PUBLIZIERBARER Endbericht Studien
(gilt nicht für andere Projekttypen)

A) Projektdaten

Titel:	Uncertainty in an Emissions Constrained World: Case Austria [PostCopUncertainty]
Programm:	ACRP 2010: 3rd Call for Proposals
Koordinator/ Projekteinreicher:	International Institute for Applied Systems Analysis (IIASA)
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Projektwebsite:	[soon to come under http://www.iiasa.ac.at/Research/ESM/index.html and http://www.iiasa.ac.at/~jonas/CV%20IIASA/IntroPage.pdf; IIASA's web site undergoes reconstruction]
Schlagwörter:	Greenhouse gas emissions, emission reduction, emission targets, emission constraints, temperature targets, sustainable land use, uncertainty, risk
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B) Projektübersicht

The *PostCopUncertainty* study is described in full length by

Jonas, M., V. Krey, F. Wagner, G. Marland, and Z. Nahorski, ~2013: Uncertainty in an emissions constrained world. *Clim. Change*.

The manuscript is currently undergoing final review/editing by the co-/authors before it will be externally reviewed for publication in a special journal issue of *Climatic Change* (to appear: in 2013). This special issue will summarize the outcome of the *3rd International Workshop on Uncertainty in Greenhouse Gas Inventories* (22–24 September 2010; Lviv, Ukraine), where the basic idea behind the *PostCopUncertainty* project had been presented by Jonas *et al.* for the first time:[1]

Jonas, M., V. Krey, F. Wagner, G. Marland and Z. Nahorski, 2010: Dealing with uncertainty in greenhouse gas inventories in an emissions constrained world. 3rd International Workshop on Uncertainty in Greenhouse Gas Inventories, 22–24 September, Lviv, Ukraine. In: Proceedings. Lviv Polytechnic National University, Lviv, Ukraine [pp. 300, ISBN: 978-966-8460-81-4], 119–128. Available at: http://ghg.org.ua/fileadmin/user_upload/book/Proceedengs_UncWork.pdf.

(See also *Options*, 2010/11: p. 19 and 26 for short overviews (i) on the importance of uncertainty in GHG inventories and (ii) the research behind the *PostCopUncertainty* project).

1 Executive Summary

The focus of our study is on uncertainty and its role in reconciling short-term commitments to reduce greenhouse gas (GHG) emissions and to meet long-term climate change objectives in the form of temperature targets. This topic had not been addressed adequately so far. The overall objective of our study is to integrate and expand our understanding of uncertainty in emissions across temporal scales. The motivation behind studying the issue of integration was twofold: We want (1) to know how to combine diagnostic (looking back in time) and prognostic (looking forward in time) uncertainty consistently and, thus, to bridge short and long-term perspectives (narrowly defined integration); and (2) to apply this knowledge to demonstrate its relevance in the context of translating mid-term emission constraints to emission targets on both the near-term time scale and the national scale (broadly defined integration). Our intention is to help avoid that the two scientific communities involved – the one coming from the short-term or emission-inventory end and the one coming from the long-term or climate-modeling end – continue following their research agendas without knowing how to integrate the uncertainty expertise of the other.

We establish a holistic emissions-temperature-uncertainty framework which allows any country to understand its national and near-term mitigation and adaptation efforts in a globally consistent and long-term emissions-temperature context. In this context, cumulative emissions are constrained and globally binding, and whether or not compliance with an agreed temperature target has actually been achieved is uncertain. The framework addresses the two objectives by way of studying various country examples.

Our study goes beyond current discussions on whether or not the future increase in global temperature can be kept below the 2ºC (more likely: 4ºC) temperature target. We show how to combine, and apply, diagnostic and prognostic uncertainty to broaden our knowledge base and take more educated (precautionary) decisions to reduce emissions in lieu of an agreed future temperature target; how to go about risk as an additional variable in dealing with both diagnostic and prognostic uncertainty; and address the difficulties to adequately embed cumulative emissions from land use and land-use change in an emission-constraining framework as well as the limits of treating uncertainty and risk in the case of sparse data as given, in general, for reporting technospheric GHG emissions by non-Annex I countries and for reporting emissions from land use and land-use change by all countries.

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[1] See http://ghg.org.ua/ for the presentation to the short paper included in the Workshop Proceedings.

1 Zusammenfassung

Der Schwerpunkt unserer Studie liegt auf der Unsicherheit und der Bedeutung, die ihr zukommt, um kurzfristige Verpflichtungen zur Reduktion von Triebhausgasen und langfristige Vorgaben zur Erreichung von Klima- bzw. Temperaturzielen in Einklang zu bringen. Unsere Studie verfolgt als grundlegendes Ziel, unser Wissen um die Unsicherheit in Emissionen zeitlich zu integrieren und zu expandieren. Es gibt zwei wesentliche Gründe, sich mit dem Aspekt der Integration genauer zu beschäftigen: (1) wollen wir verstehen, wie Unsicherheit diagnostischer Natur (mit Blick zurück) und Unsicherheit prognostischer Natur (mit Blick nach vorne) konsistent zu verknüpfen sind, um kurz- und langfristige Sichtweisen zu überbrücken (Integration im engeren Sinne); und (2) wollen wir dieses Wissen zur Anwendung bringen, um zu zeigen, wie wichtig es ist bei der Übersetzung von mittelfristigen Emissionsvorgaben in kurzfristige Emissionsziele auf nationaler Ebene (Integration im weiteren Sinne). Unsere Intention, den beiden involvierten wissenschaftlichen Gruppen – jene, die gedanklich vom kurzfristigen Ende kommt bzw. bei Emissionsinventuren ansetzt, und jene, die gedanklich vom langfristigen Ende kommt bzw. bei Klimamodellierungen ansetzt – zu helfen, dass sie nicht weiterhin wissenschaftlich vor sich hin arbeiten, ohne zu wissen, wie sie das Unsicherheitswissen der jeweils anderen Gruppe integrieren können.

Unser Vorgehen ist holistisch. Wir erstellen ein Emissions-Temperatur-Unsicherheits-Rahmenkonzept, welches jedem Land erlaubt, seine nationalen und kurzfristigen Emissionsminderungs- und Anpassungsanstrengungen in einem konsistenten und langfristigen Emissions-Temperatur-Kontext zu sehen. In diesem Kontext sind Emissionen kumulativ beschränkt und global bindend, und ihre Unsicherheit entscheidet darüber, ob ein vorab vereinbartes Temperaturziel tatsächlich eingehalten worden ist. Das Rahmenkonzept erlaubt, die beiden o.a. Integrationsziele am Beispiel einiger Länder aufzugreifen und zu analysieren.

Unsere Studie geht über die gegenwärtige Diskussion hinaus, ob der zukünftige Temperaturanstieg unter 2ºC (wahrscheinlicher jedoch: 4ºC) gehalten werden kann. Wir zeigen, wie Unsicherheiten diagnostischer und prognostischer Art zu kombinieren sind und wie sie anzuwenden sind, damit wir unsere Wissensbasis erweitern und bessere Vorkehrungen treffen können für die Reduktion von Emissionen unter Berücksichtigung eines zukünftigen Temperaturziels; wie mit Risiko als einer zusätzlichen Variable beim Umgang mit diagnostischer und prognostischer Unsicherheit zu verfahren ist; welche Schwierigkeiten wir überwinden müssen, um kumulative Emissionen aus der Landnutzung in das Emissions-begrenzende Rahmenkonzept adäquat übernehmen zu können; und inwiefern Unsicherheit und Risiko bei unzureichender Datenlage aufgelöst werden können (wie, z.B., im Falle der von nicht-Annex-I-Ländern berichteten technosphärischen Emissionen oder der von allen Ländern berichteten Landnutzungsemissionen).

2 Hintergrund und Zielsetzung

The focus of our study is on uncertainty and its role in reconciling short-term greenhouse gas (GHG) emission commitments and long-term climate change objectives in the form of temperature targets. This topic has not been addressed adequately so far and can be considered a legacy of the 2nd International Workshop on Uncertainty in Greenhouse Gas Inventories (see Jonas et al. 2010a: Section 4). Integration of knowledge including uncertainty across temporal scales is at the center of our study. We do not aim at advancing the treatment of uncertainty from a disciplinary perspective. To facilitate understanding, we summarize briefly the status of both climate change policy and the concept of constraining cumulative GHG emissions to meet an agreed temperature target in the future, and then we define our integration task in narrow and broad terms.

The status of climate change policy-making. An urgent task under the United Nations Framework Convention on Climate Change (UNFCCC) is to agree on a climate treaty beyond 2012, when commitments under the Kyoto Protocol (KP) will have ceased. Leaders of the world's major industrialized countries have formally agreed in the wake of the 2009 UN climate change conference in Copenhagen, Denmark, that the change in average global temperature should be held below a 2°C increase from its pre-industrial level (FCCC 2009a,b; Schiermeier 2009; USCAN 2009; WBGU 2009a,b: Section 2).

The Copenhagen Accord (FCCC 2009b: Point 1) states that "To achieve the ultimate objective of the Convention to stabilize greenhouse gas concentration in the atmosphere at a level that would prevent anthropogenic interference with the climate system, we shall, recognizing the scientific view that the increase in global temperature should be below 2 degrees Celsius, on the basis of equity and in the context of sustainable development, enhance our long-term cooperative action to combat climate change." However, international climate change negotiations have shown only limited progress on this issue since then and negotiators have even deferred action into the future. The 2011 UN climate change conference in Durban, South Africa, initiated a new process of negotiations to commence work in 2012, to be finalized no later than 2015 (in order for the adoption of a protocol, legal instrument or legal outcome under the Convention; requiring all Parties to meet as-yet-unspecified emission targets), and to come into effect from 2020 (Tollefson 2011).

