotiating countries. Different assumptions on the *rules of the game* lead to a wide range of possible of outcomes in terms of equilibrium characteristics of coalitions.[30] A first rule of the game concerns the timing of the decisions announced by players. Coalitions can be formed in a setting in which each player announces simultaneously his/her optimal choice, or they can be built in a sequential process in which each player makes his/her announcement following a pre-determined order. Games with the former set of rules are called *simultaneous* games, while games with the latter are called *sequential games*. These two broad

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[29] In the absence of externalities, partition functions and characteristic functions are indeed equivalent (Carraro, Marchiori and Sgobbi, 2006).

[30] We follow here closely Carraro and Marchiori (2003) and Carraro, Marchiori and Sgobbi (2006).

categories of games can be used to illustrate the most relevant rules of the game and their implications in terms of coalition formation.

Simultaneous games

In simultaneous games, all players announce at the same time their decision to form a coalition. In such games, the set of Nash equilibria is often quite large, forcing researchers to use some refinements in order to make interesting predictions. As noticed by Bloch (1997), these refinements are usually of a cooperative nature. Hence, the study of simultaneous games of coalition formation is at the frontier between cooperative and non-cooperative game theory.

Another important distinction is on the norms that govern coalition membership. Three cases can be identified: *i) open membership; ii) exclusive membership;* and, *iii) coalition unanimity* rules. These rules govern the process of coalition formation and the possibility that existing coalitions break apart, admit new members or merge with other coalitions.

In *open membership* games, each country is free to join or leave the coalition without any need to seek the permission of other coalition members (D'Aspremont *et al.* 1983; Carraro and Siniscalco, 1993; Yi and Shin, 1994). Also, each player that wants to be part of the coalition cannot be refused membership. Freedom of entry does not apply instead to the case of *exclusive membership* games (Yi and Shin, 1994), for which participation to a coalition is conditional on approval from all coalition members. Exit without permission remains an option for coalition members in this class of games as well. In *coalition unanimity* games (Chander and Tulkens, 1997; Yi and Shin, 1994; Bloch, 1997), the formation and the existence of the coalition are conditional on the unanimous participation of all coalition members. If one of them decides to abandon the coalition to behave as a singleton, the coalition collapses and all players behave as singletons.[31]

In simultaneous games with positive externalities, the grand coalition is rarely an equilibrium outcome for any of the membership rules mentioned above, and only partial agreements form (Carraro and Marchiori, 2003). The grand coalition is however more likely to emerge at the equilibrium under the coalition unanimity rule. If a partial coalition forms, the *size* of the partial agreement(s) which arise at the equilibrium is usually very small. The intuition behind this result is that under positive externalities, the incentives to free-ride increase as coalitions get bigger.

The shape of the payoff function of coalition members and the response of countries outside the coalition also matter when characterising the equilibrium coalition structure and its stability. Monotonously increasing payoffs imply that as the coalition gets bigger, the payoff of its members increase as well, and this fosters cooperation. Access of non-signatories might then be encouraged, and the grand coalition is a plausible, albeit unlikely, outcome. If instead the payoff function is humped-shaped, there may be an optimal size of the coalition below the grand coalition where all players cooperate. If the rule of *exclusive membership* is applied, the optimal size can be enforced and coalitions smaller than the grand coalition may emerge and be stable.

As regards the behaviour of non signatories, the literature has defined two possible cases. In the first case, singletons outside the coalition do not have the incentive to expand their negative externality as a reaction to the effort of coalition members. The reaction function is then said to be *orthogonal*, the environment certainly benefits from cooperation, payoffs of coalition members benefit from the positive feedback, and incentives to free-ride are diminished. If instead the best response of non-cooperating singletons implies an

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[31] Yi (1997) provides an interesting analysis of the results of simultaneous games of coalition formation for the different membership rules described above.

increase in (the optimal level of) their individual emissions, the environmental benefits of cooperation are reduced, and the incentive to free-ride is increased. In this case, cooperation might not be profitable, especially if coalitions are small (Botteon and Carraro, 1997).

A final distinction can be made regarding how players build their conjectures on their counterparts' responses to their optimal strategy. In the *Nash conjecture* case, players' decisions are taken by assuming the other player's choices as given. For example, a player that decides to defect compares his payoff in the coalition with the payoff outside the coalition, while all the other members stick to their announced strategy of cooperation. Under *Nash conjectures* the incentive to free-ride is greater and coalitions tend to be less stable and/or small.

Another approach to expectation formation assumes that players form *rational conjectures* on the consequences of their choice on other players' actions. In the case of *rational conjectures,* a coalition is internally stable if no cooperating player would be better off in the coalition structure induced by his defection. In this case, both the grand coalition and a sequence of smaller coalitions may be stable (Carraro and Moriconi, 1998). However, equilibrium decisions in games with rational conjectures are not best response strategies to the other players' decisions.

Sequential games

In *sequential games* of coalition formation, the negotiating process is described by an explicit extensive form non-cooperative game. In the context of games *without* spillovers, sequential processes have been proposed by Selten (1981), Chatterjee *et al.* (1993), Moldovanu (1992) and Perry and Reny (1994), among others.

In most of these games, the basic structure is an extension to *n* players of the Rubinstein's (1982) alternating-offer bargaining model. This structure was extended to games *with* spillovers by Bloch (1997) and Ray and Vohra (1997). All these works, although different with respect to the presence of externalities, are based on a common assumption, namely that once a coalition is formed, the game is only played among the remaining players. The typical structure of the game is as follows. Players are ordered according to a fixed rule and the first player starts by proposing the formation of a coalition C to which he/she belongs. Each prospective member responds to the proposal in the order determined by the fixed rule. If one of the players rejects the proposal, he/she must make a counteroffer and propose a coalition C' to which he/she belongs. If, instead, all proposed members accept, the coalition C is formed. All players belonging to C then withdraw from the game, and the first player in $N\backslash C$ starts making a proposal. However, the assumption of *immediate exit* usually results in inefficient outcomes (Carraro, Marchiori and Sgobbi, 2006).

In order to avoid these inefficiencies, other authors have proposed coalitional bargaining models where agents cannot choose to exit, but they are given the possibility to renegotiate over the formation of a coalition. In particular, Seidmann and Winter (1998) have focused on games without externalities, while Gomes (2005) has extended the analysis to the case of positive and negative spillovers. In these games with *continuous renegotiations*, the grand coalition is ultimately formed, as players carry on bargaining until all gains from cooperation are exhausted. However, delays may arise in the enrichment of the agreement. Unlike games with immediate exit, the models with continuous renegotiations do usually produce efficient equilibrium outcomes.

Coalition *unanimity*, or at least minimum participation rules (see Carraro, Marchiori and Oreffice, 2009), *continuous sequential* moves and *orthogonal free-riding* are features of the game which favour the stability of large coalitions. However, it is not always clear under what conditions it is possible to construct international agreements in which these rules of the game can apply. For example, coalition unanimity or minimum participation rules may help to achieve stability when all players are symmetric, or of similar size. But, they might not improve the chances of a stable climate agreement if countries are strongly asymmetric among themselves.

Bargaining over the rules of the game

The wide array of possibilities from which players can choose the rules of the game necessarily leads to the question of how players agree on a particular set of rules. In order to investigate this issue, the game described so far can be enriched by a preliminary stage in which countries bargain on the rules that govern the process of coalition formation. The decisions taken in the preliminary stage constrain the players to a specific set of possible equilibrium coalitions that will eventually emerge from the bargaining process.

