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UNCERTAINTY IN AN EMISSION CONSTRAINED WORLD

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Uncertainty in an Emissions Constrained World

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Abstract

The focus of this study is uncertainty and its role in reconciling short-term commitments to reduce greenhouse gas (GHG) emissions and long-term efforts to meet global warming targets. The overall objective of our study is to integrate and expand our understanding of uncertainty in emissions across temporal scales. We (1) combine diagnostic (looking back in time) and prognostic (looking forward in time) uncertainty consistently and, thus, bridge short and long-term perspectives; and (2) apply this knowledge to demonstrate its relevance in the context of translating emission constraints to emission targets on both the near-term scale and the national scale. We combine uncertainty from current emissions inventories with uncertainty from scenarios of future emissions. 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 that 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 country examples. We chose a contraction and convergence model as an illustrative foundation for this analysis

Our study does not primarily address whether or not the future increase in global temperature can be kept below the 2, 3 or 4°C (more likely 4°C) temperature target but uses these targets to demonstrate the framework. We show 1) how to combine, and apply, diagnostic and prognostic uncertainty to broaden our knowledge base and to take more precautionary decisions on emissions reduction given an agreed future temperature target; 2) how to treat risk as an additional variable in dealing with both diagnostic and prognostic uncertainty; and we also address 3) 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.

Keywords: Greenhouse gas emissions, cumulative emissions, emission constraints, temperature targets, emission reduction, sustainable land use, uncertainty, risk

Acronyms and nomenclature

act	actual
BSA	Burden sharing agreement
C	Carbon
CAIT	Climate Analysis Indicators Tool
cap	Capita
CDIAC	Carbon Dioxide Information Analysis Center
CH_4	Methane
CI	Confidence interval
CICERO	Center for International and Environmental Research
CO_2	Carbon dioxide
CPR	Climate protection report
D	Diagnostic
e	Embodied
ESAT	Energy strategy Austria
eq	Equilibrium
EPA	Environmental Protection Agency
eq	Equivalent
EU	European Union
Exp	Export
F	Fluorinated
FF	Fossil fuel
FCCC	Framework Convention on Climate Change
GAINS	Greenhouse gas - Air pollution INteractions and Synergies (model)
GCP	Global Carbon Project
GDP	Gross domestic product
GEE	Global emissions equity
GHG	Greenhouse gas
GTEM	Global Trade and Environment Model
GWP	Global warming potential
h	Harvest
HANPP	Human appropriation of NPP
HFC	Hydrofluorocarbon
IFF	Faculty of Interdisciplinary Studies
Imp	Import
IMAGE	Integrated Model to Assess the Greenhouse Effect
IPCC	Intergovernmental Panel on Climate Change
KP	Kyoto Protocol
LC	Land conversion and land use
LU	Land use and land-use change
LULUCF	Land use, land-use change, and forestry
max	Maximum
min	Minimum
NPP	Net primary production
N_2O	Nitrous oxide
P	Prognostic
PFC	Perfluorocarbon

POLES	Prospective Outlook on Long-term Energy Systems (model)
Pop	Population
SCOPE	Scientific Committee on Problems of the Environment of ICSU
SF_6	Sulfur hexafluoride
t	time
Trade	Trade
UN	United Nations
Und	Undershooting
UNFCCC	United Nations Framework Convention on Climate Change
VT	Verification time
WBGU	German Advisory Council on Global Change
WHRC	Woods Hole Research Center
WRI	World Resources Institute
Δ	Delta
0	Potential

1. Introduction

The focus of this study is uncertainty and its role in reconciling short-term greenhouse gas (GHG) emission commitments and long-term efforts to meet 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 (Jonas et al. 2010a: Section 4). We do not aim at advancing the treatment of uncertainty from a disciplinary perspective, rather the core of our study is on integrating the treatment of uncertainty across temporal scales. To facilitate understanding, we begin by summarizing very briefly the current status of both climate change policy and the concept of constraining cumulative GHG emissions to meet an agreed temperature target. Thereupon 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, and to come into effect from 2020 (Tollefson 2011).

The status of constraining GHG emissions. Compliance with the 2°C 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 the 2°C target (WBGU 2009b: Section 5; Allen et al. 2009; Meinshausen et al. 2009). Limiting global cumulative emissions constitutes a methodologically robust step in translating long-term GHG concentration or temperature targets to mid-term emission constraints. However, these emission constraints need to be translated further, notably (i) to emission targets in the near-term, 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 global annual emissions, with even greater reductions for industrialized countries (EU 2007, 2009; Jonas et al. 2010a; FCCC 2011). This is why reaching a 2°C target was considered by some observers to be a political delusion already prior to the Copenhagen conference (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 … 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?" (Jonas et al. 2010a: Section 4.3).

The overall objective of this 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 consider higher temperature targets (3 and 4°C). 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; and (2) to apply this knowledge to demonstrate its relevance in the context of translating emission constraints to emission targets on both the near-term scale and the national scale. 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.

Addressing the two objectives requires looking at a number of crucial issues, e.g.: (i) how to monitor compliance with emission targets and pledges in the presence of uncertainty; (ii) 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 (iii) how to translate among different metrics to monitor emission changes. We do this in a holistic emissions-temperature-uncertainty framework that allows any country to understand its national and near-term mitigation and adaptation efforts in a globally consistent and long-term 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 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 2°C from its pre-industrial level. Meinshausen et al. expressed 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 and the risk of exceeding the temperature target in 2050 and beyond.[1] We refer to the uncertainty in the cumulative emissions as prognostic. This uncertainty is derived, in combination with the aforementioned risk, from a multitude of model-based, forward-looking emission-climate change scenarios.

Diagnostic uncertainty, on the other hand, relates to the risk that true (but uncertain) GHG emissions are greater than the inventoried emissions reported at a given point in time. GHG inventories contain uncertainty for a variety of reasons related to our ability to measure or estimate emissions, 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 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 emissions estimates. Claims of compliance can easily become disputable (Jonas et al. 2010b).

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

Our emissions-temperature-uncertainty framework builds on the assumption that unaccounted emissions do not exist. It allows combining both emissions and uncertainty diagnostically and prognostically, i.e., consistently over time.

In contrast to diagnostic uncertainty and the associated risk that true (but uncertain) GHG emissions are greater than inventoried emissions, the interdependence between the uncertainty in cumulative emissions and the risk of exceeding a given temperature target (2°C 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. 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 (and vice versa). This interdependence poses a challenge for decision-makers because they have to deal with the two uncertainties simultaneously.

Our study is structured as follows: Section 2 gives an overview of the data, techniques and models that we employ. Section 3 provides the methodological overview and describes the steps taken to establish the holistic emissions-temperature-uncertainty framework issues. Section 3 prepares the basis for addressing our two objectives, which we do in Section 4. In section 4 we present examples of applying our emissions-temperature-uncertainty monitoring framework to selected countries. We summarize our findings and conclusions in Section 5.

2. Overview of data, techniques and models

We make use of emission and other data that are publicly available (Tab. 1). We refer to the time period 1990–2008/09 as the diagnostic part (D) of our study (although not all data are available up to 2008/09) and to the time period 2008/09 and beyond as its prognostic part (P).

In establishing the emissions-temperature-uncertainty framework for countries, we also employ a number of techniques and models that are publicly available and/or have been described in the scientific literature. Table 2 provides an overview of the techniques and models, the mode of applying them, and how their output is used.

3. Methodology

3.1 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. The WBGU had raised in 1995 the idea of determining an upper limit for the tolerable increase of the mean global temperature and deriving a global CO_2 reduction target by means of an inverse approach, i.e., a backward calculation (WBGU 1995). The budget concept (WBGU 2009b: Section 5) is the further development of this idea.

The important point is that to keep atmospheric warming below 2°C 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 among countries, subject to negotiation but based on the polluter-pays principle, the precautionary principle, and the principle of equality (WBGU 2009: Section 5).