The status of constraining GHG emissions. Compliance with the 2°C (or any other) temperature target can be expressed equivalently in terms of limiting cumulative GHG emissions globally (for example up to 2050) while considering the risk of exceeding this 2°C target (WBGU 2009b: Section 5; Allen et al. 2009; Meinshausen et al. 2009). Global cumulative emission budgets constitute an important, methodologically robust step in translating long-term GHG concentrations or temperature targets (for example, for 2100) to mid-term emission constraints (here in terms of constraints until 2050). However, these need to be translated further, notably (i) to emission targets on the near-term time scale, and (ii) to emission targets on the national scale, so that governments can implement these through tangible policy efforts. The emission reductions required until 2050 for staying within the 2°C temperature target in 2050 and beyond are substantial: 50–80% below the 1990 level at the global scale, with even greater reductions for industrialized countries (EU 2007, 2009; Jonas et al. 2010a; FCCC 2011). This is why reaching this target was considered by some observers to be a political delusion already prior to the Copenhagen conference: "probably far beyond what real governments can achieve" (Victor 2009).

The system-analytical challenge of dealing with uncertainty. We start from where the 2nd Uncertainty Workshop ended: "The consequence of including inventory uncertainty in policy analysis has not been quantified to date. The benefit would be both short-term and long-term, for example, an improved understanding of compliance (already a research focus) or of the sensitivity of climate stabilization goals to the range of possible emissions, given a single reported emissions inventory. That is, given that emissions paths are sensitive to starting conditions and uncertain relative to what is being mandated, what is the probability that long-term targets might be missed? Further efforts in the latter direction are critical for addressing the practical concerns of policymakers" (Jonas et al. 2010a: Section 4.3).

The overall objective of our study is to integrate and expand our understanding of uncertainty in GHG emission estimates across temporal scales. Because more data are available we focus initially on the 2°C temperature target and disregard the current dispute over whether or not this target can be achieved. Later in the analysis we deviate to higher temperature targets (3 and 4°C) and expand the scope of our study. In detail we have two objectives. We want (1) to know how to combine diagnostic (looking back in time) and prognostic (looking forward in time) uncertainty consistently and, thus, to bridge short and long-term perspectives (narrowly defined ‘integration’); and (2) to apply this knowledge to demonstrate its relevance, preferably in the context of translating mid-term emission constraints to emission targets on both the near-term time scale and the national spatial scale (broadly defined ‘integration’). Our intention is to help avoid that the two scientific communities involved – the one coming from the short-term or emission-inventory end and the one coming from the long-term or climate-modeling end – continue following their research agendas without knowing how to integrate the uncertainty expertise of the other.

3 Projektinhalt und Ergebnis

Addressing the two objectives requires looking at a number of crucial issues: e.g., how to monitor compliance with emission targets and pledges, as well as sustainability, in lieu of uncertainty; which boundary conditions to follow in defining our emission-systems perspective (e.g., technosphere versus biosphere) while paying attention to officially and/or widely available data; and how to translate between different metrics to monitor emission changes. We do this in a holistic emissions-temperature-uncertainty framework that we provide and which allows any country to understand its national and near-term mitigation and adaptation efforts in a globally consistent and long-term emissions-temperature context. In this context cumulative emissions are constrained and globally binding, and whether or not compliance with an agreed temperature target has been achieved is uncertain. We are aware that we cannot address each of the aforementioned issues in depth here.

The emissions-temperature-uncertainty framework for countries follows directly from Meinshausen et al.’s (2009) global-scale research, which centers on constraining the increase in average global temperature to 2ºC from its pre-industrial level. Meinshausen et al. express compliance with this temperature target in terms of limiting cumulative CO_2 or CO_2-eq emissions between 2000–2049, while considering the uncertainty in both the cumulative emissions between 2000–2049 and the risk of exceeding the temperature target in 2050 and beyond.[2] We refer to the uncertainty in the cumulative emissions as prognostic (or ‘top-down’). This uncertainty is derived, in combination with the aforementioned risk, from a multitude of model-based, forward-looking emission-climate change scenarios.

Diagnostic (or ‘bottom-up’) uncertainty, on the other hand, relates to the risk that true (but unknown) GHG emissions are greater than historically inventoried emissions reported at a given point in time. GHG inventories contain uncertainty for a variety of reasons, and these uncertainties have important scientific and policy implications. It is important to recognize that diagnostic uncertainty stays with us also in the future. It becomes particularly crucial in the context of compliance with agreed commitments in the form of emission reductions or limitations. For most countries the emission changes agreed to under the KP are of the same order of magnitude as the uncertainty that underlies their combined (i.e., CO_2-equivalent; CO_2-eq) emissions estimates. Claims of compliance can easily become disputable in cases where countries claim fulfilment of their commitments to reduce or limit emissions (Jonas et al. 2010b).

Under the prime assumption that unaccounted emissions do not exist, our emissions-temperature-uncertainty framework allows combining bottom-up emission estimates with top-down, scenario-derived cumulative emission constraints. When uncertainty is brought into consideration, the framework also allows combining diagnostic with prognostic uncertainty consistently over time.

In contrast to diagnostic uncertainty and its bearing on the risk that true (but unknown) GHG emissions are greater than inventoried emissions, the interdependence between the uncertainty in both the cumulative emissions and the risk of exceeding a given temperature target (2ºC in the case of Meinshausen et al.) has been much less explored. For any given set of forward-looking emission-climate change scenarios, this interdependence obeys a principle similar to Heisenberg’s uncertainty principle. This becomes obvious from Fig. 3 in Meinshausen et al. and Fig. S1a in their supplementary information. The uncertainty in the cumulative emissions and the uncertainty in the risk of exceeding the given temperature target cannot be reduced simultaneously. If the first is reduced the latter increases

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[2] A better term for uncertainty resulting from looking forward in time would be ‘unsharpness’, here meaning that cumulative emissions and risk can only be grasped ‘unsharply’, i.e., in the form of intervals.

(and vice versa).[3] This interdependence poses a challenge for decision-makers because they have to deal with the two uncertainties simultaneously. We translate the uncertainty interdependence from 2ºC to other temperature targets (in particular, 3 and 4ºC) below. This translation is approximate but sufficient for the purposes of our study and realized with the help of Meinshausen (2005) (Figures 33 and 34 therein quantify the probability of overshooting global mean equilibrium warming ranging from 1.5 to 4ºC for different stabilization levels of CO_2-eq concentration).

We present examples of applying our emissions-temperature-uncertainty monitoring framework with the focus on selected countries. The selection is governed by data availability in the first place and system relevance (e.g., with reference to country seize or country emissions) in the second place, not by national circumstances. Instead, the emphasis is on attaining an overview on the limitations of our monitoring framework and existing knowledge, in particular with reference to uncertainty. This is also why we stay focused by selecting 1990 as our start year.

USA as a data-rich country example. Figure 1a (cf. also Tab. 1) shows that each individual within the US must reduce his or her GHG emissions on average between 88% and 74% between 1990 and 2050. The dark and light gray lines (solid and broken) indicate the reference pathways or emission target paths that emissions must follow to achieve universal per-capita targets between 3.0 and 6.4 t CO_2-eq. Countries that emit per-capita quantities above these lines will need to compensate by emitting below the gray lines before 2050 to ensure the targets are reached.

The emission target paths can be interpreted in terms of multiple combinations of uncertainty in both the per-capita emissions by 2050 and the risk of exceeding a specified temperature target at 2050 and beyond, here ranging between 2 and 4ºC. Table 2a reproduces min/max and max/min alternatives of these combinations.

The thick solid black curve shows the technospheric emissions of the six Kyoto GHGs (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6; excluding CO_2 emissions from land use and land-use change) between 1990 and 2009 as reported by the US to the UNFCCC, while the thin solid black curve additionally consideres fossil fuel emissions embodied in trade, indicating that the US turned from a net exporter to a net importer around 1993/94. When compared against the aforementioned emission target paths, it becomes clear that the US operates beyond a 4ºC global warming regime. The US' technospheric emissions fall far above the most upper emission target path which satisfies a cumulative emissions constraint of 2400 Pg CO_2-eq for 2000–2049 and which, as Table 2a indicates, must be interpreted preferably with reference to 4ºC (and higher) temperatures at 2050 and beyond.

Underneath, the (hardly visible) red line shows what per-capita emission levels the US would have committed to in 2010 had it ratified the Kyoto Protocol stipulating a 7% emission reduction. Per-capita emissions would have practically followed the 2400 Pg CO_2-eq constraint.

The solid black dot represents the estimated emissions for 2010 according to IIASA's GAINS model.

The broken blue and orange lines (the latter covers the first) show expected per-capita emission reductions for 2010–2020 according to the conservative and optimistic pledges made by the US in 2010 (the two pledges – 17% until 2020 relative to 2005 – are identical in the case of the US). The costs for achieving these pledges by applying known mitigation techniques are mentioned in the blue and orange-framed boxes (output of GAINS). The conservative and optimistic pledges to reduce emissions until 2020 are not necessarily identical for the other Annex I countries. IIASA's GAINS model is run in a mode that allows the exchange of emissions among Annex I countries, and between Annex I and developing countries (i.e., 'with Annex I trading' and 'with CDM measures'). The conservative and optimistic pledges of the other Annex I countries do not affect the pledge of the US to reduce emissions but impact the costs to achieve this reduction. The costs differ depending on whether GAINS applies conservative or optimistic country pledges. Negative costs mean that implemented emission reduction measures pay back already during their lifetime.