One example is the process of adoption of a *minimum participation rule*, which consists in determining the minimum number of signatories for the agreement to become effective. This rule is present in several international agreements for the protection of global public goods, and it has been shown to induce higher cooperation among players (see Black, Levi and de Meza, 1992; Rutz, 2001). These first analyses of games with minimum participation clauses were carried out using two-stage games and the rule was imposed on players exogenously. Carraro, Marchiori and Oreffice (2009) have instead explicitly introduced the *constitutional stage* in which players bargain on whether or not to introduce the minimum participation rule and at what level the threshold has to be fixed. The decision is taken non-cooperatively and unanimously by anticipating the implications on the second and third stages of the game. In this setting, Carraro, Marchiori and Oreffice (2009) are able to confirm the results previously achieved in two-stage games, by showing that there is fact an incentive for countries to adopt a minimum participation rule. The optimal level of the threshold above which the agreement comes into force does not necessarily coincide with the grand coalition. The intuition is that too large coalitions would reduce the likelihood for players that opt for the minimum participation rule in the first stage of the game to become free-riders in the second stage. It is indeed important to note that the best outcome for a player is to enjoy the global public good behaving as a singleton outside the coalition. The grand coalition is formed only if the payoffs from cooperation increase fast and are sufficiently large for a minimum participation threshold close to the total number of negotiating countries. In this case, no player would have the incentive to run the risk of not forming the coalition by behaving as a free-rider.

In Carraro, Marchiori and Oreffice (2009) a crucial assumption is that players are symmetric. In reality there will be countries for which the coalition is profitable and countries for which it is not. Minimum participation thresholds in this case would be counterproductive if not associated to transfers among players that make the agreement profitable to all countries.

The enlargement of coalitions

A large number of studies, both theoretical and empirical, has shown that coalitions that emerge from non-cooperative games – *i.e.* coalitions that are *profitable* and *stable* – are usually smaller than the grand coalition, and under many circumstances they may easily be too small to have a meaningful impact on the stock of the global public good (Hoel, 1991, 1992; Carraro and Siniscalco, 1993; Barrett, 1994, 1997; Heal, 1994). This is particularly troublesome in all those cases in which there would be significant payoffs from greater cooperation and global welfare might be enhanced by larger coalitions. For this reason, a wide set of studies has started to explore possible ways to induce greater coalitions at the equilibrium.

Two major ideas have been discussed in the literature. The first concerns the possibility of expanding coalitions by means of side payments, *transfers*, between players of the game. The second concerns the possibility of reducing free-riding incentives by coupling the global public good treaty with a treaty that allows the possibility of enjoying access to a *club* or *quasi-club* good. In the literature this is often referred to as *issue linkage* in international negotiations. This section highlights the major developments of the literature on transfers, while the final section of this survey discusses issue linkage.

Two properties are useful to study the structure of a coalition in coalition formation games. The first property is called *superadditivity,* and concerns the welfare of countries that are coalition members. A coalition game is *superadditive* if the welfare of the coalition when a new member is included is higher than the sum of the welfare of the smaller coalition and the new member playing as a singleton. The welfare improvement constitutes the gain from increased cooperation and cooperation is said to be *coalitionally rational*. The second property has already been mentioned above and is called *positive spillovers*. It concerns the welfare of countries that remain outside the coalition. A coalition game is said to exhibit positive spillovers if, when a new member joins the coalition, all countries that remain outside the coalition are better off. *Superadditivity* and *positive spillovers* imply together that global welfare increases when cooperation increases.

One simple way to enlarge the coalition is to use self-financed transfers from the cooperating countries to the non-cooperating ones. Coalition members would "buy in" the cooperation of non-signatory countries to participate in the coalition benefiting from the positive externality that an additional member would generate (Carraro and Siniscalco, 1993; Barrett, 2002). Also, non signatory countries might "buy in" other non signatory countries to join the enlarging coalition. However, Carraro and Siniscalco (1993) show that enlarging the coalition by means of self-financed transfers is not possible without some form of commitment if players are symmetric.[32] The intuition is that the transfer necessary to induce a non cooperating country to enter the coalition would induce cooperating countries to behave as free-riders. However, if the rules of the game are changed or if players are not symmetric, there is space for transfers to enlarge the coalition.

Carraro and Siniscalco (1993) consider the effect of introducing partial commitment (only a subset of the countries commit to cooperation). Commitment acts as a tool to preserve the stability introduced by the welfare transfer necessary to "buy in" non signatory countries. The commitment of only a fraction of the *n* countries is shown to ensure the stability of a larger coalition and even lead to full cooperation.

Various forms of commitment have been explored in a variety of contributions to the literature (Botteon and Carraro, 1997; Jeppesen and Andersen, 1998; Petrakis and Xepapadeas, 1996). However, the problem of introducing commitment as a rule of the game, even if partial, is that in reality countries that sign international agreements can withdraw. The possibility of withdrawal is indeed explicitly permitted in international treaties to protect global goods. This limitation of responsibility in international agreements has however not impeded the formation and the successful operation of international treaties to govern global common goods and side payments have played a substantial role in spreading this cooperation to reluctant countries.

The efforts of the literature have therefore been in the direction of explaining how transfers would allow coalition enlargement in a world in which explicit commitment is not credible. Barret (2001) has shown that commitment is not strictly necessary to guarantee the possibility of enlarging a coalition by means of transfers when countries are strongly asymmetric, for example if one group is severely affected by the global externality while the other is not. This structural difference among the two countries guarantees that those with low marginal negative impacts from climate change will not sign the treaty unless they are compensated by side payments. Asymmetry changes the rules of the game and makes the choice of not participating into the coalition credible. Non-signatory countries appear as if they had explicitly "committed" to their choice, and side payments become a tool to allow greater payoffs in the coalition.

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32. Transfers are self-financed if the total transfer is lower than the gain that the committed countries obtain from expanding the coalition (Carraro and Siniscalco, 1993).

This result is quite robust and ensures that larger coalitions can be formed in a world in which strong asymmetries among countries are pervasive.

A second response has come from the empirical models that simulate negotiations among countries. A wide range of papers has shown that transfers can foster coalition enlargement and lead to the construction of self-enforcing agreements (*e.g.* Botteon and Carraro, 1997; Altamirano-Cabrera and Finus, 2006; Bosello *et al.,* 2003, 2004; Carraro and Siniscalco, 2001; Eyckmans and Finus, 2003, 2004a; Finus *et al.,* 2004; Weikart *et al.,* 2006). This strand of the literature has also taken into account complex transfer schemes which include many possible patterns of burden sharing.

The full potential of transfers

A weakness of the first wave of empirical studies is that results are fragmentary and depend on *ad-hoc* transfer rules, on the design of the empirical model, and on data used for calibration. The controversy that surrounds the role of transfers in coalition theory requires instead a unified approach which is capable of delivering consistent insights on the role of transfers in coalition formation theory. Carraro, Eyckmans and Finus (2006) provide a thorough assessment of the "full potential of transfers", using a very simple theoretical framework of analysis and a stylized integrated assessment model of climate policy. Their contribution is followed here in order to give a comprehensive taxonomy of transfers in coalition formation theory. The bargaining process that leads to cooperation is modelled following the scheme of the two stages γ-game outlined above. Whenever the grand coalition does not emerge as the stable coalition, the outcome is not globally optimal, and there is space for increased cooperation.