WBGU thus broke down the global emissions budget into 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 year and (ii) end year for the total budget period; (iii) the cumulative emissions constraint or, equivalently, the probability of exceeding the 2°C temperature target; and (iv) the year of reference for global population. Our choices for the four parameters – (i) 1990 (to be in line with the KP) and 2000 (as an alternative to study the impact of another start year on national emission budgets); (ii) 2050; (iii) alternative combinations of uncertainty in both cumulative emissions and risk of exceeding temperature targets ranging from 2 to 4°C; and (iv) 2050 – differ from the options investigated by WBGU.[2] In addition, we also assess alternative as well as imperative global emission reduction concepts. These later are linked, e.g., to reducing emission intensity for technospheric emissions and to 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 that no country can escape. If a country wants to choose another, e.g., later start 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 (Section 3.5 below). Accounting emissions in a target or commitment year can involve constant, increased, or decreased uncertainty as compared with the start 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 with time. 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

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[2] 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 2°C temperature target refers to cumulative emission constraints for 2000-2049.

2010). For simplicity we assume that our knowledge of uncertainty in the target or commitment year will be the same as today's in relative terms.

3.2 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 for 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 (Tab. 3 and Fig. 1). 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 (we refer to 2050 as end year hereafter) 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 balance. Our underlying assumptions are (i) that the remainder of the biosphere (including oceans) stays in or returns to an emissions balance – which must be questioned (Canadell et al. 2007); (ii) that this return, which refers to CO_2-C, implies in turn that the 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%.[3] We find 2050 GEE values of 3.0 and 2.3 t CO_2-eq / cap for 1990–2050 and 2000–2050, respectively (Tab. 3 and Fig. 1).

3.3 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 2000–2050 and the risk of exceeding 2°C global warming in 2050 and beyond are interdependent. The uncertainties in the cumulative emissions and in the risk of exceeding the 2°C target are inversely proportional.[4] The 2°C Check Tool provided by Meinshausen et al. (Tab. 2) 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 2000–2050. 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 2000–2050, but the risk and the uncertainty in the risk do not change.

The 2000–2050 constraint of 1500 Pg CO_2-eq entails a risk ranging from 10–43% of exceeding 2°C, with its center at 26% (Tab. 4; see also Tab. 1 in Meinshausen et al.). By way of comparison, running the 2°C Check Tool (in a repetitive, trial-and-error mode) to determine the upper and lower CO_2-eq constraints for keeping the risk of exceeding 2°C constant at 26% we find 1189 and 1945 Pg CO_2-eq cumulative emissions, respectively,

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

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

acknowledging that the 2°C Check Tool does not allow inserting cumulative constraints for 2000–2050 below 1189 Pg CO_2-eq (see also Fig. S1a in Meinshausen et al.).

The uncertainty in cumulative emissions of 1189–1945 Pg CO_2-eq for 2000–2050 translates into an uncertainty in GEE values that depends on the choice of the start year (1990 or 2000). For 1990 as start year we find a GEE interval of 1.8–4.7 with its center at 3.0 t CO_2-eq / cap, and for 2000 as start year we find a GEE interval of 0.9–4.4 with its center at 2.3 t CO_2-eq / cap. Considering, in addition, the uncertainty in the 2050 population estimate, we find 1.5–5.4 t CO_2-eq / cap for 1990–2050 and 0.8–5.1 t CO_2-eq / cap for 2000–2050 (Tab. 5: column '1500 Pg CO_2-eq').

Finally, we apply a minor tweak to the min-max uncertainty combination. The case of no uncertainty in the cumulative emissions constraint (1500 Pg CO_2-eq) – this case comes with a maximum uncertainty in the risk of exceeding the 2°C target (10–43%) – is also impacted, if expressed on a per-capita basis, by the uncertainty in the population estimate. The respective GEE intervals are 2.5–3.5 t CO_2-eq / cap for 1990–2050 and 2.0–2.7 t CO_2-eq / cap for 2000–2050 (it is these adjusted GEE intervals that are reported in Tab. 5). We did not re-apply the 2°C Check Tool to adjust the uncertainty in the risk of exceeding 2°C.

3.4 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 2 to 3 and 4°C. 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 4°C translates into a stepwise increase of the 2050 GEE values. The crucial question is whether these GEE values can still be distinguished from each other given the underlying uncertainties in cumulative emissions and the risk.

The translation is realized with the help of Figures 33 and 34 in Meinshausen (2005), which quantify the risk of overshooting global mean equilibrium warming ranging from 1.5 to 4°C for different stabilization levels of CO_2-eq concentration. The details are outlined in the Supplementary Information (Note 2).

With this translation at hand and with the support of the 2°C Check Tool, we can explore the min/max and max/min uncertainty combinations investigated in Section 3.3 for cumulative emission constraints for 2000–2050 other than 1500 Pg CO_2-eq and with reference to temperature targets for 2050 and beyond other than 2°C. In the first step, we keep the temperature target at 2°C and expand our investigation of the Heisenberg-like uncertainty relationship over a range of cumulative constraints that is well covered by the 2°C Check Tool, here to cumulative constraints of 1800, 2100 and 2400 Pg CO_2-eq. In the next step we translate the risk contained in these min/max and max/min uncertainty combinations into the risk of exceeding 3 and 4°C. Table 5 summarizes the expansion and translation process.

To sound a note of caution, the assumptions underlying this expansion and translation process are that the risk of overshooting is more or less stable and independent of the particular warming situation, equilibrium or transient, when going from, e.g., 2 to 3°C; and that deviations from this assumption are minor compared to the considerable change in risk when going from 2 to 3°C under either warming, equilibrium or transient.

Table 5 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 (Tab. 5a) results in a risk of exceeding the 2°C 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 2°C temperature target decreases to about 38%. (Note that applying the 2°C Check Tool as described in Section 3.3 but to a cumulative emissions constraint for 2000–2050 of 1800, instead of 1500, Pg CO_2-eq does not encounter any limitations which is why the risk interval is minimal for maximal per-capita emissions and consists of a single value only.) 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 3°C 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 4°C in 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 4°C 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 7.4 t CO_2-eq / cap (with its center at 6.4 t CO_2-eq / cap) (columns '2100 Pg CO_2-eq' and '2400 Pg CO_2-eq' in Tab. 5a).

The additional comparison of Table 5a (start year 1990) with Table 5b (start year 2000) also indicates that uncertainty becomes too large for cumulative constraints for 2000–2050 beyond ~2100 Gt CO_2-eq. GEE values 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 in 2050 and beyond.

3.5 Uncertainty in inventoried emissions

In this section we introduce uncertainty in GHG emission inventories and combine it with uncertainty in cumulative emissions. Inventoried emissions contain uncertainty for a variety of reasons and analyzing uncertainty is an important tool for improving inventories (Lieberman et al. 2007, White et al. 2011).

Jonas et al. (2010b) describe six techniques to analyze uncertain emission changes (signals) and we apply two of those techniques here: the undershooting (Und) and the combined undershooting and verification time concept (Und & VT). The uncertainty contained in inventoried emissions translates into a risk that true (but uncertain) emissions are greater than those estimated and reported. Undershooting can help to limit, or even reduce, this risk from 50% (in the case of compliance without undershooting) to 0% (in the case of compliance with undershooting). The Und concept accounts for the trend uncertainty in the emission estimates between any two points in time, e.g., start year and target 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 but also accounts for the linear dynamics of the emission signal between the start year and target year, and the total uncertainty at the latter.

Diagnostic and prognostic uncertainty can be combined as they are independent (cf. Fig. 2). The combination can 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 but also reduces the risk of exceeding a given temperature target. However, such an exercise only makes sense if our systems views (bottom-up from ground to atmosphere and top-down from atmosphere to ground) are consistent, by which we mean that all emissions are accounted for. At this stage of our study we report diagnostic and prognostic uncertainty separately and do not combine them.

3.6 Land use and land-use change until 2050

In this section we explain how we deal with emissions from LU activities, which are included in the model-based, 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% interval range) over the period 2007 to 2050 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.

Net emissions from LU activities are the least certain in our current understanding of the anthropogenic changes in the global carbon cycle (Peters et al. 2011a). They are about 3.3 ± 2.6 Pg CO_2 in 2010 and appear to have declined on average, from 5.5 Pg CO_2 / yr during 1990–1999 to 4.0 Pg CO_2 / yr during 2000–2009 (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).

LU emissions at the country level are equally difficult to deal with (IIASA 2007; Jonas et al. 2010c, 2011) and have comparable uncertainty at least. 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 (Section 3.7), 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, when we require net emissions from LU activities to balance at zero.