The ranges shown numerically in the red, blue and orange boxes and graphically by the 'I' shape at the end of the red, blue and orange lines reflect the current range of uncertainty (0.7–1.3 t CO_2-eq/cap) in estimating emissions bottom-up; or, alternatively, the undershooting required to reduce the risk from 50–0% that true (but unknown) emissions are greater than agreed targets or pledges. The uncertainty ranges take into account: (1) uncertainty in

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[3] Entering the aforementioned figures with a 'sharp' cumulative emissions value results in an 'unsharp' risk value of exceeding the 2ºC temperature target, and vice versa.

GHG inventories in both start (or reference) year and target (or commitment) year, and (2) uncertainty in the GHG inventory in only the target year.[4] They are derived by applying two of the six emission change-uncertainty analysis techniques described by Jonas et al. (2010b): the Und (undershooting) concept and the Und&VT (combined undershooting and verification time) concept. Adjusting the pledges of a country for undershooting – in the case of the USA from 17.2 to 16.5 t CO_2-eq / cap according to the Und concept and from 17.2 to 16.0 t CO_2-eq / cap according to the Und&VT concept – and reapplying GAINS allows specifying the uncertainty in mitigation costs (cf. blue and orange boxes).

With reference to 2050, a bottom-up uncertainty of this order has not been introduced and combined with the top-down uncertainties which we show (in gray) for the lowest and highest GEE (global emissions equity) targets (3.0 and 6.4 t CO_2-eq / cap, respectively). Considering bottom-up uncertainty would result in a downward shift of their uncertainty intervals derived top-down without reducing the associated (top-down) risks of exceeding agreed temperature targets (cf. Fig. 2).[5]

Both the solid green line and the solid brown line show per-capita emissions from land use and land-use change within the territory of the USA, the first LU emissions for 1990–2005 (from GCP's LU emissions for 1850–2005) and the second LULUCF emissions for 1990–2009 (reported by the US under the UNFCCC). The difference between the two is considerable. For comparison, the thin solid green line shows LU emissions for 1990–2010 (from GCP's LU emissions for 1850–2010) but for North America as a whole. GCP's LU emissions for 1850–2005 classify the US as a moderate sink and Canada as a moderate source (with the first being slightly greater than the second in absolute terms), while North America as a whole only turns from a moderate source to a moderate sink around 2006/07 according to GCP's LU emissions for 1850–2010.

Both the solid green dot and the solid brown dot correct the US' per-capita emissions from land use and land-use change for biomass embodied in trade ($eTrade_{LU}$) in 2000. The corrections refer to the GCP LU emissions for 1850–2005 and to the UNFCCC LULUCF emissions for 1990–2009. With these corrections we switch the perspective from production to consumption indicating that, while the directly human-impacted part of the US' terrestrial biosphere acts as a net sink, the country is also a net exporter of biomass. According to case 4 in Figure 3 (solid arrow), the USA should have a great interest to switch to a reporting that accounts for $eTrade_{LU}$.

Although data are only available for 2000 to study $eTrade_{LU}$, the magnitude of the adjustment involved in switching from a production to a consumption perspective is substantial and greater in relative terms than switching perspectives for technospheric emissions. The dotted gray lines acknowledge this finding, here with the focus on the US. They represent the paths to lower the country's per-capita emissions from land use and land-use change plus those embodied in $eTrade_{LU}$ to zero assuming that the terrestrial biosphere as of today (~2000) represents a sustainable state to be reached by 2050.

Figure 1b takes over some, not all, technospheric emission entries of Figure 1a. In addition, it shows three solid, dark to light, green lines. They reflect typical aggressive, long-term emission reduction scenarios (excluding CO_2 emissions from land use and land-use change; in t CO_2-eq / cap) as realized by GTEM, IMAGE and POLES for the US and explained in Section 4. Even these scenarios fail to meet the condition of equal emission shares above and below the gray reference pathway, which reflects the cumulative constraint of 1500 Gt CO_2-eq for 2000–2050 and ensures reaching the 2ºC target (cf. Tab. 2a). However, this looks different at the global scale. The additional thin solid light green line shows how per-capita emissions decrease globally. It belongs to POLES, one of the three emission reduction scenarios that had been extracted and used for the USA. The global emission reduction scenarios that are behind the other two scenarios for the US are not shown. They are very similar to the global

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[4] We employ a total uncertainty in relative terms of 7.5% (representing the median of the relative uncertainty class 5–10%) for reporting the emissions of the six Kyoto GHGs excluding emissions from LU in both reference and target year; and 0.75 for the correlation in these uncertainties (cf. Jonas et al. 2010b).

[5] Combining bottom-up and top-down uncertainty will be at the center of another study. However, we can indicate the order of magnitude involved: Employing a total uncertainty in relative terms of 10% (representing the mean of Marland and Rotty's 1984 precision estimate of 6 to 10% for a CI of 0.9, here with reference to a CI of 0.95; note that the inaccuracy at the global scale is not known and that the authors' precision estimate has never been reworked formally and is belived to be appropriate still) and 0.75 for the correlation in these uncertainties, results in a downward shift of 2–3% of the 1500 Pg CO_2-eq cumulative constraint for 2000–2049, depending on the emission change-uncertainty analysis technique applied.

POLES scenario shown in the figure. In 2050, the global POLES scenario undershoots the GEE target of 3.0 t CO_2-eq / cap (belonging to the 1500 Gt CO_2-eq constraint; cf. Tab. 1) considerably.

Emission intensity paths (in kg CO_2-eq per 2005 US $) for the USA that correspond to the per-capita emission reduction paths (solid, dark to light, green lines) are entered with the help of an additional vertical axis (cf. vertical axis to the right in Fig. 1b). The emission intensity paths correspond in color but are indicated as broken lines. The purpose of this exercise is to show that switching between different 'negotiation worlds' is straightforward, here from an 'equal emissions per capita world' to an 'emissions intensity world', and back. However, we do not elaborate this aspect of the monitoring framework further in our study.

Austria as a small country example under the EU as a data-rich legal entity. Figure 4 (cf. also Tab. 1) shows that each individual within Austria must reduce his or her GHG emissions on average between 71% and 37% between 1990 and 2050. In contrast to the US, Austria had agreed to an 8% emission reduction under the KP and to a 13% emission reduction (reflected in Fig. 4) under the EU burden sharing agreement (BSA). If Austria would have adhered to the BSA, its territorial emissions would have practically followed the target path belonging to the cumulative emissions constraint of 1800 Pg CO_2-eq for 2000–2049 (with 8.1 t CO_2-eq / cap in 2010), aiming at a temperature target of 3ºC (rather than 2ºC) at 2050 and beyond (cf. Tab. 2a).

In addition, Figure 4 shows Austria's targeted and projected emissions as specified for 2020 under Austria's energy strategy (ESAT) and 2030 in Austria's climate protection report (CPR) 2011 (BMWFJ/LFUW 2010; UBA 2011). These emissions translate to 8.7 and 8.8 t CO_2-eq / cap, respectively, in these years and fall above the emission target path belonging the cumulative constraint of 2400 Gt CO_2-eq (2020: 8.3 t CO_2-eq / cap; 2030: 7.6 t CO_2-eq / cap) but, at least, would ensure that Austria's emissions stay within the target path's uncertainty range (determined by the maximal uncertainty in the 2050 GEE value) and that a temperature target of 4ºC at 2050 and beyond does not get out of reach. However, this appears unlikely if we switch the perspective from production to consumption. Taking into account fossil-fuel embodied in trade increases Austria's territorial emissions. Austria is a (considerable) net importer.

The undershooting required to reduce the risk from 50 to 0% that (true) emissions exceed emission targets and pledges in 2010 (EU BSA), 2020 (ESAT), and 2030 (CPR 2011) is identical (if resolved to the first digit). It ranges between 0.3 to 0.6 t CO_2-eq / cap, depending on emission change-uncertainty analysis techniques applied.

Austria is too small to be resolved by the LU emission data (cf. Section 4) of the Global Carbon Project (GCP). Only LULUCF emissions for 1990–2009 (reported by Austria under the UNFCCC) are available, classifying Austria as a small sink. The brown dot corrects Austria's per-capita emissions from LULUCF for biomass embodied in trade ($eTrade_{LU}$) in 2000, indicating that Austria needed to net-import biomass to satisfy its consumption (cf. Fig. 1).

For comparison and to better understand the relevance of this (here: upward) correction, Figure 4 also shows for Europe as a whole both the GCP LU emissions for 1990–2005 and the UNFCCC LULUCF emissions for 1990–2009 (thin solid, green and brown, lines in the figure). The difference between the two is larger (by about a factor of two) than the production-to-consumption correction of Austria's LULUCF emissions in 2000. This observation is similar to our earlier observation for the US. The difference between its LU and LULUCF emissions also outstrips our (there: downward) corrections in 2000 of switching the perspective from production to consumption (cf. Fig. 1a). This relation – uncertainty in land use and land-use change emissions being greater than the production-to-consumption correction of these emissions – is opposite to how we can currently handle technospheric emissions, at least for countries with good emission statistics.

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Figures

Fig. 1a USA (1990–2050): National GHG emissions and removals and near-term mitigation policies and measures in the context of a globally consistent and long-term GHG emissions-temperature-uncertainty framework where technospheric emissions are budget-constrained (globally binding) for 2000–2049 while emissions from land use and land-use change (LU and LULUCF) reduce to zero, global temperature targets for 2050 and beyond fall between 2–4°C, and compliance with an agreed temperature target is uncertain both bottom-up and top-down and entails an uncertainty-dependant risk of noncompliance. For further explanations see text.

