Supplementary Information

Uncertainty in an Emissions-Constrained World

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Table S1 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 (available via archive-org.com).

[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, 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/EPAactivities/economics/nonco2projections.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 (available via archive-org.com); the data are from G.P. Peters from the Center for International Climate and Environmental Research (see 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://esa.un.org/wpp/index.htm.

[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 S2 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,d]	**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; the 2 °C Check Tool is applied in Section 2.3 (see also Tab. S4 in Supplementary Information: Note 3)

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

[c] Amann et al. (2009): http://gains.iiasa.ac.at/Annex1.html

[d] Supplementary Information: Note 4

Note 2: From global to national: per capita emissions equity in 2050

Table S3 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. S1).

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)**	**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.

Note 3: Uncertainty in cumulative emissions and the risk of exceeding 2 °C global warming

Table S4 Uncertainty in the cumulative emissions for 2000–2050 versus uncertainty in the risk of exceeding 2 °C global warming in 2050 and 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.

Note 4: Making use of the GAINS model and three large-scale, energy-economic and integrated assessment models

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).

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 land use and land-use change activities). They are compatible with reaching the 2 ºC 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. 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).

The models follow 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.

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

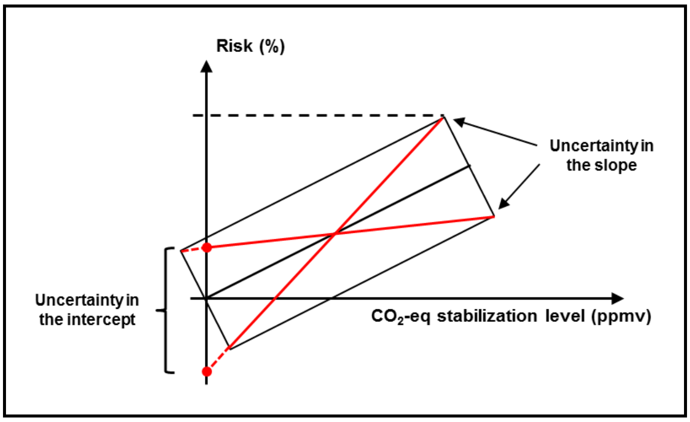
This translation is graphically based and realized with the help of Figures 33 and 34 in Meinshausen (2005), which quantify the risk (in %) of overshooting global mean equilibrium warming ranging from 1.5 to 4 °C for different stabilization levels of CO_2-eq concentration (in ppmv). We proceed in three 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 ºC (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 ºC (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 ºC translates into the risk of exceeding 3 and 4 ºC for a given CO_2-eq stabilization level.

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

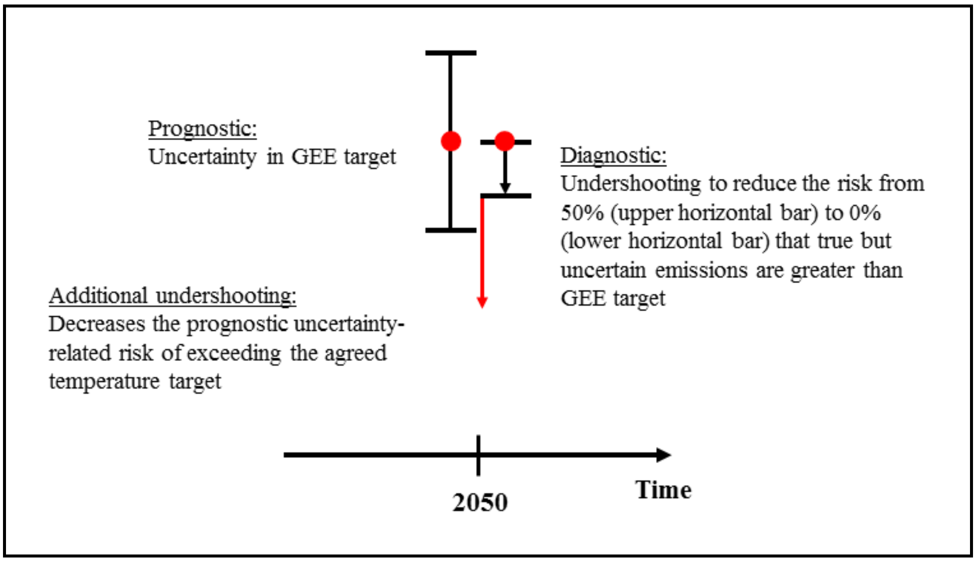
Fig. S1 Approximate, graphical-based translation of the the min/max and max/min uncertainty combinations for cumulative emissions and risk from 2 to 3 and 4 ºC. The translation is realized with the help of Figures 33 and 34c,d in Meinshausen (2005), which quantify the risk (in %) of overshooting 2, 3 and 4 ºC 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 ºC. 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 ºC.