Given the long response times inherent in the terrestrial biosphere (Jonas et al. 1999) and also the time needed for counter-measures to become effective (UNESCO-SCOPE 2006), we do not consider this case realistic. However, it does allow us to evaluate the challenge of reducing technospheric GHG emissions globally under the assumption that the terrestrial biosphere behaves deterministically (without surprises and feedbacks).

3.7 Accounting for known CO_2 emission transfers

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

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 offshore in areas under the country's jurisdiction. This territorial-based approach (production perspective) 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 (EC 2011). To account for international CO_2 transfers, we make use of the trade-linked global database for CO_2 emissions developed by Peters et al. (2011b). It covers 113 countries and/or regions and 57 economic sectors through time (1990–2008; see also Tab. 1: the GCP makes available updated data up to 2010) while excluding emissions from LU.

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 (see 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 ecosystem as a source of nutritional energy and other ecosystem processes".[5] 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 6.2 Pg CO_2 in 2000 and are thus of global significance. They outpace global net emissions from LU (Section 3.6).

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 4°C temperature target. Although the intention behind developing the HANPP concept was different at the time, we consider it useful for tracking sustainability (Supplementary Information: Note 3).

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 (GCP's carbon budget 2010; Peters et al. 2011a), only resolve large regions/continents, not yet large countries. We preserve GCP's previous set of global LU emission data because, although it only lists emissions until 2005, it does resolve 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 against the land use, land-use change, and forestry (LULUCF) emissions that these countries report under the UNFCCC. These discrepancies are also noted by the World Resources Institute, whose Climate Analysis Indicators Tool (CAIT) makes use of additional land-use change and forestry data published in the 2010 *World Development Report* to resolve the 25 largest contributors of these emissions for 1990–2005 (WRI 2011: Section 3).

We cope with the current data situation and the problem of inconsistent and missing knowledge as follows. On the one hand, we consider LU and LULUCF emissions data – they are typically in disagreement to each other and also underestimate real emissions as observed top-down by the 'atmosphere' – 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, we use HANPP embodied in biomass trade ($\mathrm{eTrade}_{\mathrm{NPP}} = \mathrm{ImpNPP} - \mathrm{ExpNPP}$) to indicate whether a country is a net importer or net exporter of biomass (Supplementary Information: Fig. S1).

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[5] 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.

We apply a globally averaged approach to link $eTrade_{NPP}$ with national LU emissions. Our approach assumes that HANPP and LU emissions 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 results in a positive flux to the atmosphere. We use the ratio of net transfer of embodied HANPP to total HANPP to specify the fraction of global LU emissions which is traded ($eTrade_{LU}$) by country.[6] Traded LU emissions are added to a country's national LU (or LULUCF) emissions by which we switch from a production to a consumption perspective. Net transfers of LU emissions balance when globally summed.

This approach is simple and straightforward, and the calculation of national plus traded emissions is unambiguous. Supplementary Information (Note 4) discusses an alternative approach.

3.8 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 (Tab. 2). 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.[7]

The second type model 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.

To ease discussions, we keep the focus in our model exercise on technospheric emissions and exclude CO_2 emissions from land use and land-use change.

The GAINS model provides a framework for a coherent international comparison of the potentials and costs for emission control measures, both for Kyoto GHGs and air pollutants. It estimates with which measures in which economic sector emissions of the six GHGs could be reduced to what extent, as well as the costs for such action. It identifies for each country the portfolio of measures that achieves a given reduction target in the most cost-effective way, and provides national cost curves that allow a direct comparison of mitigation potentials and associated costs across countries. Using a bottom-up approach that distinguishes a large set of specific mitigation measures, relevant information can be provided on a sectoral basis, and implied costs can be reported in terms of upfront investments, operating costs and costs (or savings) for fuel input. An on-line calculator is available on the Internet (http://gains.iiasa.ac.at/MEC) that enables a comparison of mitigation efforts between Annex I countries for four different regimes of flexible instruments (i.e., with and without JI trading of carbon permits within Annex I countries, and the use of CDM credits from non-Annex I countries).

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[6] Haberl *et al.* (2007: Tab. 1) estimate total HANPP in 2000 to be 57.2 Pg CO_2 (including human-induced fires), of which about 6.2 Pg CO_2 is internationally transferred (net transfer) according to Erb et al. (2009b: Tab. 2) (about 7.2 Pg CO_2 according to the data communicated to us).

[7] See http://unfccc.int/parties_and_observers/parties/annex_i/items/2774.php for Annex I countries to the UNFCCC.

The GAINS (and its predecessor, the RAINS) models have been applied before in international negotiations to identify cost-effective air pollution control strategies, and to study the co-benefits between GHG mitigation and air pollution control in Europe and Asia (Hordijk et al. 2007; Tuinstra 2007). Detailed documentation of the methodologies and assumptions that have been employed for the analysis of the various source sectors is available in companion documents (Amann et al. 2009; Borken-Kleefeld et al. 2009; Höglund-Isaksson et al. 2009). Open access to all input data that are used for the assessment is provided through the on-line implementation of the GAINS model (http://gains.iiasa.ac.at/Annex1.html).

For this study we have used the GAINS implementation of the World Energy Outlook scenario of the International Energy Agency (IEA 2009), which – to a limited extent – reflects the implications of the economic crisis. The pledges made by Annex I countries for the year 2020 were analyzed in Wagner and Amann (2009).

To illustrate how regional GHG emissions trajectories from scenarios generated with large-scale, energy-economic and integrated assessment models compare to the normative approach taken in this study, we use three scenarios that stabilize CO_2 equivalent concentrations around 450 ppmv by the end of the century (including emissions/removals from LU). They are compatible with reaching the 2°C target. Important methodological characteristics of the models producing these scenarios are: (1) they capture, in a single integrated platform, many of the key interactions that serve as the environment in which renewable energy technologies will be deployed, including interactions with other technologies, other parts of the energy system, other relevant human systems (e.g., agriculture, the economy as a whole), and important physical processes associated with climate change (e.g., the carbon cycle); (2) they are based economically in the sense that decision-making is largely based on economic criteria; (3) they are long-term and global in scale, but with some regional detail; (4) they include the policy levers necessary to meet emission outcomes; and (5) they have sufficient technology detail to create scenarios of renewable energy deployment at both regional and global scales. A more detailed discussion on energy-economic model and IAMs can be found in Krey and Clarke (2011).

Given that the results shown in Section 4 concentrate on country level information, we have selected models for this comparison that represent these countries individually. In addition, the three models used – GTEM, IMAGE, and POLES – are representatives of this model class that rely on different methodological approaches. GTEM (scenario taken from Gurney et al. 2009) is an intertemporal computable general equilibrium model that emphasizes the link between mitigation action and the economy and its different sectors; while POLES (Kitous et al. 2010) is a simulation model with high technology resolution in the energy system; and IMAGE (van Vuuren et al. 2007) is an integrated assessment model with an elaborate land use module. Regardless of these differences, decision making in all three models is based on economic criteria under first best assumptions, i.e., allowing full when-and-where flexibility for achieving global mitigation targets.

4. Results

We present examples of applying our emissions-temperature-uncertainty monitoring framework with the focus on two selected countries, the US and China. Supplementary Information (Note 5) includes a third example, Austria. We select 1990 as our start year.

4.1 USA, a data-rich country with high total and per-capita emissions

Figure 3a (cf. also Tab. 6) shows that in order to meet global cumulative emission constraints for 2000–2050 ranging between 1500 and 2400 Pg CO_2-eq, each individual within the US must reduce his or her production-based 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 currently 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.

As explained in Sections 3.3 and 3.4, the emission target paths can be interpreted in terms of multiple combinations of uncertainty in both the per-capita emissions in 2050 and the risk of exceeding a specified temperature target in 2050 and beyond, ranging between 2 to 4°C. Table 5a reproduces min/max and max/min alternatives of these combinations.