Ex-Ante Transfer Schemes

The decision of the transfer scheme can be contextual to the choice of strategies in the second stage of the game. In this case, transfers are said to be *ex-ante*. They can be either "simple" or "optimal". Simple *ex-ante* transfer schemes derive from cooperative game theory, but do take into account the strategic behaviour of non-coalition members. It is thus not guaranteed that they allow countries to reach the highest possible level of welfare. Hence, the effects on the stability of coalitions are not unequivocal.

One key notion to study optimal *ex-ante* transfer schemes is that of *potentially internally stable* (PIS) coalitions. A coalition is *PIS* if the aggregate welfare level of cooperating countries is at least as high as the sum of the welfare that its members would enjoy behaving as free-riders. PIS coalitions have enough resources to guarantee (at least potentially) cooperation from all members. An *optimal ex-ante* transfer scheme allocates to each coalition member at least its free-riding level of welfare and then redistributes the remaining welfare among coalition members following an arbitrary distribution rule. The choice of the criteria to allocate the extra welfare affects neither internal nor external stability. Thus, a simple decision criterion is to maximize the aggregate welfare of the coalition. The resulting coalition structure will be stable and optimal.

Ex-Post Transfer Schemes

Ex-post transfers are used to enlarge a coalition once it has already been formed. There are two possible types of transfers (Carraro and Siniscalco, 1993). Coalition member can "buy in" non-cooperating countries into the coalition, or a non signatory country can buy in another non signatory country to join the coalition. In the first case, it is said that the coalition is expanded by *internal means,* while in the second case the coalition is expanded by *external means*.

The standard procedure to analyse the expansion of coalitions through internal means is to pick a stable coalition as starting point, and to check whether expansion of this coalition is possible when current coalition members pay some outsider for joining them (Botteon and Carraro 1997). A coalition can be expanded if: *i)* the expansion is a Pareto-improvement for all members of the coalition and for the newcomer; and, *ii)* the enlarged coalition is internally stable. The first requirement is equivalent to superadditivity, while the second is equivalent to potential internal stability. The highest ranking of all PIS coalitions in terms of welfare, which emerges from optimal *ex-ante* transfers, cannot be improved by internally financed transfers, and thus cannot be enlarged with *ex-post* transfers.

Also in the case of *external means,* the coalition enlargement must constitute a Pareto improvement, and the enlarged coalition must be stable. However, the case of externally financed transfers implies that the coalition is stable and does not have resources to enlarge participation – *i.e.* it is not potentially internally stable. Thus, the participant that "buys in" others must have sufficient resources to make the enlarged coalition potentially internally stable. This means this participant should have enough resources to compensate the new member of the coalition, while at the same time benefiting itself. This condition is met only if the positive spillover that follows the enlargement of the coalition is greater than the incentive to free-ride generated by the perturbation of stability. The possibility of expanding coalitions using *external means* opens the possibility of scenarios in which countries that remain outside international coalitions may still play a role in fostering international cooperation by financing the protection of the global common good in other non participatory countries, which might eventually find convenient to become active members of the international coalition.[33]

Issue Linkage

Another possibility to enlarge coalitions at the equilibrium is to couple the negotiations on the global public good with negotiations on other issues.[34] Such issue linkage was introduced in the economic literature on international environmental cooperation by Folmer *et al.* (1993) and by Cesar and De Zeeuw (1996) to solve the problem of asymmetries among countries. In this case, issue linkage works very much as a transfer among asymmetric players. Another reason for which issue linkage has been advocated is that it has the potential to reduce free-riding incentives, especially when the linked negotiation concerns *club* or *quasi-club* goods. The idea is to introduce forces that work against the free-riding incentive induced by the negotiation over the public good. The literature has mostly concentrated on linking environmental negotiations with negotiations on trade liberalisation (Barrett, 1995, 1997), and with agreements on technological cooperation (Carraro and Siniscalco, 1995, 1997; Katsoulacos, 1997; Buchner *et al.*, 2002).

It has been shown that, in general, issue linkage does increase the degree of cooperation among countries and leads to coalition structures that generate higher global welfare. However, the optimal number of issues that countries should tie together in the negotiation process is unclear. There is indeed a trade-off between wider participation to the environmental agreement and participation on the issue that is linked to negotiations. For example, some countries, for which the participation to the environmental agreement is particularly expensive, might not receive high enough benefits from the access to the club good, and consequently would choose a non cooperative behaviour with respect to both issues. This may happen also if, in principle, they would have accepted to join an agreement on the club good. In these cases, the enlargement of the coalition comes at the cost of having a smaller number of countries participating to the second agreement.

Carraro and Marchiori (2003) explore this trade-off by modelling a three-stage non cooperative sequential game in which players bargain over the number of issues to link in the negotiation in a first stage in which the rules of the bargaining process are chosen. The key question is: do players have an incentive to link the negotiations on two different issues instead of negotiating on the two issues separately? This can be

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[33] The financing of GHG emissions abroad through the Clean Development Mechanism may be seen as an example.

[34] We follow here closely Carraro and Marchiori (2003).

analysed by assuming that countries can negotiate over two issues either jointly or separately. The first negotiation concerns the provision of a global public good, while the second issue regards a club or semi-club good. A necessary condition to link negotiations is that the players that start cooperating over the provision of the public good have large enough benefits from cooperation. A necessary and sufficient condition is instead that the welfare gain induced by greater cooperation on the public good is large enough to compensate the welfare loss from a smaller coalition on the club good induced by the choice of issue linkage.

Two elements from this literature are of particular interest from a policy perspective: *i)* the way in which participation to the two agreements changes when they are linked and *ii)* the way in which welfare changes when coalition size changes as a result of linkage. The larger the increased benefits induced by a larger cooperation on the public good issue, the larger the likelihood that issue linkage be adopted. Similarly, the smaller the loss from reduced cooperation on the club good agreement, the larger the likelihood that issue linkage be adopted. The ultimate impact on welfare, and thus on the desirability of linkage, emerges as the outcome of these two combined effects.

ANNEX 3. DAMAGE FUNCTIONS AND AGGREGATION OF CLIMATE IMPACTS IN INTEGRATED ASSESSMENT MODELS (IAMS)

This annex describes how integrated assessment models (IAMs) capture the impacts from climate change through what is known in the literature as climate change damage functions. It also surveys the estimates used as a background for the calibration and the construction of WITCH's damage functions.

Damage functions in Integrated Assessment Models

IAMs integrate the economic aspects of climate change with the science and the dynamics of the climate system. However, the time scale of natural dynamics is much larger than that of economic dynamics. In order to be computationally tractable, these modelling tools include reduced-form climate modules, consisting of few equations that describe the relationship between emissions, concentration, radiative forcing, temperature and that replicate the results from more complex General Circulation Models (GCMs). Similarly, the impacts from climate change are commonly represented using a climate change damage function that translates a given set of physical, environmental and social impacts into monetary units such as percentage of GDP. IAMs can therefore provide aggregate estimates of climate change impacts at regional or global level, over time. Results from alternative modelling exercises are not always fully comparable because models are characterised by different climate modules, make diverse assumptions about adaptation, do not share the same regional aggregation, include climate change impacts on different sectors and shape the relationship between temperature and GDP differently.

Among the many IAMs that have become available in the literature, the most representative can be considered to be the DICE/RICE (Nordhaus and Boyer, 2000 for an exhaustive review), the Mendelshon model (Mendelshon *et al.,* 2000), Fund (Tol, 2002, 2002a), PAGE (Hope, 2003) and MERGE (Manne *et al.,* 1995; Manne and Richels, 2004) models. A first review of these models appeared in Third Assessment Report (IPCC, 2001), which mostly describes the results from Mendelshon, Tol and Nordhaus. Warren (2006) provides an updated review of the FUND, DICE/RICE, MERGE and PAGE models.