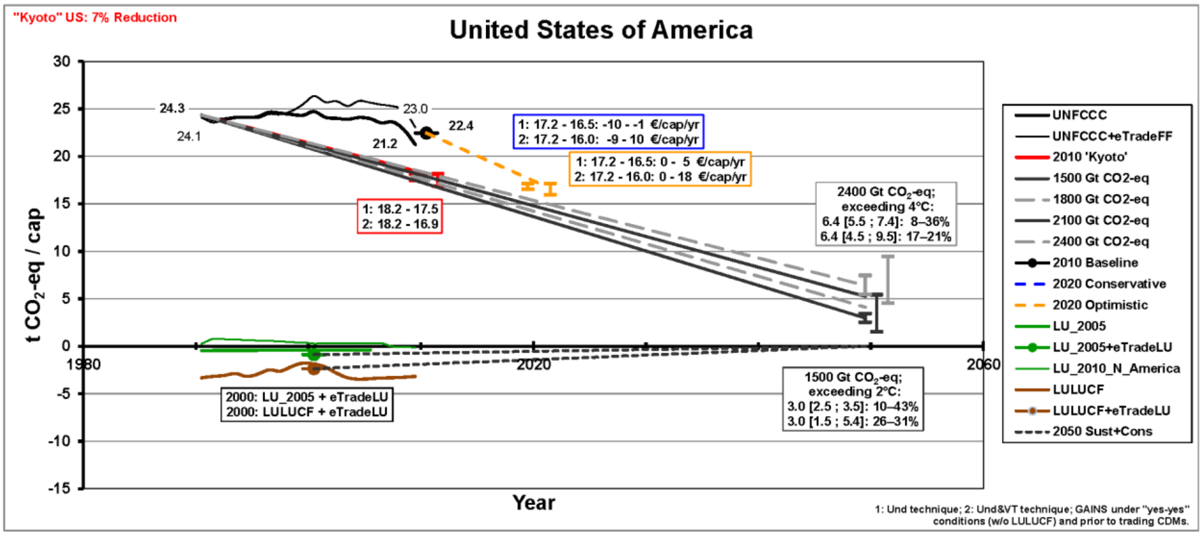
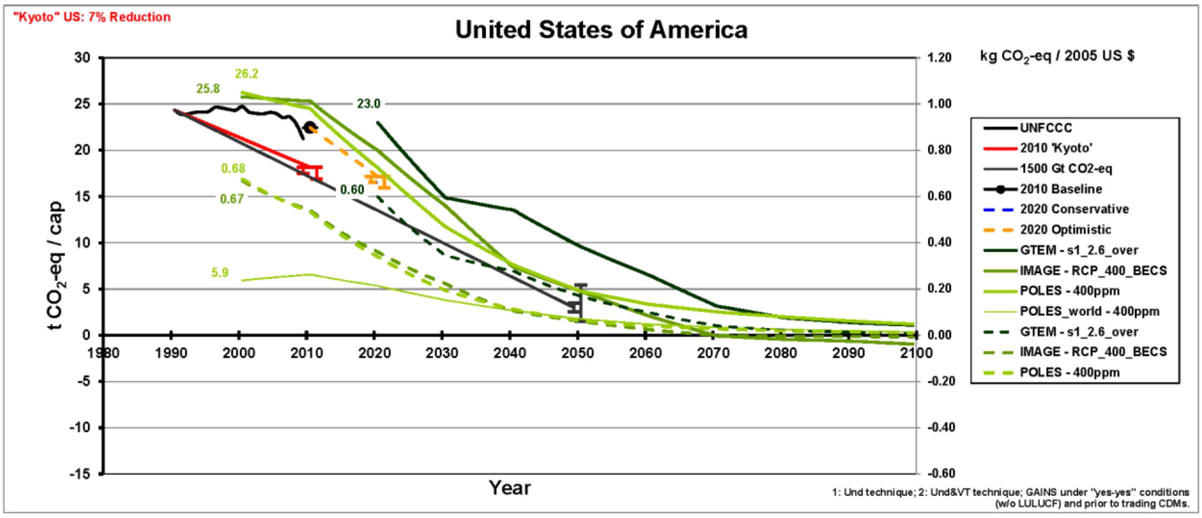


Fig. 1b USA (1990–2050): The figure takes over relevant technospheric emission entries of Figure 1a. In addition, the figure shows three globally-embedded, long-term emission reduction scenarios as realized by GTEM, IMAGE and POLES for the USA. They allow switching between emission reduction perspectives, here from emission reduction per capita (thick solid, dark to light, green lines; in t CO_2-eq / cap) to emission reduction per GDP (thick broken, dark to light, green lines; in kg CO_2-eq per 2005 US $), and back. The additional thin solid, light green line allows comparing the effectiveness of emission reduction from a country versus global perspective (here in terms of t CO_2-eq per capita). The line belongs to POLES, one of the three scenarios that had been extracted and used for the USA.



1: Und technique; 2: Und&VT technique; GAINS under "yes-yes" conditions (w/o LULUCF) and prior to trading CDMs.

Fig. 2 Combining top-down and bottom-up uncertainty (illustration). Top-down: An uncertainty in the cumulative emissions, thus in the GEE target, comes with an uncertainty in the risk (not shown) of exceeding a given temperature target (red dot; here at 2050). Bottom-up: Undershooting the GEE target helps to counterbalance the uncertainty contained in inventoried emissions and to reduce the risk that true (but unknown) emissions are greater than target emissions, i.e., the GEE target. Top-down and bottom-up: Only an additional undershooting beyond that applied to reduce the bottom-up risk to 0% leads to a downward shift of the top-down interval that characterizes the risk of exceeding the given temperature target.

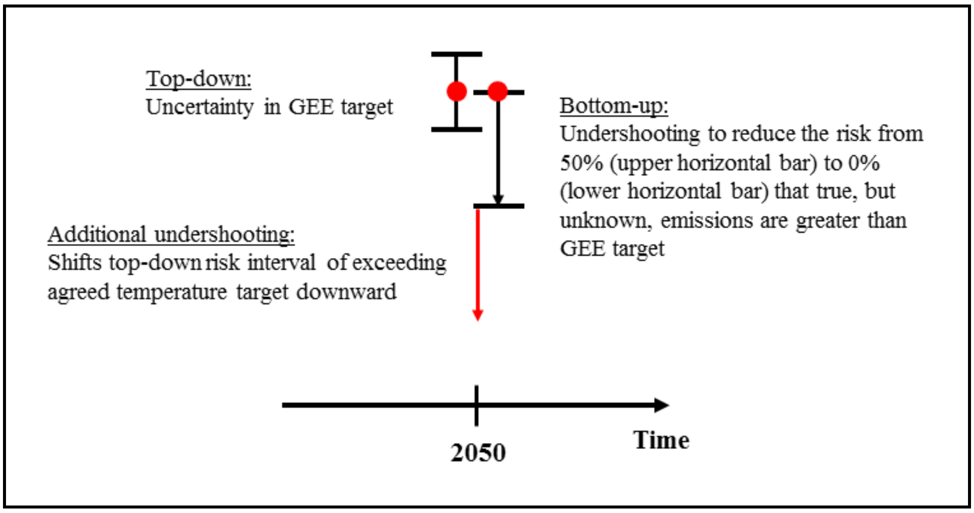


Fig. 3 Emissions resulting from LU (and LULUCF): Switching the perspective from production to consumption. We make use of LU emissions and HANPP (human appropriation of NPP) embodied in biomass trade (eTrade$_{NPP}$) to decide (i) whether a country's directly human-impacted terrestrial biosphere acts as a net source (≥ 0) or net sink (< 0); and (ii) whether the country is a net importer (≥ 0) or net exporter (< 0) of biomass. **A and solid (left) arrows in B:** Applying a globally averaged approach under which the appropriation of biomass results in a positive flux (local LU emissions) to the atmosphere, four cases can be distinguished that look at the effect of adding traded biomass (expressed as traded LU emissions, eTrade$_{LU}$) to national LU emissions: **(1)** Net source + net importer: The country's own LU emissions increase. The country has no interest to report eTrade$_{LU}$. **(2)** Net source + net exporter: The country's own LU emissions decrease. The country has a great interest to report eTrade$_{LU}$ because not considering eTrade$_{LU}$ means that the country takes the burden of other countries. **(3)** Net sink + net importer: The country's own removals (measured positively) decrease. The country has no interest to report eTrade$_{LU}$ because not considering eTrade$_{LU}$ means that the country can take full advantage of its removals. **(4)** Net sink + net exporter: The country's own removals increase because offsetting LU emissions are exported. The country has a great interest to report eTrade$_{LU}$. **Dotted (right) arrows in B:** The directly human-impacted part of a country's terrestrial biosphere is perceived as a whole (average over all local LU emissions) and serves as the principal unit for reporting GHG emissions and removals and as reference for the trade of biomass. To simplify the above case differentiation, we assume that countries only import or only export biomass: **(1)** Net source + import only: The country's own LU emissions increase or decrease depending on whether the exporting country exhibits a LU source or sink. **(2)** Net source + export only: The country's own LU emissions decrease. **(3)** Net sink + import only: The country's own removals (measured positively) decrease or increase depending on whether the exporting country exhibits a LU source or sink. **(4)** Net sink + export only: The country's own removals decrease.