The thick solid black curve in Figure 3a 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 considers fossil-fuel emissions embodied in trade, indicating that the US turned from a net exporter to a net importer between 1994 and 1998. When compared against the aforementioned emission target paths, it becomes clear that the US operates beyond a 4°C global warming. 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 2000–2050 and which, as Table 5a indicates, must be interpreted preferably with reference to 4°C (and higher) temperatures in 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 shows estimated production-based 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% reduction 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 these reductions. 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 diagnostically; or, alternatively, the undershooting required to reduce the risk from 50 to 0% that true (but uncertain) emissions are greater than agreed targets or pledges. The uncertainty ranges take into account:

(1) uncertainty in GHG inventories in both start year and target year, and (2) uncertainty in the GHG inventory in only the target year.[8] They are derived by applying the two emission change-uncertainty analysis techniques mentioned in Section 3.5. 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, diagnostic uncertainty has not been introduced and combined with the prognostic uncertainties which we show (in gray) for the lowest and highest GEE targets (3.0 and 6.4 t CO_2-eq / cap, respectively). Considering diagnostic uncertainty would result in a downward shift of the prognostic uncertainty intervals without reducing the associated risks of exceeding agreed temperature targets (cf. Fig. 2 and Supplementary Information: Note 6).

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. The US should have a great interest to switch to a reporting that accounts for $eTrade_{LU}$ (cf. Supplementary Information: Fig. S2 – case 4, solid arrow).

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. They represent the paths to lower the US' 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 in 2050.

Figure 3b takes over some, not all, technospheric emission entries of Figure 3a. In addition, the figure 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 3.8. Even these scenarios fail to meet the condition of equal emissions above and below the gray reference pathway, which reflects the cumulative

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[8] 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 land use and land-use change in both reference and target year; and 0.75 for the correlation in these uncertainties (Jonas et al. 2010b).

constraint of 1500 Gt CO_2-eq for 2000–2050 and ensures reaching the 2°C target (Tab. 5a). However, this looks different at the global scale. The additional thin solid light green line belongs to POLES. It shows how per-capita emissions decrease globally. 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 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; Tab. 6) considerably.

Emission intensity paths (in kg CO_2-eq per 2005 US $) for the US 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. 3b). 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'.

4.2 China, a developing country with high total but low per-capita emissions

Figure 4a is similar to Figure 3a but shows data for China, a country with high total emissions, no commitments under the KP, and less abundant data on GHG emissions and sinks. We use CDIAC (CO_2) and EPA (non-CO_2) emission data to visualize China's technospheric emissions for 1990–2005 (Tab. 1) because emissions reported under the UNFCCC comprise only one year (1994). The difference between technospheric emissions in that year was about 0.5 CO_2-eq / cap (CDIAC-EPA: 3.9; UNFCCC: 3.4). The UNFCCC emissions value still falls below the highest emission target path which the figure resolves and which reflects the cumulative emissions constraint of 2400 Pg CO_2-eq for 2000–2050 (target path in 1994: 3.5 CO_2-eq / cap). For a better overview we entered only this emission target path. It indicates that China's per-capita emissions were allowed to increase by 93% between 1990 and 2050 (Tab. 6). But it also shows that, from about 2000 onward, China's emissions began to exceed this target path and its upper 'uncertainty wedge' (determined by the maximal uncertainty in the 2050 GEE value). To recall, the cumulative emissions constraint of 2400 Pg CO_2-eq must be interpreted preferably with reference to 4°C in 2050 and beyond. However, considering fossil-fuel emissions embodied in trade – China is a net exporter resulting in a reduction of its territorial emissions – brings its emissions back into the wedge-shaped uncertainty range.

GCP's LU emissions for 1850–2005 classify China as a moderate source before 1999/2000 and as a moderate sink thereafter. However, considering the import and export of biomass and, thus, embodied LU emissions – China was a net importer of biomass in 2000 – appears to nullify this sink and to re-classify China as a moderate source.

Figure 4b is similar to Figure 3b. As for the US, the aggressive, long-term emission reduction scenarios (in t CO_2-eq / cap) of GTEM, IMAGE and POLES fail to meet the condition of equal emissions above and below the gray reference pathway, which belongs to the cumulative constraint of 1500 Gt CO_2-eq for 2000–2050 and ensures reaching the 2°C target (Tab. 5a). However, in contrast to the US, two of the reduction scenarios (those of IMAGE and Poles) show that, in the long-term, China's per-capita emissions closely follow the global average (by POLES) or even fall below.

Another difference is the remarkable decrease of China's emission intensities realized by all three models. This, together with its low per-capita emissions and the projected rapid growth of its economy, helps to understand why China's national response strategy to climate change prioritizes improvement of energy conservation, reduction of energy intensity, and improvement of the efficiency of energy use (http://www.beconchina.org/energy_saving.htm).

5. Conclusions

The focus of this study is uncertainty and its role in reconciling short-term commitments to reduce GHG emissions and long-term efforts to meet global warming targets. The overall objective is to integrate and expand our understanding of uncertainty in emissions across temporal scales. As detailed objectives we have sought to (1) combine diagnostic (looking back in time) and prognostic (looking forward in time) uncertainty consistently and, thus, bridge short and long-term perspectives; and (2) apply this knowledge to demonstrate its relevance in the context of translating mid-term emission constraints to emission targets on both the near-term scale and the national scale.

We established a holistic emissions-temperature-uncertainty framework that 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 studying two country examples, the US and China. Our study does not primarily address whether or not the future increase in global temperature can be kept below the 2, 3 or 4°C (more likely 4°C) temperature target but uses these targets to demonstrate the framework. We show

- that considering both diagnostic and prognostic uncertainty helps to take more educated (precautionary) decisions to reduce emissions given an agreed future temperature target.
- how diagnostic and prognostic uncertainty can be combined, although 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 from ground to atmosphere and top-down from atmosphere to ground) are consistent and account for all emissions. This is believed to be the case for the technosphere, but is not yet fulfilled for the terrestrial biosphere.
- how to add risk as a variable in dealing with both diagnostic and prognostic uncertainty. Diagnostic uncertainty refers to the uncertainty contained in inventoried emissions. Accounting for this uncertainty, e.g., by way of undershooting helps to limit the risk that true emissions are greater than reported emissions. 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).
- 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*.
- 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.
- that the interdependence in the uncertainty in both the per-capita emissions in 2050 and the risk of exceeding a 2, 3 or 4°C global warming in 2050 and beyond cannot be

resolved properly beyond certain limits. It becomes increasingly difficult to distinguish per-capita emissions in 2050 from each other. The uncertainties become too large and strongly overlapping for cumulative emission constraints for 2000–2050 and beyond greater than ~2100 Gt CO_2-eq. As a result, our approach cannot be used for temperature targets in 2050 and beyond greater than 4°C.

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Figures

Fig. 1 Global linear emission target paths for 1990–2050 and global emission targets (global emissions equity, GEE, in parentheses) for 2050 (cf. Tab. 3). Emissions between 2000 and 2050 are assumed to be constrained by 1500 Pg CO_2-eq. Emissions are per annum and in Pg CO_2-eq (GEE in t CO_2-eq / cap). The global target paths are for (i) total GHG emissions (solid red line); (ii) total emission excluding emissions from land use and land-use change (LU), i.e., emissions from fossil-fuel burning and cement production and for technospheric GHGs other than CO_2 ('FF-plus'; solid brown line); and (iii) emissions from LU (solid green line). The 2050 global targets for total GHG emissions and FF-plus emissions are identical (25.9 Pg CO_2-eq and 3.0 t CO_2-eq / cap, respectively) because the 2050 global target for LU emissions is set to zero. The solid black and dashed black curves show actual estimates of total GHG emissions and LU emissions.

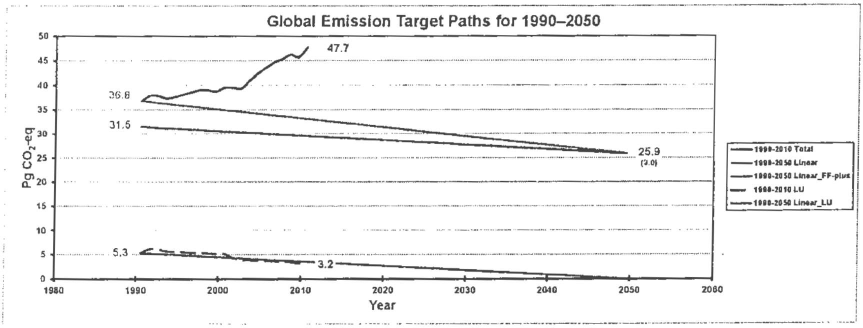


Fig. 2 Illustration of combining prognostic and diagnostic uncertainty. Prognostic: An uncertainty in the cumulative emissions, thus in the GEE target, comes with an uncertainty in the risk (not shown) of exceeding a given temperature target (red dot; here in 2050). Diagnostic: Undershooting the GEE target helps to counterbalance the uncertainty contained in inventoried emissions and to reduce the risk that true (but uncertain) emissions are greater than target emissions, i.e., the GEE target. Prognostic and diagnostic: Only an additional undershooting beyond that applied to reduce the diagnostic risk to 0% leads to a downward shift of the prognostic interval that characterizes the risk of exceeding the given temperature target.