The damage function of the WITCH model is based on Nordhaus and Boyer (2000) of which it shares both the functional form and the impact estimates. For this reason, a detailed description of the damage function implemented in the DICE/RICE models family is provided below.

The DICE/RICE models

The RICE and DICE models (Nordhaus and Boyer, 2000) include a climate change damage function that describes a quadratic relationship between temperature and output. The quadratic functional form makes it possible to capture mixed effects, as moderate warming can be beneficial for some regions.

The calibration of the damage function starts off with a bottom-up assessment of climate change impacts in different sectors of the economy based on sectoral studies and/or expert judgment collected by the authors. Climate change impacts are estimated for two hypothetical scenarios of temperature increase above 1900 levels, 2.5°C and 6°C, and for a number of sectors including agriculture, coastal, other vulnerable markets, health, non-market time use, human settlements and ecosystem, catastrophic events. This sectoral information, which is made available for each region of the RICE model, is then compounded into regional damage estimates. The parameters of the climate change damage function, whose functional form is common to all regions, are then calibrated so as to reproduce the estimated regional damages or benefits. For each region, the authors define an impact index which represents the willingness to pay to avoid the consequences of temperature increases in that sector. Future impacts are projected to 2100 using an income adjustment factor, which leads to the definition of a future impact index.

The sources used for the estimation of the various types of impacts are the following:

- Agricultural impacts are based on Darwin *et al.* (1995) who provide regional estimates of the share of agricultural revenue lost with a CO2 doubling. The resulting damage function for agriculture is a quadratic function of temperature, with net benefits accruing for temperature levels below 11.5°C.

- For the coastal sector, Nordhaus and Boyer refer to the study by Yohe and Schlesinger (1998) carried out for the US to infer that 0.1% is a reasonable willingness to pay for preventing a 2.5 degree warming. An index of coastal vulnerability is used for extrapolating estimates for the other regions.

- The category "other vulnerable markets" includes forestry, energy, water systems, constructions, fisheries and outdoor recreation. These sectors are estimated to be relatively invulnerable with the only exception of the energy sector. Nordhaus and Boyer assume a 5% reduction in energy expenditure in cold climates, to reflect a heating effect, and an increase of 8% in tropical and semitropical regions, to obtain a cooling effect.

- The assessment of impacts on health are based on Murray and Lopez (1996) who estimated the impacts of malaria, other tropical diseases and pollution in terms of "years of life lost" for a number of regions that match those contained in the RICE model. The impacts on developing countries, especially on Sub-Saharan Africa, are particularly large, essentially because of the presence of malaria. In developed countries the impact comes mostly through pollution.

- For amenity impacts, regional estimates are based on a study carried out by Nordhaus (1998) for the US, which found that for temperature levels below 20°C, an increase in temperature will have a positive amenity impact of 0.3%. Extrapolating from this study, the net amenity value of an increase in temperature is assumed in the model to be positive in cold regions and negative in warm regions.

- The impacts on human settlements and natural ecosystems are based on "rough estimates" of the authors, who found that the capital value of climate-sensitive human settlements and natural ecosystem ranges between 5% and 25% of regional output and that the willingness to pay to avoid a 2.5°C temperature increase is 1% of that capital. Higher numbers are assumed for Europe, Japan, small countries and countries with sensitive ecosystems.

- The impacts of catastrophic events are evaluated in two steps. First, based on an expert's survey carried out by Nordhaus (1994), the probability of a catastrophic event is estimated for 3°C and 6°C warming. Second, the willingness to pay is calculated assuming a rate of relative risk aversion of 4.

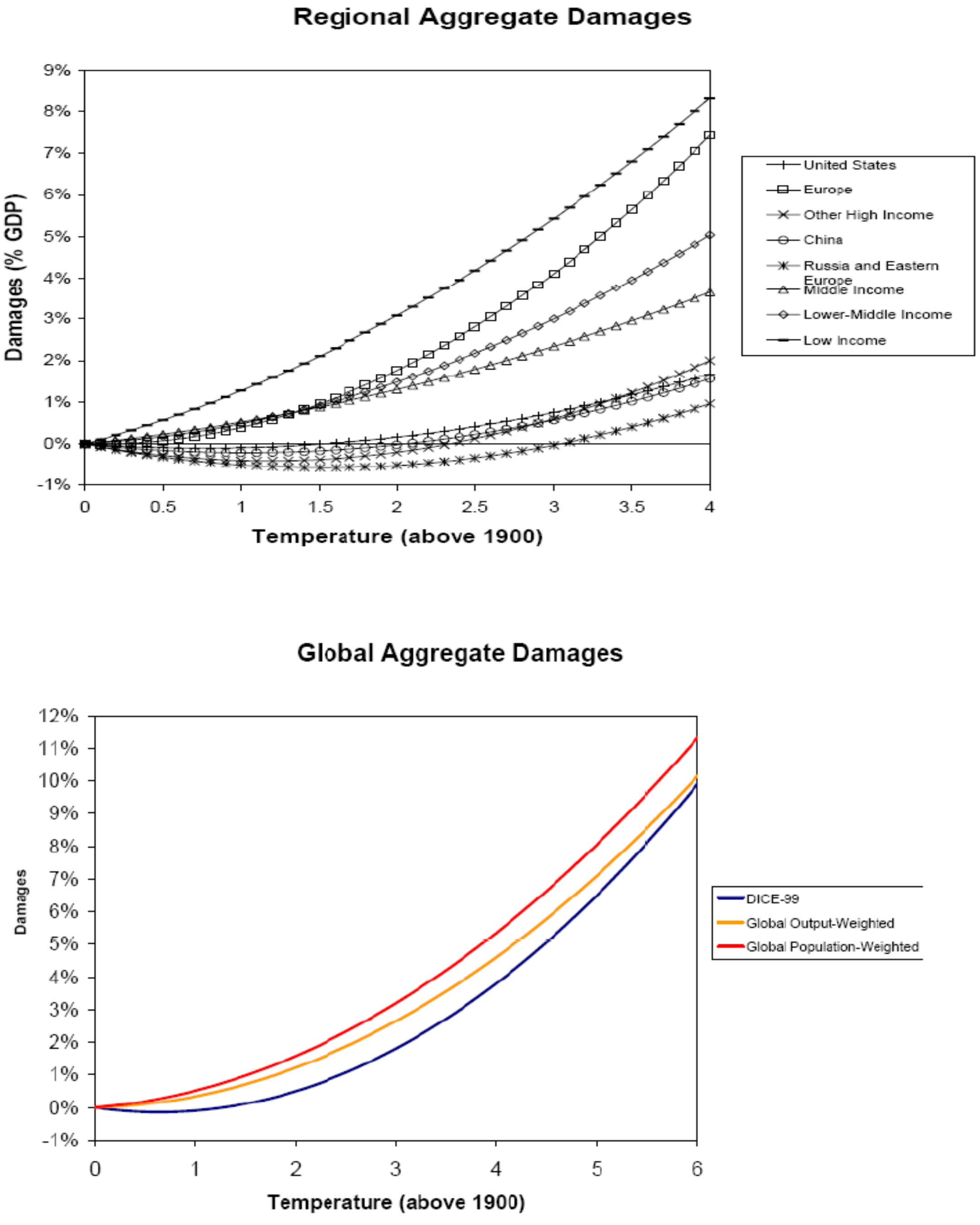
Table A3.1 summarizes the damage estimates for a 2.5°C increase in global temperature above its 1900 level, both for the whole economy (Total) and broken down by sectors. Among rich countries, Europe is estimated to suffer most from climate change, because of the assumption of high vulnerability to catastrophic events. Among developing regions, Africa and India face larger climate impacts due to impacts on health and catastrophic events, respectively.