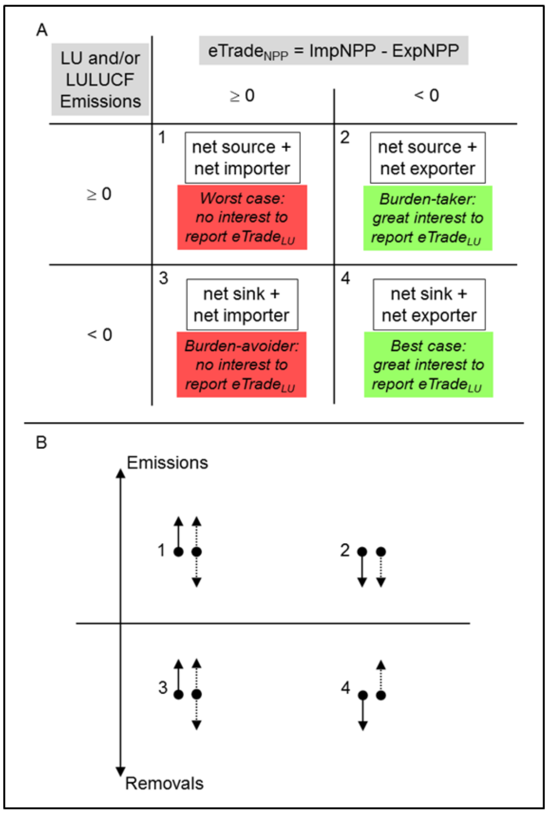
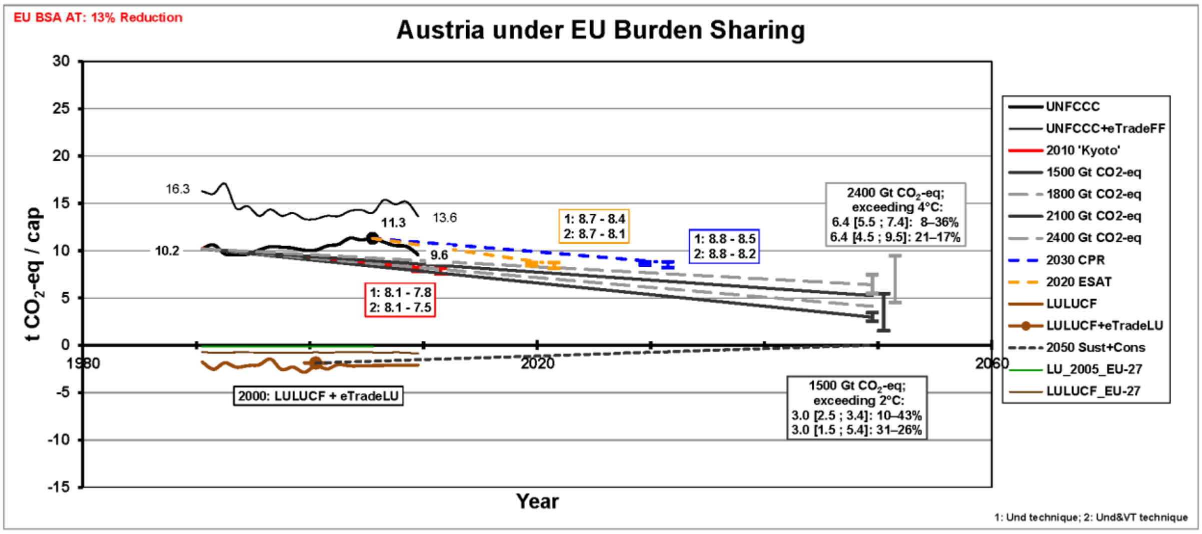


Fig. 4 Austria (1990–2050): See caption to Figure 5a and text.



Tables

Table 1 Per-capita GHG emissions (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6; excluding CO_2 emissions from land use and land-use change) globally and by country in 1990 and for 2050 required to meet global cumulative emission constraints for 2000–2050 ranging between 1500 and 2400 Gt CO_2-eq. Per-cent emission reductions refer to 1990–2050 (negative reduction = increase).

Global / Country	**1990 Emissions**	**2050 GEE target under a cumulative emissions constraint for 2000–2050 of**			
		1500 Gt CO_2-eq	**1800 Gt CO_2-eq**	**2100 Gt CO_2-eq**	**2400 Gt CO_2-eq**
	t CO_2-eq / cap	t CO_2-eq / cap	t CO_2-eq / cap	t CO_2-eq / cap	t CO_2-eq / cap
▨	▨	3.0	4.1	5.2	6.4
		1990–2050 emission reduction			
		% / cap	% / cap	% / cap	% / cap
Global[a]	5.9	50	30	11	-8
USA[b]	24.3	88	83	78	74
China[c]	3.3	11	-24	-59	-93
Austria[b]	10.2	71	60	48	37

[a] POLES; [b] UNFCCC; [c] CDIAC, EPA and UN POP.

Table 2 Interpreting the global cumulative GHG emission constraints for 2000–2050 of 1500 to 2400 Gt CO_2-eq with reference to the start year **a)** 1990 (1990–2050) and **b)** 2000 (2000–2050), and in terms of uncertainty in both the per-capita emissions (GEE) by 2050 and the risk of exceeding a temperature target at 2050 and beyond ranging between 2 and 4ºC. These uncertainties are inversely proportional. To facilitate the interpretation of a cumulative emissions constraint against a selected temperature target the table lists two combinations of uncertainties (min/max versus max/min).

a) Start year 1990 (1990–2050):

T	**Uncertainty** **min/max – max/min**	**in 2050 under a cumulative GHG emissions constraint for 2000–2050 of** **1500 Pg CO_2-eq**	 **1800 Pg CO_2-eq**	 **2100 Pg CO_2-eq**	 **2400 Pg CO_2-eq**
ºC	Uncertainty in emissions Uncertainty in risk	t CO_2-eq / cap %	t CO_2-eq / cap %	t CO_2-eq / cap %	t CO_2-eq / cap %
2	in emissions in risk of exceeding **2ºC**	3.0 [2.5 – 3.5] 10 – 43	4.1 [3.5 – 4.8] 20 – 58	▨	▨
	in emissions in risk of exceeding **2ºC**	1.5 – 5.4 26 – 31	2.1 – 6.3 38	▨	▨
3	in emissions in risk of exceeding **3ºC**	▨	4.1 [3.5 – 4.8] 5 – 26	5.2 [4.5 – 6.1] 11 – 40	▨
	in emissions in risk of exceeding **3ºC**	▨	2.1 – 6.3 12 – 17	3.5 – 7.8 21 – 26	▨
4	in emissions in risk of exceeding **4ºC**	▨	▨	5.2 [4.5 – 6.1] 4 – 21	6.4 [5.5 – 7.4] 8 – 36
	in emissions in risk of exceeding **4ºC**	▨	▨	3.5 – 7.8 9 – 13	4.5 – 9.5 17 – 21

b) Start year 2000 (2000–2050):

T	**Uncertainty** **min/max – max/min**	**in 2050 under a cumulative GHG emissions constraint for 2000–2050 of** **1500 Pg CO_2-eq**	 **1800 Pg CO_2-eq**	 **2100 Pg CO_2-eq**	 **2400 Pg CO_2-eq**
ºC	Uncertainty in emissions Uncertainty in risk	t CO_2-eq / cap %	t CO_2-eq / cap %	t CO_2-eq / cap %	t CO_2-eq / cap %
2	in emissions in risk of exceeding **2ºC**	2.3 [2.0 – 2.7] 10 – 43	3.7 [3.2 – 4.3] 20 – 58	▨	▨
	in emissions in risk of exceeding **2ºC**	0.8 – 5.1 26 – 31	1.5 – 6.2 38	▨	▨
3	in emissions in risk of exceeding **3ºC**	▨	3.7 [3.2 – 4.3] 5 – 26	5.1 [4.4 – 5.9] 11 – 40	▨
	in emissions in risk of exceeding **3ºC**	▨	1.5 – 6.2 12 – 17	3.2 – 7.9 21 – 26	▨
4	in emissions in risk of exceeding **4ºC**	▨	▨	5.1 [4.4 – 5.9] 4 – 21	6.5 [5.5 – 7.5] 8 – 36
	in emissions in risk of exceeding **4ºC**	▨	▨	3.2 – 7.9 9 – 13	4.4 – 10.0 17 – 21

3 Schlussfolgerungen und Empfehlungen

The focus of our study is on uncertainty and its role in reconciling short-term commitments to reduce GHG emissions and to meet long-term climate change objectives in the form of temperature targets. This topic had not been addressed adequately so far and had been listed at the 2nd International Workshop on Uncertainty in Greenhouse Gas Inventories as a problem that still requires tackling. The overall objective of our study is to integrate and expand our understanding of uncertainty in emissions across temporal scales. The motivation behind studying the issue of integration was twofold: We wanted (1) to know how to combine diagnostic (looking back in time) and prognostic (looking forward in time) uncertainty consistently and, thus, to bridge short and long-term perspectives (narrowly defined integration); and (2) to apply this knowledge to demonstrate its relevance in the context of translating mid-term emission constraints to emission targets on both the near-term time scale and the national scale (broadly defined integration). Our intention is to help avoid that the two scientific communities involved – the one coming from the short-term or emission-inventory end and the one coming from the long-term or climate-modeling end – continue following their research agendas without knowing how to integrate the uncertainty expertise of the other.

To these ends, we establish a holistic emissions-temperature-uncertainty framework which allows any country to understand its national and near-term mitigation and adaptation efforts in a globally consistent and long-term emissions-temperature context. In this context, cumulative emissions are constrained and globally binding, and whether or not compliance with an agreed temperature target has been achieved is uncertain. The framework addresses the two objectives by way of studying various country examples – the US, China and Austria. The selection of countries is governed by data availability in the first place and system relevance in the second place, not by national circumstances. The purpose is to attain an overview on the limitations of our monitoring framework and existing knowledge, in particular with reference to uncertainty. 1990 is our selected start (or reference) year.

Our study goes beyond current discussions on whether or not the future increase in global temperature can be kept below the 2ºC (more likely: 4ºC) temperature target. By way of analyzing the country examples, we show:

- that considering both diagnostic and prognostic uncertainty helps to considerably broaden our knowledge base and take more educated (precautionary) decisions to reduce emissions in lieu of an agreed future temperature target, but also that this is possible already.