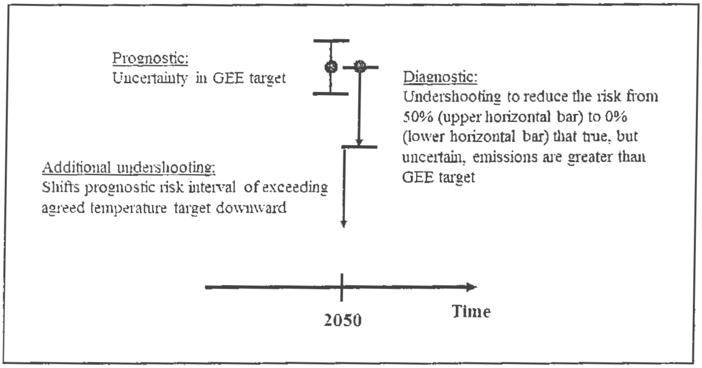


Fig. 3a USA (1990–2050): National GHG emissions and removals and near-term mitigation policies and measures in the context of a globally consistent and long-term GHG emissions-temperature-uncertainty framework. Technospheric emissions are budget-constrained (globally binding) for 2000–2050; while emissions 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.

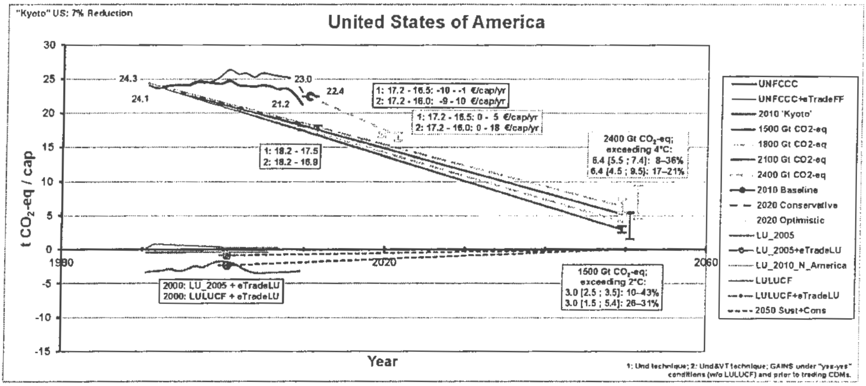


Fig. 3b USA (1990–2050): The figure takes over relevant technospheric emission entries of Figure 3a. In addition, the figure shows three globally-embedded, long-term emission reduction scenarios as realized by GTEM, IMAGE and POLES for the US. They allow switching between emission reduction perspectives, 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 $). The additional thin solid, light green line also belongs to POLES. It shows how POLES performs globally (in t CO_2-eq / cap). It allows putting the effectiveness of the US' emission reduction into a global perspective.

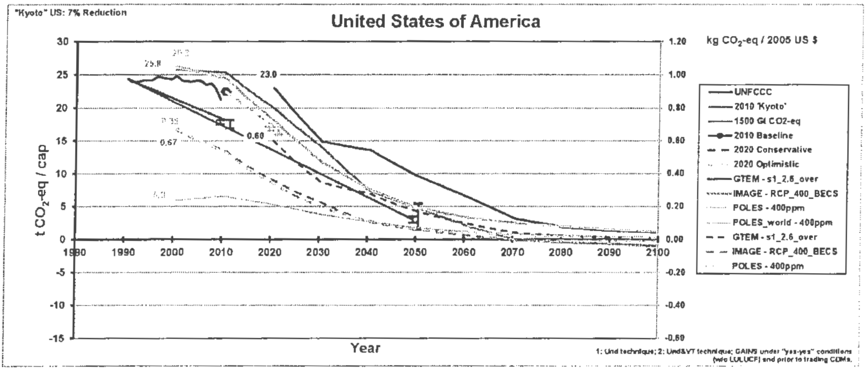


Fig. 4a China (1990–2050): See caption to Figure 3a and text.

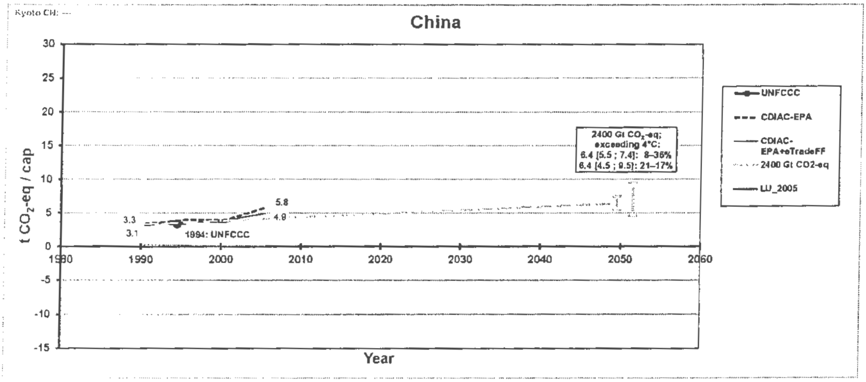
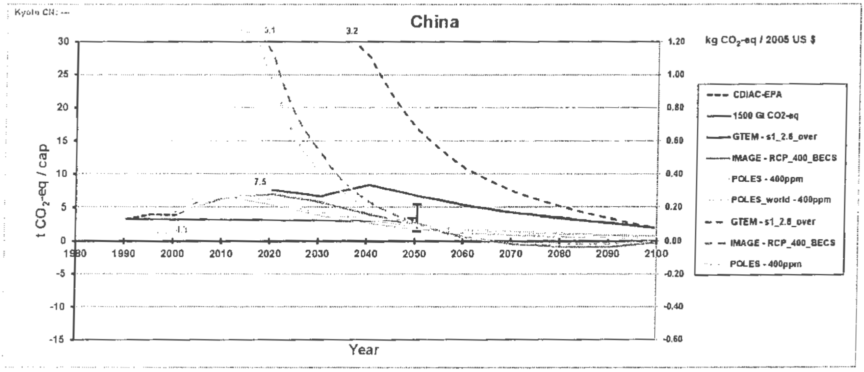


Fig. 4b China (1990–2050): See caption to Figure 3b and text.



Tables

Table 1 Overview of diagnostic (D) and prognostic (P) input data. 'Diagnostic' refers to the study period 1990–2008/09, while 'prognostic' refers to 2008/09 and beyond (to 2008/09 only – see population data of IIASA's World Population Program – if not covered diagnostically at the time). Dots indicate if additional data are available outside the study period. For abbreviations see acronyms and nomenclature.