Table A3.1. **Climate change impacts in different world regions under a 2.5°C increase in global temperature above its 1900 level**

Region	TOTAL	Agriculture	Other vulnerable market	Coastal	Health	Non-market time use	Catastrophic	Settlements
United States	0.45	0.06	0	0.11	0.02	-0.28	0.44	0.1
China	0.22	-0.37	0.13	0.07	0.09	-0.26	0.52	0.05
Japan	0.5	-0.46	0	0.56	0.02	-0.31	0.45	0.25
EU	2.83	0.49	0	0.6	0.02	-0.43	1.91	0.25
Russia	-0.65	-0.69	-0.37	0.09	0.02	-0.75	0.99	0.05
India	4.93	1.08	0.4	0.09	0.69	0.3	2.27	0.1
Other high income	-0.39	-0.95	-0.31	0.16	0.02	-0.35	0.94	0.1
High-income OPEC	1.95	0	0.91	0.06	0.23	0.24	0.46	0.05
Eastern Europe	0.71	0.46	0	0.01	0.02	-0.36	0.47	0.1
Middle-income	2.44	1.13	0.41	0.04	0.32	-0.04	0.47	0.1
Lower middle-income	1.81	0.04	0.29	0.09	0.32	-0.04	1.01	0.1
Africa	3.91	0.05	0.09	0.02	3	0.25	0.39	0.1
Low-income	2.64	0.04	0.46	0.09	0.66	0.2	1.09	0.1
Global								
Output-weighted	1.5	0.13	0.05	0.32	0.1	-0.29	0.17	1.02
Population-weighted	2.19	0.17	0.23	0.12	0.56	-0.03	0.1	1.05

Figure A3.1 depicts the regional damage functions obtained with the RICE model, and their aggregate counterpart using different regional weights. GDP losses for a 4°C increase above pre-industrial levels range from 1% in Russia and Eastern Europe to 8% in low-income countries. Population-weighted global losses are higher than output-weighted ones because negative impacts are more frequent in developing countries.

Figure A3.1. **Regional and global damage functions in the RICE/DICE models**



Source: Warren *et al.* 2006.

The MERGE model

In the MERGE model (Manne *et al.*, 1995; Manne and Richel, 2004) both market and non-market damages are taken into account. Market effects can be valued using prices and observed changes in demand and supply, whereas non-market effects have no observable prices and therefore require other methods such as valuations based on willingness to pay.

Two different damage functions are used to characterize market and non-market impacts. For market impacts, following Nordhaus, MERGE includes a quadratic relationship between temperature and damages. The damage function has been calibrated so that a 2.5 °C temperature increase above 1990 levels leads to a GDP loss of 0.25% in developed countries and of 0.5% in developing countries. These figures are extrapolations from current literature and are comprehensive of all market impacts. At higher or lower temperature levels than 2.5 degrees, they assume that market losses would be proportional to the change in mean global temperature from its level in 2000.

Non-market damages include impacts on human health, species losses and deterioration of environmental quality and they have been estimated using a willingness-to-pay approach. The damage function is calibrated so that the willingness to pay to avoid a 2.5°C increase in temperature is equal to 2% of GDP. Each region values non-market damages independently of where such damages occur. The damage function for non-market impacts is s-shaped in per-capita income so that lower income countries place a lower value on those impacts. As a consequence, non-market damages are higher for developed countries. Non-market losses are estimated to be larger than market losses, accounting for about 80% of the total in MERGE (Table A3.2). This suggests that the monetary costs of climate change including only market impacts are likely to omit potentially important and large impacts.

Table A3.2. **Climate damages in the MERGE model**

MERGE Manne, Mendelsohn and Richels, 1995				
°C above pre-industrial levels	**Market damages, developed countries**	**Market damages, developing countries**	**Non-market damage**	**Total damage**
0.5	0.01	0.02	0.08	**0.1**
1	0.04	0.08	0.32	**0.4**
1.5	0.09	0.18	0.72	**0.9**
2	0.16	0.32	1.28	**1.5**
2.5	0.25	0.5	1.99	**2.4**
3	0.36	0.72	2.87	**3.4**
3.5	0.49	0.98	3.91	**4.6**
4	0.64	1.28	5.12	**6.1**
4.5	0.81	1.62	6.46	**8.1**

Source: Warren *et al.* (2006).

The PAGE model

In the PAGE model (Hope 2003), the climate change damage function is calibrated to replicate a damage lying between a 2% loss and a 0.1% gain of world GDP when the temperature exceeds by 2.5°C a “tolerable” temperature level that by default is set equal to 2°C. These estimates are consistent with those reported in the IPCC’s Third Assessment Report (TAR) (IPCC, 2001).

Climate change impacts are a polynomial function of the temperature increase above a tolerable level of temperature change, ($T-T_o^n$), and they are region-specific. PAGE is one of the first models to include an “expenditure for adaptation” variable, which can increase the tolerable level of temperature change (T_o) and that can reduce the intensity of climate change impacts. However, adaptation is imposed exogenously and it is not determined by the model optimization process.

The PAGE model distinguishes between markets and non-market damages and it accounts for discontinuity impacts, *e.g.* damages due to rapid climate change also referred to as singularities. When temperature rises between 2°C and 8°C (with a mean value of 5°C) above pre-industrial levels, the risk of big losses can increase by between 1% and 20% (with a mean value of 10%) for each subsequent degree of temperature increase. Damages are an uncertain power function of temperature rise. The exponent n which determines the convexity of the damage function is an uncertain parameter whose minimum, most likely and maximum values are respectively 1, 1.3 and 3.

Impacts are computed for each region and for the two sectors, and they are translated into monetary terms using weights. Weights are chosen so that regional damages are in line with the IPCC’s TAR. In some cases, such as for Eastern Europe, weights are negative to reproduce a gain from climate change. Impacts are particularly large in Africa and Latin America.

The FUND and Mendelshon models

The FUND (Tol, 1999, and subsequent versions) and Mendelsohn (Mendelsohn *et al*., 2000) models share similar features. Both specify a sector-specific climate change damage function for each of the economic sectors or impact areas considered in the model.

The FUND model can be considered one of the first attempts of dynamic estimation of impact-specific damage functions, which means that information on sectoral impacts is available over time and not just for a specific point such as for a doubling of CO_2 concentration. In the FUND model, climate change costs on agriculture, forestry, water, energy consumption, sea-level rise, ecosystems, vector-borne and heath/cold-stress related diseases – are assessed. In some cases, such as for sea-level rise, damages are assumed roughly linear in temperature increase. In other cases, like for health, they are not. Non linearities and different dynamics in damages are thus impact specific. No unique assumptions are imposed on the time-evolution of different damages.