- how diagnostic and prognostic uncertainty can be combined and that this combination is straightforward as they are independent. However, although possible, we still report diagnostic and prognostic uncertainty separately at this stage of our study. Their combination only makes sense if our systems views, bottom-up and top-down, account for all emissions. This is believed to be the case for the technosphere, but not yet fulfilled for the terrestrial biosphere.

- that we need to add risk as a variable in dealing with both diagnostic and prognostic uncertainty. However, in either case, uncertainty and risk are interdependent. Diagnostic uncertainty refers to the uncertainty contained in inventoried emissions. It translates into a risk that true (but unknown) emissions are greater than those estimated and reported. Accounting for this uncertainty, e.g., by way of undershooting, helps to limit, or even reduce, this risk. By way of contrast, prognostic uncertainty is derived from a multitude of model-based, forward-looking emission-climate change scenarios. The uncertainty contained in cumulative emissions links with the uncertainty in the risk that an agreed future temperature target is exceeded. The two cannot be reduced simultaneously (for any given set of forward-looking emission-climate change scenarios). This interdependence has been much less explored and poses a challenge for decision-makers because a guideline of how to deal with them in combination does not yet exist.

- that scientists face difficulties to adequately embed cumulative emissions from land use and land-use change in an emission-constraining framework because they cannot yet define an achievable future state of sustainability for the terrestrial biosphere *in toto*, in consideration of biodiversity, other biogeochemical cycles, etc.

- that treating uncertainty and risk reaches its limits in the case of sparse data as given, in general, for reporting technospheric GHG emissions by non-Annex I countries and for reporting emissions from land use and land-use change by all countries. The consequences of sparse data are associated with advancing two important and well-known disparities which are addressed by us and others. These are the emission-uncertainty disparity and the production-consumption disparity, both of which are expected to gain political momentum in the future.

The emission-uncertainty disparity refers to the observation that uncertainties reported for annual CO_2 emissions from land use and land-use change in Annex I countries – typically, they are greater than the uncertainties reported or technospheric CO_2 emissions – range from less than 10% to 100%, while the true uncertainty probably exceeds 100% in many or most non-Annex I countries (e.g., NRC 2010: Section 2). On the other hand, the land use and land-use change sector is responsible, on average, for a much greater component of total emissions in developing countries than in developed countries because of tropical deforestation and lower levels of industrial development – which manifests as a system-inherent emission-uncertainty disparity between developing and developed countries.

The production-consumption disparity is a direct consequence of how the KP is framed. Mitigation policy under the Protocol takes place at the country level and applies only to GHG emissions and removals that occur within the national territory or in offshore areas under the country's jurisdiction. This territorial-based approach does not consider transfers of emissions between countries as a result of international trade and may lead to a misleading interpretation of factors driving emission trends and therefore mitigation policies. In contrast to grasping the spatial transfer of fossil-fuel emissions embodied in trade, grasping the spatial disconnect between biomass production and consumption is less advanced. Both, however, pose a challenge for skillful decision-making because of the unsatisfying data situation.

- and that the interdependence in the uncertainty in both the per-capita emissions in 2050 and the risk of exceeding a 2, 3 or 4ºC global warming at 2050 and beyond cannot be resolved properly any more beyond certain limits, not only but also as a result of the graphically based, approximate approach that we apply. In particular, it becomes increasingly difficult to distinguish per-capita emissions (GEE) in 2050 from each other. Their uncertainties become too large and strongly overlap for cumulative emission constraints for 2000–2050 beyond ~2100 Gt CO_2-eq. As a result, our approach cannot be used for temperature targets at 2050 and beyond greater than 4ºC – which, unfortunately, may become necessary.

C) Projektdetails

4 Methodik

The methodological steps below are not all explained in full detail. Where explanations are kept short, the reader is referred to the forthcoming publication by Jonas et al. (cf. Section 1).

4.1 Global emission constraints

The notion of constraining cumulative emissions gained momentum with the publications of Allen et al., Meinshausen et al. and the German Advisory Council on Global Change (WBGU), all in 2009. It had been at the center of numerous scientific discussions for many years. The WBGU raised in 2005 the idea of determining an upper limit for the tolerable warming (i.e., mean global temperature) and deriving a global CO_2 reduction target by means of an inverse approach (i.e., backward calculation) (WBGU 1995). The budget concept (WBGU 2009b: Section 5) is the further development of this idea and links it to current international climate policy (but see Victor 2009).

The important point is that to keep atmospheric warming below 2ºC, the total amount of anthropogenic CO_2 emitted to the atmosphere must be limited. WBGU proposed adopting a binding upper limit for the total amount of CO_2, which could be emitted from fossil-fuel sources up to 2050, and allocating the defined amount of emissions subject to negotiation. WBGU proposed to base the allocation of emission rights on three principles: the polluter pays principle, the precautionary principle, and the principle of equality.[6]

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[6] Under the polluter pays principle, it is the industrialized countries that have a particular responsibility to cut their GHG emissions due to their high cumulative emissions in the past. The precautionary principle acknowledges, in line with the principle of sustainability, that timely action is required to prevent irreversible damage to present and future generations. The

WBGU broke down the global emissions budget to national emission budgets based on an equal per-capita basis. The budget concept contains four parameters that are political (i.e., negotiable) by nature. These are: (i) the start and (ii) end year for the total budget period; (iii) the cumulative emissions constraint or, equivalently, the probability of exceeding the 2ºC temperature target; and (iv) the year of reference for global population. Our choice of the four parameters – (i) 1990 (to be in line with the KP under which 1990 is the base year for most countries; Jonas et al. 2010b: Tab. 1,2) and 2000 (as an alternative to study the impact of another start year on national emission budgets); (ii) 2050; (iii) alternative (min-max and max-min) combinations of uncertainty in both cumulative emissions and risk of exceeding temperature targets ranging from 2 to 4ºC; and (iv) 2050 – differs from the options investigated by WBGU.[7] In addition, we also assess alternative as well as imperative global emission reduction concepts. These are linked, e.g., to reducing emission intensity for technospheric emissions and achieving sustainability across land use and land-use change (LU) activities *in toto*. Costs of mitigation measures (and the uncertainty in the costs that result from the uncertainty in emissions) can be expressed as marginal costs and per capita costs. In our study we refer to per capita costs.

A particular strength of applying the concept of constraining cumulative emissions globally is immediately obvious: it is compelling – no country can escape. If a country wants to choose another, e.g., later start or base year, it must make clear how its emissions for the missing years are balanced in a global context; i.e., how the community of other countries shall take over the country's emissions burden for these years.

However, another strength is less obvious. Our emissions-temperature-uncertainty concept allows combining diagnostic and prognostic uncertainty consistently over time (see also Section 3.5 below). Linking the two is not an easy task and is complex. Accounting emissions in a target or commitment year can involve constant, increased or decreased uncertainty as compared with the start (or base) year, depending on whether or not our knowledge of emission generating activities and emission factors has become more accurate. By way of contrast, uncertainty under a prognostic scenario always increases *per definitionem*. Research on how our diagnostic capability of monitoring inventory uncertainty has changed in the past is emerging only slowly (e.g., Marland et al. 2009; Hamal 2010). Although the emission change-uncertainty analysis techniques that we apply (cf. Section 3.5) allow factoring in a change in uncertainty, we follow the typical approach to date which assumes that our knowledge of uncertainty in the target or commitment year will be the same as today's in relative terms.[8]

4.2 From global to national: per-capita emissions equity by 2050

In this section we translate a cumulative emissions constraint from the global to the national level. We apply a 'contraction & convergence' approach as an initial reference approach (GCI 2012). This allows establishing global linear target paths for 1990–2050 (from 36.8 Pg CO_2-eq in 1990 to 25.9 Pg CO_2-eq in 2050) and 2000–2050 (from 39.5 Pg CO_2-eq in 2000 to 20.5 Pg CO_2-eq in 2050), and deriving global emission targets for 2050. To be in accordance with Meinshausen et al. (2009) we assume an emissions constraint of 1500 Pg CO_2-eq for the period 2000–2049 to which we add the CO_2-eq emissions that were emitted cumulatively between 1990 and 1999 in the case that we choose 1990 as start year. In addition, we stipulate that the emission targets derived for 2050 are exclusively available for technospheric emissions. The imperative that we follow for net emissions from LU activities is that these will be reduced linearly to zero by 2050; that is, we assume that deforestation and other LU mismanagement will cease and net emissions become sustainable by 2050. Our underlying assumptions are (i) that the remainder of the biosphere (including oceans)[9] stays in or returns to an emissions balance – which must be expected not to happen (Canadell et al. 2007); (ii) that this return, which refers to CO_2-C, implies in turn that the

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principle of equality postulates individuals' equal rights without distinction, to the benefits of the global commons (WBGU 2009b: Section 5).

[7] The four parameters in WBGU's 'historical responsibility' approach are (i) 1990, (ii) 2050, (iii) 25% and (iv) 1990; whilst they are (i) 2010, (ii) 2050, (iii) 33% and (iv) 2010 in its 'future responsibility' approach. In the two approaches the probability of exceeding the 2ºC temperature target refers to cumulative emission constraints for 2000-2049.

[8] So far, we are able to estimate and distinguish between changes in uncertainty due to (1) learning and (2) structural changes in emitters, but only for a few countries with good emissions statistics and inventories; and we believe to know that the first effect currently outpaces the second. However, this knowledge is still poor and not yet robust (cf. Hamal 2010).

[9] The remainder of the terrestrial biosphere is also called the not directly human-impacted part of the terrestrial biosphere.

emissions and removals of CH_4, N_2O, etc. also return to an emissions balance; and (iii) that these returns happen without systemic surprises of the terrestrial biosphere.