Data	Source	Period	Spatio-temporal Resolution
Global carbon cycle			
D: Coupled carbon-climate-human system components (CO_2)	GCP[a]	…1990–2010	global annual
Technosphere: GHG emissions including emissions embodied in trade, population and gross domestic product			
D: CO_2, CH_4, N_2O, HFCs, PFCs, SF_6 (Kyoto GHGs)	UNFCCC[b]	1990–2009	by country (Annex I) annual
D: CO_2	CDIAC[c]	…1990–2008	globally by country annual
D: CH_4, N_2O, high GWP emissions	EPA[d]	1990–2005…	globally by country (117) in steps of 5 years
D: CO_2 (FF) embodied trade	CICERO[e]	1990–2010	by country/region (113) annual
D: Population, gross domestic product	UNFCCC[b]	1990–2009	by country (Annex I) annual
D: Population (2008 Revision)	UN Pop Division[f]	…1990–2005…	globally by country in steps of 5 years
Technosphere: Context relevant input data required for target setting at 2050			
P: Population	IIASA[g]	2008–2100	globally by world region annual
Technosphere: Context relevant input data required to enable model and scenario analyses			
D+P: GAINS baseline emissions (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6), population and GDP	GAINS[h]	1990–2030	by country (Annex I) in steps of 5 years
D+P: Long-term illustrative scenario data on population and related to GDP	van Vuuren et al. (2007), Gurney et al. (2009), Kitous et al. (2010)	2000–2100	globally by world region (and large countries) in steps of 5 (until 2010) and 10 years (until 2100)
Terrestrial Biosphere: CO_2 emissions including emissions embodied in biomass trade			
D: CO_2 from LU	WHRC[i]	…1990–2005	globally by world region (and large countries) annual
D: CO_2 from LU	WHRC[j]	…1990–2010	globally by world region (and large countries) annual
D: CO_2 from LULUCF	UNFCCC[b]	1990–2009	by country (Annex I) annual
D: CO_2 (HANPP) embodied in trade	IFF[k]	2000	by country (176) annual

[a] Global Carbon Project: http://www.globalcarbonproject.org/carbonbudget/10/data.htm.

[b] UN Framework Convention on Climate Change: http://unfccc.int/di/FlexibleQueries.do.

[c] Carbon Dioxide Information Analysis Center: http://cdiac.ornl.gov/trends/emis/overview_2008.html. The GCP updated the global carbon budget and carbon trend analyses in December 2011 (http://www.globalcarbonproject.org/carbonbudget/), among other things based on CDIAC's preliminary estimates of CO_2 emissions from fossil-fuel combustion and cement manufacture for 2009 and 2010. However, the latter emissions are only available globally and for a number of selected countries, but not yet for all countries.

[d] Environmental Protection Agency: http://www.epa.gov/climatechange/economics/international.html. The gases include the (direct) technospheric GHGs–other than CO_2–covered by the UNFCCC: CH_4, N_2O, and the high global warming potential (GWP) gases including substitutes for ozone-depleting substances and industrial sources of HFCs, PFCs and SF_6.

[e] Via the Global Carbon Project: http://www.globalcarbonproject.org/carbonbudget/10/data.htm; the data are from G.P. Peters from the Center for International Climate and Environmental Research (cf. also Davis et al. 2011 and http://supplychainco2.stanford.edu/).

[f] Via IIASA's World Population Program (K. Samir, pers. comm.); for the 2010 revision of the data from the UN Population Division see http://www.un.org/esa/population/.

[g] IIASA's World Population Program: http://www.iiasa.ac.at/Research/POP/proj07/index.html.

[h] IIASA's Mitigation of Air Pollution & Greenhouse Gases Program (via P. Rafaj, pers. comm.): http://gains.iiasa.ac.at/index.php/online-access/access-to-inputdata.

[i] Via the Carbon Dioxide Information Analysis Center: http://cdiac.esd.ornl.gov/trends/landuse/houghton/houghton.html; the data are from R.A. Houghton from the Woods Hole Research Center.

[j] The data are from R.A. Houghton (2011; pers. comm.) from the Woods Hole Research Center.

[k] The data are from K.-H. Erb (2012; pers. comm.) from the Vienna-based Institute of Social Ecology, Faculty of Interdisciplinary Studies (IFF) of the Alpen Adria University Klagenfurt.

Table 2 Overview of the applied techniques and models, their mode of application and output used in the study. For abbreviations see acronyms and nomenclature.

Technique / Model	**Mode of Application**	**Output / Use**
2°C Check Tool[a]	**P:** Statistical analysis building on multiple model-based, forward-looking global emission-climate change scenarios until 2100	Interdependence between the uncertainty in both cumulative emissions for 2000–2050 and risk of exceeding 2°C global warming in 2050 and beyond
Emission change-uncertainty analysis techniques[b]	**D:** Two-points-in-time approach applied at country scale between reference year (1990) and target year (e.g., 2010 or 2020) to construct linear target paths for emissions	Undershooting required, e.g., in 2010 or 2020 to reduce the risk that true (but unknown) emissions are greater than target/pledged emissions
GAINS model[c]	**P:** Two-points-in-time approach applied at country scale between reference year (1990) and target year (2020) to construct linear target paths for emissions	Potential emission reduction by (Annex I) country achievable between 2010–2020 (with reference to 1990) by means of available mitigation measures, and associated costs
Long-term scenario data[d]	**D+P:** Forward-looking, medium to long-range scenarios for the 21st century from large-scale energy-economic and integrated assessment models	Emissions (CO_2-eq, CO_2, CH_4, N_2O, F-Gases) and GDP by world region (resolving large countries) in 5 and 10-year steps until 2100, and atmospheric CO_2 concentration at 2100

[a] Meinshausen et al. (2009): https://sites.google.com/a/primap.org/www/nature

[b] Jonas et al. (2010b): http://www.iiasa.ac.at/Research/FOR/unc_prep.html

[c] Amann et al. (2008): http://gains.iiasa.ac.at/Annex1.html

[d] cf. Supplementary Information: Note 1

Table 3 Data to establish global linear emission target paths for 1990–2050 and 2000–2050 and to derive global emission targets (in Pg CO_2-eq) and global emissions equity (GEE; in t CO_2-eq / cap) for 2050 (cf. Fig. 1). Emissions between 2000 and 2050 are assumed to be constrained by 1500 Pg CO_2-eq. Emissions are per annum and encompass CO_2 emissions from fossil-fuel (FF) burning and cement production (other), from land use and land-use change (LU), and from anthropogenic GHGs other than CO_2 (non-CO_2). Data sources: Global Carbon Project, US Environmental Protection Agency, and IIASA's World Population Program (cf. Tab. 1).

Year	CO_2 FF Pg CO_2	CO_2 Other Pg CO_2	CO_2 LU Pg CO_2	Non-CO_2 Pg CO_2-eq	Total excl. LU Pg CO_2-eq	Total incl. LU Pg CO_2-eq
1990	21.97	0.58	5.32	8.93	31.48	36.79
1991	22.29	0.59	6.05	8.94	31.82	37.87
1992	22.05	0.61	6.20	8.96	31.62	37.82
1993	21.98	0.65	5.72	8.98	31.61	37.33
1994	22.34	0.68	5.57	9.00	32.03	37.60
1995	22.82	0.72	5.50	9.02	32.56	38.06
1996	23.27	0.74	5.43	9.12	33.13	38.56
1997	23.65	0.77	5.35	9.22	33.64	38.99
1998	23.58	0.77	5.32	9.32	33.66	38.98
1999	23.33	0.80	5.17	9.41	33.54	38.71
Cumulative 1990–1999	**227.29**	**6.90**	**55.62**	**90.90**	**325.09**	**380.71**
2000	23.92	0.83	5.24	9.51	34.26	39.51
2001	24.47	0.87	4.55	9.65	34.99	39.53
2002	24.67	0.92	3.92	9.79	35.38	39.30
2003	26.12	1.01	3.81	9.92	37.06	40.87
2004	27.43	1.09	3.74	10.06	38.59	42.33
2005	28.49	1.17	3.67	10.20	39.86	43.53
2006	29.32	1.30	3.67	10.36[b]	40.97	44.64
2007	29.91	1.40	3.48	10.51[b]	41.83	45.31
2008	30.67	1.42	3.45	10.67[b]	42.76	46.20
2009[a]	30.13	1.51	3.23	10.83[b]	42.48	45.70
2010[a]	31.87	1.64	3.19	10.99[b]	44.50	47.69
Cumulative 2000–2008	**245.00**	**10.02**	**35.53**	**90.68**	**345.69**	**381.22**
Linear Target Path	▨	▨	**2050 Target Pg CO_2-eq (t CO_2-eq / cap)**	▨	**2050 Target Pg CO_2-eq (t CO_2-eq / cap)**	**2050 Target Pg CO_2-eq (t CO_2-eq / cap)**
1990–2050	**For a global population of 8.75 10^9 in 2050**		**0.0 (0.0)**	▨	**25.90 (2.96)**	**25.90 (2.96)**
2000–2050			**0.0 (0.0)**	▨	**20.49 (2.34)**	**20.49 (2.34)**

[a] Preliminary estimates.