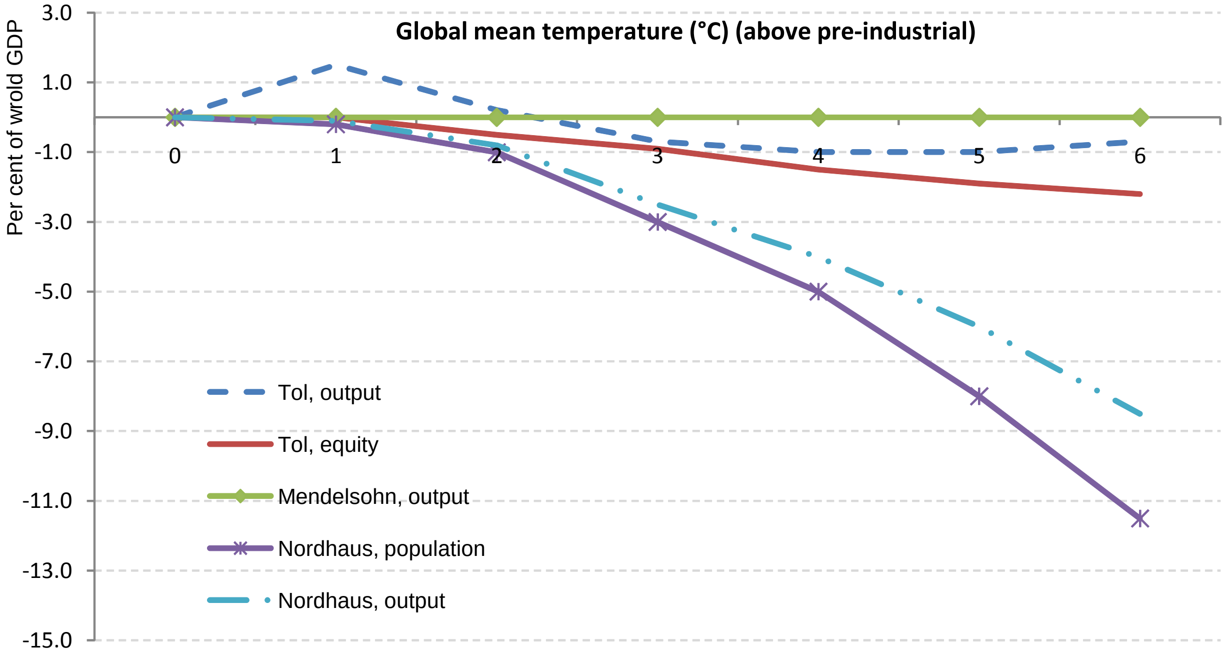
A similar approach is followed in the Mendelsohn model (Mendelsohn *et al*. 2000). Impact areas considered are: agriculture, forestry, coastal resources, energy and water. For each of them, a complex reduced form equation specifies welfare losses (or potential gain) as a function of climatic variables (temperature, precipitation, CO_2 concentration), physical variables (sea level rise, land areas, lengths of coastline) and economic variables (GDP growth, agricultural GDP growth, land values). The Mendelsohn model computes damages for 178 world countries. However, the parameterisation of the climate change damage functions are based on extrapolations from US data and estimates are proposed for market damages only.

Comparison across models

Four major elements that differentiate the treatment of climate change damages across studies: adaptation, catastrophic and extreme events, uncertainty and the shape of the damage function:

- Figure A3.2 depicts the relationship between GDP and temperature produced by three different models. Mendelsohn *et al.* (2000) includes aggregate regional monetary estimates for five market sectors (agriculture, forestry, energy, water, coastal zones) without equity weighting. He finds positive global impacts up to 4°C because of optimistic assumptions on adaptation possibilities and the exclusion of non-market effects. Nordhaus and Boyer (2000) include the risk of catastrophic events, which explains the large increase in damage beyond 3°C. Overall impacts are larger when greater weight is assigned to poor, largely populated countries. Tol (2002, 2002a) computed aggregate regional estimates of damages with and without utility-based equity weighting. He included both markets (agriculture, forestry, energy, water, coastal zones) and non-markets impacts (*e.g.* health, ecosystems). Negative global impacts appear earlier, beyond 1°C, when using equity weights because major losses occur in poor countries.

Figure A3.2. **Selected damage functions**



1. Estimates represent the annual GDP impact (relative to a no-climate-change scenario) of a given increase in temperature, as observed at the time when this increase in temperature is reached. They come from studies by Tol (2002), Mendelsohn (1998), Nordhaus and Boyer (2000) and Stern (2007). In “Tol, output”, impacts across regions are simply added while in “Tol, equity”, they are weighted by regional per capita income. In “Nordhaus output”, impacts are weighted by GDP while in “Nordhaus equity”, they are weighted by population.

Source: IPCC (2007).

- The shape of the damage function is also different across models. Nordhaus and Boyer (2000) assume a quadratic, smooth relationship between output and temperature. Tol (2002, 2002a) instead estimates climate change impacts using a dynamic approach, relying on sector-specific damage functions. When aggregating sectoral and regional estimates, the final shape is not smooth, reflecting the sectoral and regional heterogeneity, which is instead less evident in Nordhaus’ damage function.

- Optimistic assumptions on adaptation capacity and effectiveness tend to lead to lower impact estimates (see *e.g.* the Mendelsohn model). Most often, climate change damage functions do not distinguish between the cost of adapting to climate change and the residual damage, essentially because adaptation responses are not explicitly modelled – as for instance in the RICE and DICE models, where total damage includes both residual damage and protection costs. Adaptation reduces the impact of climate damages, but its effectiveness depends on the sector considered and the type of impact. For example, in the case of extreme weather events, adaptation can play only a marginal role, and most damages cannot be avoided.

- The inclusion of catastrophic and extreme events typically leads to higher estimates, as it is the case in RICE/DICE and PAGE, which produce higher damages than FUND.

Most damage functions are calibrated using information on impacts for a doubling of CO_2 concentration. The shape of damages, which describes the time relationship between temperature and GPD, also affects marginal damages and thus cost-benefit analysis. For example, "hockey-stick" damage functions give results very similar to linear functions before a doubling of CO_2 concentration, but impacts increase much more sharply in the former than in the latter beyond that point. The inclusion of even small threshold-specific damages can significantly increase the optimal level of abatement, as found for example in Keller *et al.* (2004). When threshold-specific damages or discontinuities are modelled, the shape of the damage function is no longer monotonic. Accounting for singularities and discontinuous impacts leads to higher impact estimates. Only the PAGE model explicitly includes a probabilistic treatment by assuming the likelihood of larger losses to be positively correlated with higher temperature increases.

It should be finally pointed out that most estimates used for the calibration of damage functions in IAMs rely on partial equilibrium analysis, neglecting indirect effect due to general equilibrium adjustments. In contrast with this methodology, Bosello *et al.* (2008) presents a novel approach of assessing climate change impacts, which takes into account also general equilibrium effects through price adjustments. According to this methodology, the economic damages from climate change appear much smaller, because of the intrinsic capability of the economic system to adjust in response to negative shocks. However, this study relies only on market impacts that translate into observable changes in demand and supply. As mentioned before, considering market effects only is very likely to underestimate climate change impacts, given that most of the expected damages are in non-market sectors.