To achieve universally applicable global emissions equity (GEE) by 2050, we divide the aforementioned global emission targets by the population that we expect to live on Earth by 2050 – which is estimated to range between 7.5 and 10.2 10^9 with a best estimate of 8.8 10^9 and a confidence interval (CI) of 95%.[10] We find 2050 GEE values of 3.0 and 2.3 t CO_2-eq / cap for 1990–2050 and 2000–2050, respectively.

4.3 Uncertainty in cumulative emissions and risk for 2°C by 2050

Figure 3 of Meinshausen et al. (2009) and Figure S1a in their supplementary information show that the cumulative CO_2 (or CO_2-eq) emissions for 2000–2049 and the risk of exceeding 2°C global warming at 2050 and beyond are interdependent. The uncertainties in both the cumulative emissions and the risk of exceeding the 2°C target are inversely proportional. The 2°C Check Tool provided by Meinshausen et al. allows exploring this relationship. In this section we apply this tool to derive min/max and max/min uncertainty combinations for cumulative emissions and risk. It is sufficient to derive these combinations for 2000–2049. In the case that we choose 1990 as start year, the cumulative CO_2-eq emissions for 1990–1999 add to the cumulative CO_2-eq emissions for 2000–2049, but the risk and the uncertainty in the risk do not change.

4.4 Uncertainty in cumulative emissions and risk for 3 and 4°C by 2050

In this section we translate the min/max and max/min uncertainty combinations for cumulative emissions and risk from 2ºC to other global temperature targets, in particular, 3ºC and 4ºC. This translation is graphically based and approximate but sufficient for what we seek to explore: The stepwise release of the global temperature target for 2050 and beyond from 2 to 4ºC translates into a stepwise release (increase) of the 2050 GEE value. The crucial question is whether these GEE values can still be distinguished from each other given the uncertainties in both cumulative emissions and risk which underlie them.

The aforementioned translation is realized with the help of Figures 33 and 34 in Meinshausen (2005), which quantify the risk (in %) of overshooting global mean equilibrium warming ranging from 1.5 to 4°C for different stabilization levels of CO_2-eq concentration (in ppmv). We proceed in three steps, the result of which is Table 2. The table is to be read as follows: The cumulative GHG emissions constraint for 2000–2050 of 1800 Gt CO_2-eq with reference to start year 1990 (cf. Tab. 2a) results in a risk of exceeding the 2ºC temperature target ranging between 20 and 58% if the per-capita emissions (GEE) in 2050 center around 4.1 t CO_2-eq within the interval from 3.5 to 4.8 t CO_2-eq. If the latter is increased to 2.1 to 6.3 t CO_2-eq, the risk interval of exceeding the 2ºC temperature target decreases to about 38%. The two examples result in lower risks ranging between 5–26% and 12–17%, respectively, if the 1800 Gt CO_2-eq constraint is interpreted with regard to exceeding the 3ºC temperature target.

The comparison of the min/max uncertainty combinations – i.e., minimal uncertainty in GEE in 2050 and maximal uncertainty in the risk of exceeding 2, 3 or 4ºC at 2050 and beyond – across cumulative emission constraints for 2000–2050 ranging from 1500 to 2400 Pg CO_2-eq (or for GEE in 2050 ranging from 3.0 to 6.4 t CO_2-eq / cap) shows that they increasingly overlap. That is, it becomes increasingly difficult to distinguish GEE values from each other. For example, with regard to exceeding the 4ºC temperature target: for the cumulative emissions constraint of 2100 Gt CO_2-eq the GEE uncertainty range goes from 4.5 to 6.1 t CO_2-eq / cap (with its center at 5.2 t CO_2-eq / cap). For comparison, for the cumulative emissions constraint of 2400 Gt CO_2-eq the GEE uncertainty range goes from 5.5 to 7.1 t CO_2-eq / cap (with its center at 6.4 t CO_2-eq / cap) (cf. columns '2100 Pg CO_2-eq' and '2400 Pg CO_2-eq' in Tab. 2a).

The additional comparison of Table 2a (start year 1990) with Table 2b (start year 2000) also indicates that uncertainty becomes too large for cumulative constraints for 2000–2050 beyond ~2100 Gt CO_2-eq. Per-capita emissions (GEE) in 2050 cannot be distinguished properly any more. This leads us to conclude that we are at the limits in terms of resolution of our graphical-based approach to interpret the interdependence in the uncertainty in both per-capita emissions by 2050 and risk of exceeding a temperature target at 2050 and beyond.

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[10] IIASA's World Population Program reports 7.8 and 9.9 for the 10th and 90th percentiles.

4.5 Uncertainty in inventoried emissions

In this section we introduce (bottom-up) uncertainty in GHG emission inventories and combine it with (top-down) uncertainty in cumulative emissions. Inventoried emissions contain uncertainty for a variety of reasons and, until recently, relatively little attention has been devoted to how uncertainty in emissions estimates is dealt with and how it might be reduced. This situation is slowly changing, with uncertainty analysis increasingly being recognized as an important tool for improving inventories of GHG emissions and removals (Lieberman et al. 2007, White et al. 2011).

Jonas et al. (2010b) make available six techniques to analyze uncertain emission changes (also called emission signals) that countries agreed to achieve by the end of the first commitment period of the Kyoto Protocol (2008-2012). The techniques allow analyzing uncertain emission signals from various points of view, ranging from signal quality (defined adjustments, statistical significance, detectability, etc.) to the way uncertainty is addressed (total uncertainty or trend uncertainty).[11] For most countries under the Kyoto Protocol the agreed emission changes are of the same order of magnitude as the uncertainty that underlies their combined (CO_2-eq) emission estimates. Any analytical technique, if implemented, could 'make or break' claims of compliance, especially in cases where countries claim fulfilment of their commitments to reduce or limit emissions.

In our study we apply two of the six techniques described by Jonas et al., the Und (undershooting) concept and the Und&VT (combined undershooting and verification time) concept. The uncertainty contained in inventoried emissions translates into a risk that true (but unknown) emissions are greater than those estimated and reported. Undershooting helps to limit, or even reduce, this risk.[12] The Und concept accounts for the trend uncertainty in the emission estimates between any two points in time, e.g., start (or reference) year and target (or commitment) year and correlates uncertainty between these two time points. The Und&VT concept also allows undershooting to limit the risk that true emissions are greater than those estimated and reported. In contrast to the Und concept, however, it accounts for the linear dynamics of the emission signal between the start year and target year, and the total uncertainty at the latter.

Bottom-up and top-down uncertainty can be easily combined as they are independent (cf. Fig. 1). The combination could even be expanded and applied in a way that undershooting not only reduces the risk that true emissions are greater than those estimated and reported (bottom-up) but also reduces the risk of exceeding a given temperature target (top-down). However, such an exercise only makes sense if our systems views, bottom-up and top-down, are consistent, by which we mean that all emissions are accounted for. At this stage of our study we report bottom-up and top-down uncertainty still separately and do not combine them.

4.6 Land use and land-use change until 2050

In this section we explain how we go about emission from LU activities. Land use and land-use change are discussed widely and controversially – either optimistically while focusing on selected regions and opportunities to reduce emissions, or unenthusiastically while focusing on the global carbon budget and LU mismanagement as an important, socio-economically rooted activity. This is reflected by the emissions from LU activities which are included in the multiple model-based, forward-looking global emission-climate change scenarios considered by Meinshausen and colleagues (2009). The model-derived cumulative CO_2 emissions from land-use activities range from -35 to 248 Pg CO_2 (80% range) over the period 2007 to 2049 with a median of 24 Pg CO_2. Cumulative emissions of 24 Pg CO_2 translate into an average of 0.56 Pg CO_2 / yr (0.15 Pg C / yr).

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[11] The total uncertainty reflects our diagnostic emission-accounting capabilities at a given point in time, that is, the uncertainty that underlies our past as well as our current accounting (i.e., in the start or reference year) and that we will have to actually cope with at some time in the future (i.e., in the target or commitment year). The trend uncertainty reflects the uncertainty of the difference in net emissions between any two points in time (e.g., start year and target year).

[12] Assuming that unaccounted emissions do not exist, the risk range is from 50% in the case of compliance with agreed emission targets or pledges, when we can judge with equal confidence that true emissions are ≤ or ≥ than (true) targets or pledges, to 0% in the case of overcompliance, when we can judge with certainty that (true) emissions are ≤ than true targets or pledges.

Net emissions from LU activities are the least certain in our current (diagnostic) understanding of the anthropogenic changes in the global carbon cycle (Peters et al. 2011a). They are about 0.9 ± 0.7 Pg C in 2010 and appear to have declined on average, from 1.5 Pg C during 1990–1999 to 1.1 Pg C during 2000–2009 (cf. also http://www.globalcarbonproject.org/carbonbudget/10/hl-full.htm and Pan et al. 2011). The net flux of carbon to the atmosphere from 1850 to 2010 is modeled as a function of documented land-use change and changes in above and belowground carbon following changes in land use, while unmanaged ecosystems are not considered (Houghton 2008).

Country-level emissions are equally difficult to deal with (IIASA 2007; Jonas et al. 2010c, 2011). Multiple estimates for a given country can differ considerably and reconciling different emission estimates is challenging because of the multitude of error sources. Summing up country estimates of carbon fluxes and reconciling these at the global level is not easy and further work is required to develop harmonized data and models to represent carbon uptake and emissions resulting from LU accurately (Höhne et al. 2010).

In the absence of a fundamental analysis of the state of carbon stocks in the future, we consider the case that the emission targets derived for 2050 are exclusively available for technospheric emissions and that deforestation and other LU mismanagement will cease by 2050, at which time net emissions from LU activities are balanced at, zero. Our underlying assumptions are those mentioned under (i) to (iii) in Section 4.2.