[b] By way of extrapolating emissions of anthropogenic GHGs other than CO_2 between 2005 and 2010.

Table 4 Uncertainty in the cumulative emissions for 2000–2050 versus uncertainty in the risk of exceeding 2°C global warming at 2050 or beyond.

2000–2050 CO_2-eq constraint [Pg CO_2-eq]		**1189[a]**		**1500**		**1945**
Lower end of probability range	**%**	5		10	→	26
Probability of exceeding 2°C	**%**	15		26		46
Upper end of probability range	**%**	31	←	43		66

[a] The 2°C Check Tool does not allow inserting cumulative constraints for 2000–2050 below 1189 Pg CO_2-eq.

Table 5 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 and b) 2000, and in terms of uncertainty in both the per-capita emissions (GEE) by 2050 and the risk of exceeding a temperature target in 2050 and beyond ranging between 2 and 4°C. 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**
°C	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 **2°C**	3.0 [2.5 – 3.5] 10 – 43	4.1 [3.5 – 4.8] 20 – 58	▨	▨
	in emissions in risk of exceeding **2°C**	1.5 – 5.4 26 – 31	2.1 – 6.3 38	▨	▨
3	in emissions in risk of exceeding **3°C**	▨	4.1 [3.5 – 4.8] 5 – 26	5.2 [4.5 – 6.1] 11 – 40	▨
	in emissions in risk of exceeding **3°C**	▨	2.1 – 6.3 12 – 17	3.5 – 7.8 21 – 26	▨
4	in emissions in risk of exceeding **4°C**	▨	▨	5.2 [4.5 – 6.1] 4 – 21	6.4 [5.5 – 7.4] 8 – 36
	in emissions in risk of exceeding **4°C**	▨	▨	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**
°C	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 **2°C**	2.3 [2.0 – 2.7] 10 – 43	3.7 [3.2 – 4.3] 20 – 58	▨	▨
	in emissions in risk of exceeding **2°C**	0.8 – 5.1 26 – 31	1.5 – 6.2 38	▨	▨
3	in emissions in risk of exceeding **3°C**	▨	3.7 [3.2 – 4.3] 5 – 26	5.1 [4.4 – 5.9] 11 – 40	▨
	in emissions in risk of exceeding **3°C**	▨	1.5 – 6.2 12 – 17	3.2 – 7.9 21 – 26	▨
4	in emissions in risk of exceeding **4°C**	▨	▨	5.1 [4.4 – 5.9] 4 – 21	6.5 [5.5 – 7.5] 8 – 36
	in emissions in risk of exceeding **4°C**	▨	▨	3.2 – 7.9 9 – 13	4.4 – 10.0 17 – 21

Table 6 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 Pg 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 Pg CO_2-eq**	 **1800 Pg CO_2-eq**	 **2100 Pg CO_2-eq**	 **2400 Pg 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.

APPENDIX

SUPPLEMENTARY INFORMATION

Supplementary Information

"Uncertainty in an Emissions Constrained World"

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Note 1: Selected large-scale, energy-economic and integrated assessment models and scenarios

As representative examples for long-term energy-climate scenarios – the three models that we use are GTEM, POLES and IMAGE – we rely on three scenarios from the EMF22 (Clarke et al. 2009; Gurney et al. 2009) and ADAM (Edenhofer et al. 2010; Kitous et al. 2010) modeling comparison exercises as well as from an individual scenario publication (van Vuuren et al. 2007), which have also been assessed in the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (Fischedick et al. 2011; Krey and Clarke 2011).

Brief model synopses are available at: Global Trade and Environment Model (GTEM); Prospective Outlook on Ling-term Energy Systems (POLES); and Integrated Model to Assess the Greenhouse Effect (IMAGE).

Note 2: Translating uncertainty in cumulative emissions and risk from 2 to 3 and 4°C

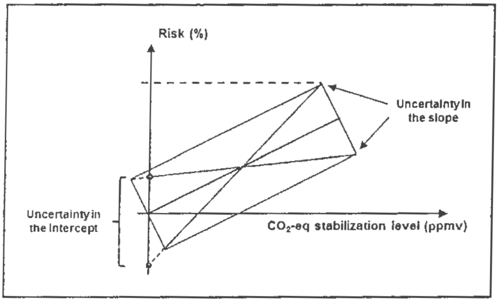
This translation is graphically based and realized with the help of Figures 33 and 34 in Meinshausen (2005), which quantify the risk (in %) of overshooting global mean equilibrium warming ranging from 1.5 to 4°C for different stabilization levels of CO_2-eq concentration (in ppmv). We proceed in three steps:

(1) We subdivide Figures 33 and 34c,d into the per-cent risk intervals [0,10[, [10,30[, [30,70[, [70,87.5[and [87.5,98.25[and determine in each interval the linear slope of the median risk of overshooting as a function of the CO_2-eq stabilization level, separately for global mean equilibrium warmings of 2, 3 and 4°C (see large black dots in Figures 33 and 34c,d). To approximate the uncertainty in the slope, we follow the standard recommendation of establishing a scatter rectangle (e.g., Eichler et al. 2006: Chapter 1; the radius of the black dots serves as an auxiliary measure of how accurately we can establish the scatter rectangle in relative terms). The uncertainty in the slope translates into an uncertainty in the intercept, i.e., the risk of exceeding 2, 3 or 4°C (Fig. S1).

(2) Knowing the piecewise linear, median-risk-of-overshooting function in dependence of the CO_2-eq stabilization level, we provide instructions of how the risk of exceeding 2°C translates into the risk of exceeding 3 and 4°C for a given CO_2-eq stabilization level.

Finally, (3) we examine how the uncertainty in the intercept resulting from a 2°C scatter rectangle translates to 3 and 4°C and compare it with the uncertainties in the intercepts resulting from the 3 and 4°C scatter rectangles determined already under (1). In most cases, the latter are greater and are therefore favored by us for precautionary reasons.

Fig. S1 Approximate, graphical-based translation of the the min/max and max/min uncertainty combinations for cumulative emissions and risk from 2 to 3 and 4°C. The translation is realized with the help of Figures 33 and 34c,d in Meinshausen (2005), which quantify the risk (in %) of overshooting 2, 3 and 4°C global mean equilibrium warming in dependence of CO_2-eq stabilization (in ppmv). These functional relationships are studied per interval. In each interval the linear slope of the median risk of overshooting is determined as a function of the CO_2-eq stabilization level, separately for global mean equilibrium warmings of 2, 3 and 4°C. The uncertainty in the slope, which is derived with the help of a scatter rectangle, translates into an uncertainty in the intercept, i.e., the risk of exceeding 2, 3 or 4°C.



Note 3: Using the HANPP concept to track sustainability

Sustainability on the global scale cannot be achieved if emissions from LU activities are not properly accounted for spatially across countries, i.e., in consideration of traded emissions, through time. To tackle the issue, and advance our understanding, of sustainability global LU emissions need to be brought down to the national and even local scale. Ultimately, we need to understand locally whether or not our actions are sustainable globally.

However, a parameter that can be used for monitoring the terrestrial biosphere and allocating LU emissions globally is not readily available. Such a parameter would have to satisfy two fundamental requirements: It would have to allow (1) scaling LU emissions meaning that summing over all countries yields global net emissions from LU; and (2) tracking sustainability meaning that net emissions from LU zero-balance globally when sustainability is reached.

Here we look into the question of whether the HANPP concept satisfies the aforementioned monitoring requirements. We find that this is possible only if NPP (or any related ecological quantity) is defined in terms of sustainability, which requires specifying a reference level that serves as a target to be reached in the future (2050). But such a definition has not yet been put forward.