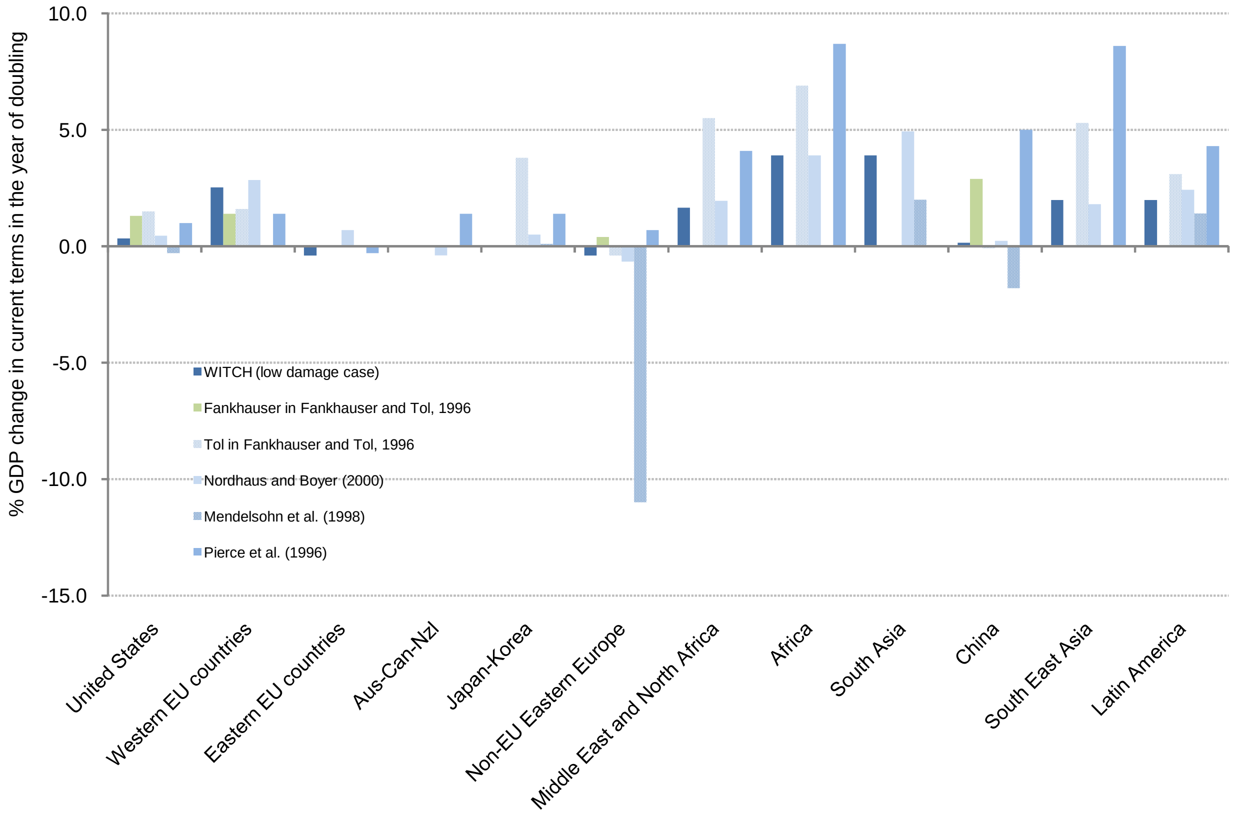
Aggregate climate impacts using IAMs

Although the impacts of climate change will be highly localised in nature, both spatially and temporally, Aggregate estimates of climate change impacts have been published since the IPCC's Second Assessment Report (SAR). This section provides an overview of the aggregate climate change impacts which have been reported in the Assessment Reports of the IPCC, together with some more recent findings.

Aggregate estimates are mostly based on IAMs. As described above, IAMs include a simplified, two-sided relationship between climate change and aggregate indicators of economic performance such as GDP, depending on the regional detail of the model. Physical and monetary impacts of climate change have been extensively reviewed for the first time by Working Group III in the IPCC's SAR (Pearce *et al.,* 1996). The analysis was confined to impact studies that used a static approach. These quantified the consequences of climate change at a particular concentration level or at a particular temperature increase above pre-industrial levels, thereby overlooking climate change dynamics. Estimates reported ranged between 1 and 2 % of GDP, whereas in developing countries and transition economies damages were shown to increase up to 9% of GDP.

Figure A3.3 gives a snapshot of the estimated damages for a doubling of CO_2 concentrations.[35] It provides a clear idea of the uncertainty surrounding impact literature. In particular, major uncertainties exist for some regions such as Transition Economies (TE), Middle East and North Africa (MENA), China but also Japan (JPNKOR), Australia and Canada (AUCANZ). In the case of TE, Mendelsohn estimates appear really out of range and this is essentially due to the assumption of costless adaptation in agriculture, which is the predominant sector in that region. Instead, estimates for USA, Europe, Africa (SSA) and India (SASIA) are quite homogeneous across studies.

Figure A3.3. **Selected damage estimates for a doubling of CO_2 concentration**



Sources: Fankhauser, S. and R.S.J. Tol (1996), The social costs of climate change. The IPCC assessment report and beyond, *Mitigation and Adaptation Strategies for Global Change*, Vol.1, No 4. Tol; R.S.J. (2005), The marginal damage costs of carbon dioxide emissions: an assessment of uncertainties, *Energy Policy*, Vol. 33, No 16.

Fankhauser and Tol (1996) provide a critical assessment of this first set of estimates. Major limitations are the exclusion of low probability/high damage events, the absence of uncertainty and the static nature of the approach. Furthermore, future impacts of climate change depend not only on the rate of climate change, but also on the future social, economic and technological state of the world. The IPCC's TAR (IPCC, 2001) made little progress compared with SAR, and reported essentially the same ranges of estimates.

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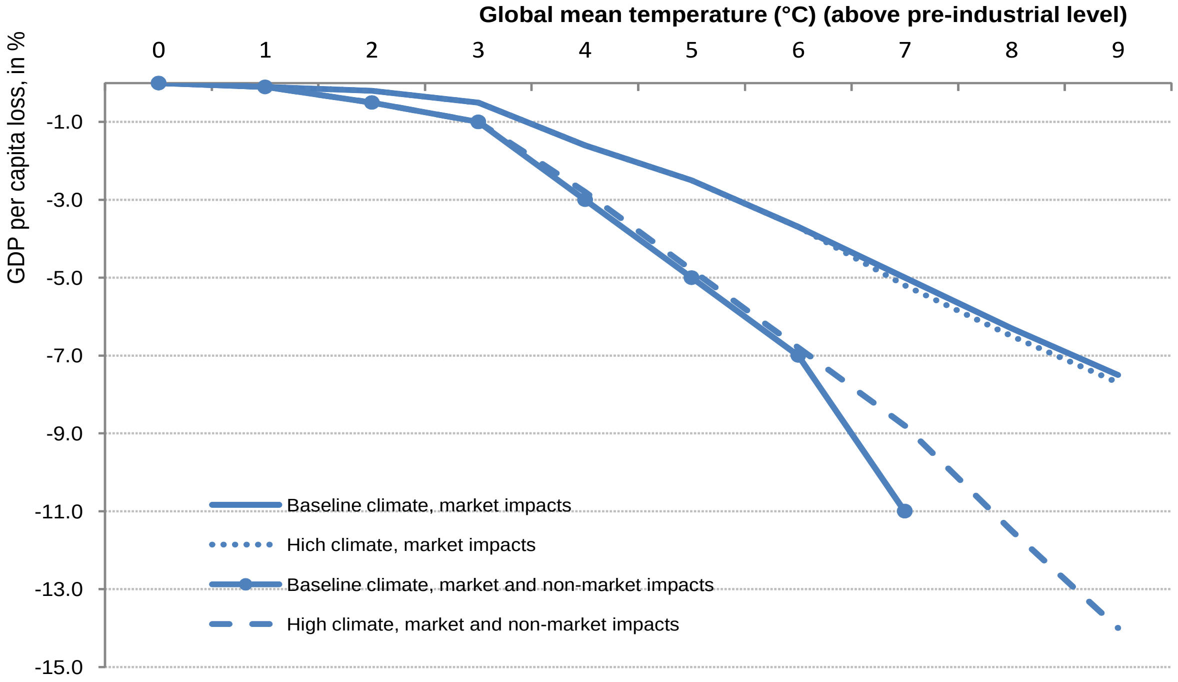
[35] Not all studies provide estimates for all regions, and the regional aggregation also differs across them.