Given the long-response times inherent in the terrestrial biosphere (Jonas et al. 1999) and also needed for counter-measures to become effective (UNESCO-SCOPE 2006), we do not consider this case very realistic. Instead, it is meant to help us in two ways: To evaluate the challenge of reducing technospheric GHG emissions globally under the assumption that the terrestrial biosphere behaves deterministically (without surprises and feedbacks); and to escape treating the biosphere in terms of uncertainty with reference to precision (but not accuracy). Specifying precision only makes sense if our basic systems understanding of the terrestrial biosphere is adequate and this is far from being the case.

4.7 Accounting for known CO2 emission transfers

We recognize that accounting for emissions can be viewed from two different viewpoints, a production perspective and a consumption perspective. In this section we integrate the consumption perspective. Historical emission estimates are becoming available but not yet their uncertainties.

Globalization is increasing quickly and the distances bridged by trade flows are increasing rapidly, resulting in a progressive separation of production and consumption and increasingly opaque causal linkages between socio-economic drivers and ecological as well as social impacts (Haberl et al. 2009: 120).

Under the KP mitigation policy takes place at the country level and applies only to GHG emissions and removals that occur within the national territory or in offshore areas under the country's jurisdiction. This territorial-based approach does not consider transfers of emissions between countries as a result of international trade and may lead to a misleading interpretation of factors driving emission trends and therefore mitigation policies. For instance, accounting of international CO_2 transfers – based on a trade-linked global inventory of CO_2 emissions for 113 countries and/or regions and 57 economic sectors through time (1990–2008) while excluding emissions from LU – indicates that developed (Annex B) countries have collectively increased their import of goods and services from developing (non-Annex B) countries (Peters et al. 2011b: the GCP makes available updated data until 2010).[13] This implies that CO_2 emissions associated with production have been shifted elsewhere. The authors show that when CO_2 emissions associated with imports are counted the overall net transfer of emissions via international trade from developing to developed countries exceeds the territorial emission reductions committed by developed countries under the KP (EC 2011).

Grasping the spatial disconnect between biomass production and consumption is less advanced. Erb et al. (2009b) use the concept of embodied human appropriation of net primary production (HANPP) to map the global pattern of net-producing and net-consuming regions in the year 2000 (cf. also Haberl et al. 2007; Erb et al. 2009a). HANPP measures to which extent "human activities affect NPP (net primary production) and its availability in the

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[13] For the 39 countries included in Annex B to the KP see http://unfccc.int/kyoto_protocol/items/3145.php.

ecosystem as a source of nutritional energy and other ecosystem processes”.[14] In contrast, embodied HANPP (eHANPP) is defined as “the NPP appropriated in the course of biomass production, encompassing losses along the production chain as well as productivity changes induced through land conversion or harvest. By making the pressure exerted on ecosystems associated with imports and exports visible, eHANPP allows for the analysis of teleconnections between producing and consuming regions” (Haberl et al. 2009: 119, 121). According to Erb et al. (2009b), international net transfers of embodied HANPP amount to 1.7 Pg C / yr in 2000 and are thus of global significance. They outpace global net emissions from LU (cf. Section 4.6).

Reducing emissions from LU to zero requires discussing the state of sustainability (including the uncertainties involved) which the terrestrial biosphere is assumed to attain by 2050 under a 2, 3 or 4ºC temperature target. However, this discussion has not yet been taken up by the science community. Although the intention behind developing the HANPP concept was different at the time, we see it as a valuable starting point for a discussion on which ecological quantity to use to track attaining sustainability.

Below we make use of HANPP embodied in biomass trade to estimate the fraction of global LU emissions which is traded. This side-step is necessary because the current situation of LU data is troublesome. Net emissions from LU for 1850–2010, as employed in the most recent global carbon budget (see GCP’s carbon budget 2010; Peters et al. 2011a), only resolve large regions/continents, not yet large countries. This is the reason why we still preserve GCP’s previous set of global LU emission data. It only lists emissions until 2005 but it additionally resolves a small number of large countries or units of countries (Canada, China, the US and Europe as a whole). Their emissions can show considerable, and intolerable, discrepancies when compared – where possible – against the land use, land-use change, and forestry (LULUCF) emissions that these countries report under the UNFCCC.

Figure 3 illustrates the current data situation and how we cope with the problems of inconsistent and missing knowledge. On the one hand, LU and LULUCF emissions data – while, typically, being in disagreement to each other and also underestimating real emissions as seen top-down by the atmosphere – are considered sufficiently good to indicate whether the directly human-impacted part of a country’s terrestrial biosphere is a net source or net sink. On the other hand, HANPP embodied in biomass trade ($\mathrm{eTrade} = \mathrm{ImpNPP} - \mathrm{ExpNPP}$) is used to indicate whether a country is a net importer or net exporter of biomass.

Here we apply a globally averaged approach to link $\mathrm{eTrade}_{\mathrm{NPP}}$ with national LU emissions. Our approach assumes that HANPP and LU emissions – while following different reference and thus measurement systems – share an identical areal reference. That is, they refer to the same directly human-impacted part of the terrestrial biosphere. A direct consequence of the globally averaged approach is that the human appropriation of biomass, irrespective of where this appropriation takes place, results in a positive flux to the atmosphere (local LU emissions),[15] while a country can even exhibit negative LU emissions resulting from regrowth subject to past interference.

We use the ratio of net transfer of embodied HANPP to total HANPP to specify the fraction of global LU emissions which is traded ($\mathrm{eTrade}_{\mathrm{LU}}$) by country.[16] Traded LU emissions are added to a country’s national emissions from land use and land-use change (LU and/or LULUCF hereafter) by which we switch from a production to a consumption perspective (which we prefer because the consumption perspective is closer to discussing sustainability). Net transfers of LU emissions balance when globally summed.

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[14] Ito (2011) provides a historical meta-analysis of global NPP (1860s–2000s) which allows putting Haberl and Erb’s HANPP concept with reference to 2000 into a long-term temporal perspective.

[15] From the HANPP perspective, the globally averaged approach results in an actual NPP ($\mathrm{NPP}_{\mathrm{act}}$) which is smaller than that of potential vegetation (NPP_0). However, there exist locations where $\mathrm{NPP}_{\mathrm{act}}$ may even be larger than NPP_0 due to intensive land management, such as fertilization or irrigation (Erb et al. 2009a: Fig. 1). That is, the next higher (second)-order approach would have to consider LU emissions geographical-explicitly.

[16] Haberl *et al.* (2007: Tab. 1) estimate total HANPP in 2000 to be 15.60 Pg C (including human-induced fires), of which about 1.7 Pg C is internationally transferred (net transfer) according to Erb et al. (2009b: Tab. 2) (about 2.0 Pg C according to the data communicated to us).

4.8 Additional insights from models

We make use of two types of models that are prognostic or that we run in a prognostic mode to generate valuable additional insight and help us bridge reference concepts and norms. The first type encompasses IIASA's GAINS (Greenhouse gas – Air pollution INteractions and Synergies) model. GAINS allows broadening our contraction & convergence approach by making the step from emissions per capita to costs per capita in the context of discussing mitigation pledges of Annex I countries for 2020.[17]

The second type encompasses the class of large-scale, energy-economic and integrated assessment models, from which we selected three scenarios that stabilize atmospheric GHG concentrations at low levels as illustrative examples. The scenarios help us deviate from our contraction & convergence reference approach by making the step from emissions per capita to emission intensities measured in terms of emissions per GDP (gross domestic product) in the context of discussing emission reduction scenarios until 2100.

5 Arbeits und Zeitplan

The study has been finalized in time.

5 Publikationen und Disseminierungsaktivitäten

Jonas, M., V. Krey, F. Wagner, G. Marland, and Z. Nahorski, ~2013: Uncertainty in an emissions constrained world. *Clim. Change* (the manuscript is currently undergoing final review/editing by the co-/authors before it will be externally reviewed for publication in a special journal issue of *Climatic Change* which is to appear in 2013)

We had presented preliminary results at the 12th Austrian Climate Colloquium in 2011:

Jonas, M., V. Krey, P. Rafaj, F. Wagner, G. Bachner, K. Steininger, G. Marland, Z. Nahorski, 2011: Uncertainty in an emissions constrained world: Case Austria. In: *Klima, Klimawandel, Auswirkungen und Anpassung in Österreich (Climate, Climate Change, Impacts and Adaptation in Austria).* 12. Österreichischer Klimatag (12th Austrian Climate Colloquium), 21–22 September, Abstracts, Vienna, Austria. Abstract and presentation (V24) available at: http://www.austroclim.at/index.php?id=101.

I am determined to present our final results at the forthcoming 13th Austrian Climate Colloquium in 2012.

We had also planned to present our final results at the 2012 Scientific Steering Committee Meeting of the Global Carbon Project (GCP) – together with our proposal "Moving to a Low Carbon World: Austria's Mitigation & Adaptation Efforts in a Globally Consistent Uncertainty-Risk-Vulnerability Framework" under ACRP 2011 (4th call), which had been identified to become a scientific key activity under the GCP, subject to external funding. However, we relinquished this idea after our proposal was rejected during the ACRP review process.

There will be one or two interesting conferences during 2012 where I am inclined to present our final results as well: the 3rd International Conference on Earth System Modeling (17–21 September 2012, Hamburg); and at the Workshop on Uncertainty and Climate Change Adaptation, a CIRCLE-2 joint initiative in climate uncertainties (8–9 November 2012, Lisbon).

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[17] For the 41 countries included in Annex I to the Convention see http://unfccc.int/parties_and_observers/parties/annex_i/items/2774.php.