Following the notation used by Haberl, Erb and collaborators (e.g., Haberl et al. 2007: Tab. 1; Erb et al. 2009: Section 2), HANPP is defined ecologically, at any point in time t, as the difference between the NPP of potential vegetation (NPP_0) and the NPP that remains in the ecosystem after harvest ($NPP = NPP_{act} - NPP_h$; with NPP_{act} being the actual NPP and NPP_h the human harvest):

$$HANPP_t = NPP_0 - NPP_t .$$

Alternatively, HANPP can be defined from a societal perspective as the aggregate effect of human harvest (NPP_h), human-induced fires (NPP_{fire}), and the human-induced alteration of NPP resulting from land conversion and land use (ΔNPP_{LC}):

$$HANPP_t = NPP_{h,t} + NPP_{fire,t} + \Delta NPP_{LC,t}$$

The two definitions inform us that the first of the two requirements, the scaling requirement, is met if we begin by taking the global viewpoint: horizontal flows balance when averaged across the globe. In addition, the ecological definition tells us that, with NPP_0 considered constant, NPP decreases with increasing human appropriation of NPP but does not free us from defining a NPP which we still consider 'sustainable' in the future and which should not be underrun.

The second requirement leads us to look at the difference of embodied HANPP against an equilibrium (eq), or sustainability, level. The domestic consumption of eHANPP is calculated for a country i as the sum of HANPP on the country's national territory and HANPP embodied in biomass imports minus HANPP embodied in exports:

$$\mathrm{eHANPP}_i = \mathrm{HANPP}_i + \left(\mathrm{ImpNPP}_i - \mathrm{ExpNPP}_i\right)$$

(Haberl et al. 2009), i.e.,

$$\begin{aligned}\mathrm{eHANPP}_{i,t} - \mathrm{eHANPP}_{i,eq} &= \left(\mathrm{HANPP}_{i,t} - \mathrm{HANPP}_{i,eq}\right)\\ &\quad + \left(\mathrm{ImpNPP}_{i,t} - \mathrm{ExpNPP}_{i,t}\right) - \left(\mathrm{ImpNPP}_{i,eq} - \mathrm{ExpNPP}_{i,eq}\right)\\ &= \left(\mathrm{NPP}_{i,eq} - \mathrm{NPP}_{i,t}\right)\\ &\quad + \left(\mathrm{ImpNPP}_{i,t} - \mathrm{ExpNPP}_{i,t}\right) - \left(\mathrm{ImpNPP}_{i,eq} - \mathrm{ExpNPP}_{i,eq}\right)\end{aligned}$$

This difference meets the second requirement. However, it is the difference $\mathrm{NPP}_{i,eq} - \mathrm{NPP}_{i,t}$ in the above equation that forces us to come to terms with respect to what 'equilibrium' or 'sustainability' means from a constrained GHG-emissions-budget point of view. This also holds if we expand the discussion and link HANPP with other ecological quantities such as net ecosystem or net biome exchange (e.g., Kirschbaum et al. 2001).

Note 4: Using the HANPP concept to estimate traded LU emissions

A direct consequence of the globally averaged approach of linking eTrade_{NPP} $(= \mathrm{ImpNPP} - \mathrm{ExpNPP})$ with national LU emissions 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),[1] while a country can even exhibit negative LU emissions resulting from regrowth subject to past interference.

In addition, under the globally averaged approach the calculation of national plus traded emissions is unambiguous (i.e., one combined emissions value per net trade value). But alternative approaches are conceivable that are even contradictory. For instance, when (i) the directly human-impacted part of a country's terrestrial biosphere is perceived as a whole, thus representing the average over all local LU emissions; (ii) it serves as the principal unit for reporting GHG emissions and removals; and (iii) it also serves as reference for the trade of biomass; a contradiction can occur. The reason is that, when referring to the country scale, the calculation of combined, national plus traded, emissions can exhibit more than one result depending on whether the traded biomass originates from a national LU source or sink (Fig. S2).

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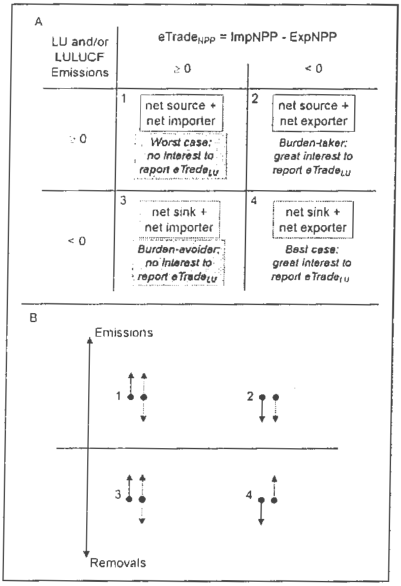
[1] From the HANPP perspective, the globally averaged approach results in an actual NPP (NPP_{act}) which is smaller than that of potential vegetation (NPP_0). However, there exist locations where NPP_{act} may even be larger than NPP_0 due to intensive land management, such as fertilization or irrigation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

Fig. S2 Emissions resulting from LU (and/or LULUCF): Switching the perspective from production to consumption. We make use of LU emissions and HANPP 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 terrestrial biosphere of a country 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 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.



Note 5: Results for Austria, a small developed country with good data and emission commitments under the Kyoto Protocol

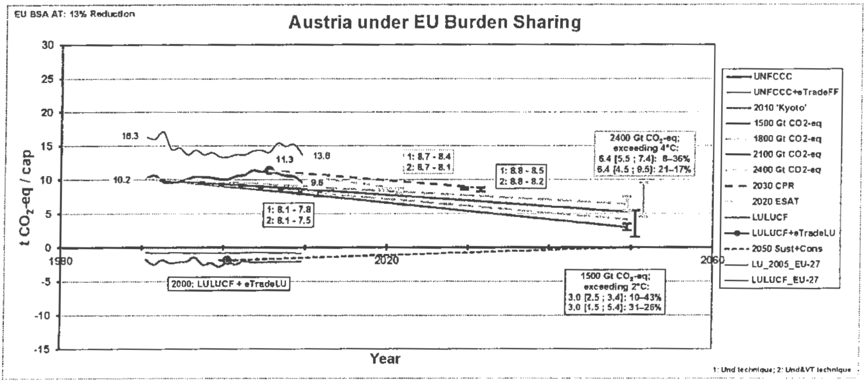
Figure S3 (see also Tab. 6) shows that in order to meet global cumulative emission constraints for 2000–2050 ranging between 1500 and 2400 Pg CO_2-eq each individual within Austria must reduce his or her GHG emissions on average between 71% and 37% between 1990 and 2050. In contrast to the US, Austria did ratify the Kyoto Protocol and agreed to an 8% emission reduction under the KP and to a 13% emission reduction (reflected in Fig. S) under the EU burden sharing agreement (BSA). If Austria would have adhered to the BSA, its territorial emissions would have followed the target path belonging to the cumulative emissions constraint of 1800 Pg CO_2-eq for 2000–2050 (with 8.1 t CO_2-eq / cap in 2010), aiming at a temperature target of 3°C (rather than 2°C) in 2050 and beyond (Tab. 5a).

In addition, Figure S3 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 to 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 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 4°C in 2050 and beyond does not get out of reach. However, this appears unlikely if we switch from a production to consumption perspective. Taking into account fossil-fuel embodied in trade increases Austria's territorial emissions. Austria is a large net importer.

The undershooting required to reduce the risk from 50 to 0% that true (but unknown) emissions exceed emission targets and pledges in 2010 (EU BSA), 2020 (ESAT), and 2030 (CPR) 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 GCP's LU emission data (Section 3.7). LULUCF emissions data for 1990–2009 (reported by Austria under the UNFCCC) are available, classifying Austria as a moderate 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 import biomass to satisfy its demand for consumption (Fig. S2).

Fig. S3 Austria (1990–2050): See caption to Figure 3a and text.



For comparison and to better understand the relevance of this upward correction, Figure S3 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 is similar to our observation for the US. The difference between its LU and LULUCF emissions also outstrips our corrections in 2000 when we switch from a production to consumption perspective (Fig. 3a). 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.

Note 6: Combining diagnostic and prognostic uncertainty

Combining diagnostic and prognostic uncertainty will be at the center of another study. However, we can indicate the order of magnitude involved: Employing for 1990 and 2050 a diagnostic uncertainty of 10% in relative terms and 0.75 for the correlation in these uncertainties results in a downward shift of about 2–5% of the 1500 Pg CO_2-eq cumulative constraint for 2000–2050, depending on the emission change-uncertainty analysis technique applied. The uncertainty value of 10% refers to fossil-fuel emissions globally and represents 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. We note that the inaccuracy at the global scale is not known and that the authors' precision estimate of fossil-fuel emissions has never been reworked formally and is believed to be appropriate still.

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