Major uncertainties on non-market damages and low probability-high consequences events remained unsettled.

A different picture emerged from the Stern Review (Stern, 2007) where larger damage estimates were reported. Using the probabilistic set up embedded in the PAGE model, two different climatic scenarios are considered: *i)* a baseline scenario consistent with the assumptions in the IPCC's TAR (mean warming around 3.9°C relative to pre-industrial levels by 2100); and, *ii)* a high climate scenario including further climate feedbacks (*e.g.* weakening of carbon sinks, natural methane release from wetlands and thawing permafrost) that augment the probability of larger temperature increase and push mean temperatures up by 0.4°C. The analysis also provides three sets of damage estimates, depending on the type of climate change impacts considered: *i)* only the impacts of gradual climate change on market sectors; *ii)* market impacts and the risk of catastrophic events at higher temperature; and, *iii)* market impacts, risks of catastrophic events and non-market, indirect impacts on health and the environment.

As shown in Figure A3.4, results are more sensitive to a change in the categories of impacts rather than to a change in climate feedbacks (risks of catastrophe). The inclusion of climate change impacts on health and environment is estimated to double the costs of climate change. The risk of abrupt or large-scale climate changes can lead to a loss between 5% and 10% for a 5-6°C warming.

Figure A3.4. **Income per capita losses induced by climate change impacts in four different scenarios**[1]



1. Estimates represent the annual GDP impact (relative to a no-climate-change scenario) of a given increase in temperature, as observed at the time when this increase in temperature is reached. There are several ways to aggregate impacts across regions. All scenarios include the risks of catastrophic events. “High climate” scenarios explore the impact of large increases in temperatures on GDP.

Source: Stern (2007).

A comparison of previous findings with those reported in the Stern Review suggests that most IAMs possibly underestimated the full impacts of climate change. There are numerous reasons behind the difference between results reported in the Stern Review and the DICE/RICE, MERGE, FUND or Mendelshon models:

- The longer the time horizon considered, the larger the damages from climate change, as temperature is projected to keep increasing. Whereas most IAMs considered the dynamics up to 2100, the Stern Review took a longer perspective, up to 2200.
- Non-market impacts are either not considered, or when accounted for they are often under-estimated. Most IAMs are indeed based on out-of-date evidence, and most regional estimates are extrapolations from studies that have been carried out for one or two regions, typically the United States (DICE/RICE, MERGE and PAGE) or the United Kingdom (FUND). Most damage functions used in IAMs have not been updated according to latest evidence on climate change, except for the PAGE model used in the Stern Review, which takes into account new evidence on more rapid warming and large-scale changes to the climate system ("system" surprise). As a consequence, previous modelling exercises exhibit impacts that, on average, are quite small compared with the results described in the Stern Review, but also compared with the latest estimates such as those reported in the UNFCCC report (UNFCCC, 2007) or in the IPCC's FAR (IPCC, 2007).

The under-estimation of damages in earlier modelling exercises showed up in a recent study that revised Nordhaus' estimates of sectoral impacts for the US (Hanemann, 2008). This study is reviewed below, comparing Hanemann's results to Nordhaus' and to other estimates that have appeared in other recent publications (UNFCCC, 2007; Stern*,* 2007; ABI, 2005; World Bank, 2006).

Non-market impacts

Looking at most recent studies, it appears that Nordhaus and Boyer's estimates of 1990 $US33 billion for damages from a doubling of CO_2 concentration, attributed to all non-market sectors (health, ecosystems and infrastructure, with the exception of amenity and outdoor recreation activity) including catastrophic events, is too small.

UNFCCC (2007) reports a cost of protecting infrastructure from climate change in North America between 1990 $US4 and 64 billion already in 2030, when temperature increase is likely to be far below 2.5°C. The Association of British Insurers (2005) quantified the current risk capital needed to cover the vast majority of US hurricane, Japanese typhoon and European windstorm claims respectively to $US67 billion, $US18 billion and $US33 billion. The Munich Re insurance company developed a database which catalogues great natural catastrophes that had severe impacts on the economic system. Such a database can substantially underestimate damages from climate, because only large events are included. Yet estimated losses are in the order of 0.5% of current world GDP, and damages are increasing at a rate of 6% a year in real terms. Using this information and adjusting for the under-reporting of other minor impacts, UNFCCC (2007) extrapolated a cost between 1 and 1.5% of world GDP in 2030, which corresponds to 1990 $US850-1 350 billion. Nordhaus and Boyer reported similar figures for total impacts (Table A3.1), and for a temperature increase of 2.5°C, which is likely to occur at least several decades after 2030.

Hanemman (2008) reports a revised amenity benefit estimate downward to 1990 $US5 billion per year, from the 1990 $US17 billion per year estimated by Nordhaus and Boyer. Hanemman also estimates larger damages for health (1990 $US10 billion per year against 2 reported in Nordhaus) and for settlements and ecosystems (1990 $US11 billion per year versus 6).

Market impacts

Other two sectors for which Nordhaus and Boyer (2000) are likely to underestimate significantly the impacts from climate change are agriculture and water. Although these two sectors are treated separately, they are related, since about 70% of freshwater is indeed used for irrigation.

First of all, Nordhaus and Boyer observed that water systems are not very vulnerable to climate change and therefore they assumed zero costs. Instead, costs for adjusting water system can be high, as already observed by Tol (2000). More recently, Kirshen (2007) proposed an estimate of the investment needed to meet projected water demand in 2030 consistent with some IPCC scenarios (B1 and A1), in eight world regions. Based on that study, UNFCCC (2007) estimated the additional investment needs for water related adaptation only. Globally, adapting water infrastructure to climate change is estimated to require an investment of roughly 1990 $US180 billion already in 2030. Larger investments would be needed in Africa (1990 $US 56 billion), developing Asia (1990 $US58 billion) and Middle East (1990 $US37 billion).

According to the Stern Review (see Box 3.4 in Chapter III, Part II), the impacts on agriculture are likely to be more severe than previously thought, especially in tropical areas including India and Africa. Recent studies found a smaller carbon fertilisation effect, implying that increasing temperatures are more likely to have negative effects on crops productivity. Climate change impacts on agriculture may also rise significantly as soon as the combined effects of several factors are taken into account. The Stern Review provides the example of the 2003 European heat wave and drought, which led to several wildfires across Spain, Portugal and France, provoking a total loss in forestry and agriculture that has been evaluated 1990 $US15 billion (by Munich Re). Another example of joint effects is the loss in agriculture due to the loss of species, which can have implications on pollination and crops reproduction, for an economic value that has been estimated between $US30 and 60 billion.

Hanemman (2008) reported a damage of 1990 $US10 billion for water and of 1990 $US15 billion for agriculture, versus Nordhaus' estimates of respectively zero and 1990 $US4 billion. Even the latest studies (UNFCC, ABI, Munich Re) acknowledge the difficulties of assigning an economic value to all effects of climate change, especially over longer time horizons. Most available estimates look at 2030, when the increase in temperature is projected to be still moderate. The largest impacts would occur after 2050 or even later, after 2080. Given the non-linearity of climate damages, any linear or proportional extrapolation of those estimates is likely to underestimate the related costs. As a result, UNFCCC (2007) and World Bank (2006) acknowledge that their latest estimates are likely to be conservative. As more information becomes available across a wide range of regions and sectors, including some fields and places not covered in previous assessments, estimates of climate change impacts are likely to improve further in reliability and spatial detail.

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