Note 6: Combining diagnostic and prognostic uncertainty

Figure S2 illustrates the combining of diagnostic and prognostic uncertainty:

Fig. S2 Illustrating the combining of diagnostic and prognostic 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 limit 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 uncertainty-related risk to 0 % leads to a downward shift of the prognostic uncertainty-related risk of exceeding the given temperature target.



We specify the order of magnitude involved in correcting the 2000–2050 cumulative emissions constraint of 1500 Pg CO_2-eq (the corresponding GEE in 2050 is 3.0 t CO_2-eq/cap) downward so that the diagnostic uncertainty-related risk vanishes. We do this for representative values of both diagnostic uncertainty (10 % constant in relative terms) and correlation in diagnostic uncertainty between 1990 and 2050 (0.75), while applying two emission change-uncertainty analysis techniques (see text).

The uncertainty 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. The correlation of 0.75 refers to countries with good inventory systems of data collection and management (Jonas et al. 2010).

Note 7: Using the HANPP concept to track sustainability

Sustainability on the global scale cannot be achieved if emissions from land use and land-use change (LU) activities are not properly accounted for spatially across countries, including 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 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).

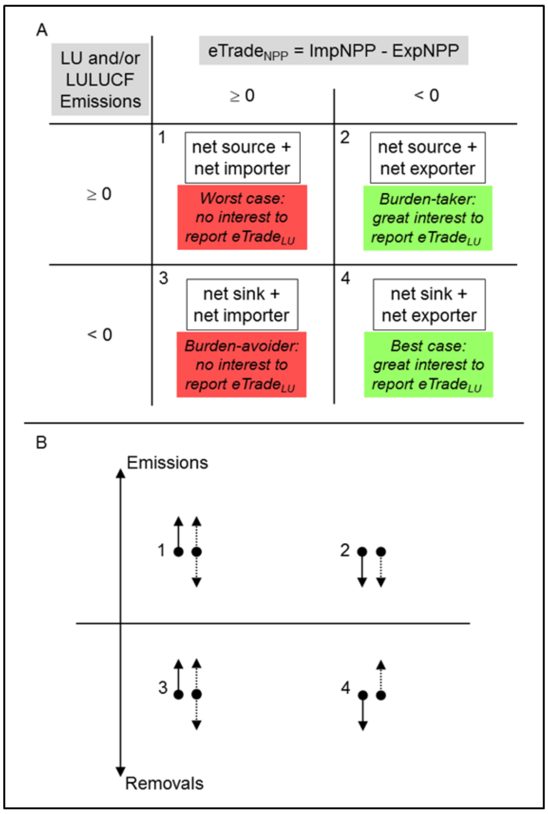
Note 8: Using the HANPP concept to estimate traded LU emissions

A direct consequence of the globally averaged approach of linking $\mathrm{eTrade_{NPP}}$ $(= \mathrm{ImpNPP} - \mathrm{ExpNPP})$ 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. S3).

[1] From the HANPP perspective, the globally averaged approach results in an actual NPP ($\mathrm{NPP_{act}}$) which is smaller than that of potential vegetation ($\mathrm{NPP_0}$). However, there exist locations where $\mathrm{NPP_{act}}$ may even be larger than $\mathrm{NPP_0}$ 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. S3 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 9: Results for Austria, a small developed country with good data and emission commitments under the Kyoto Protocol

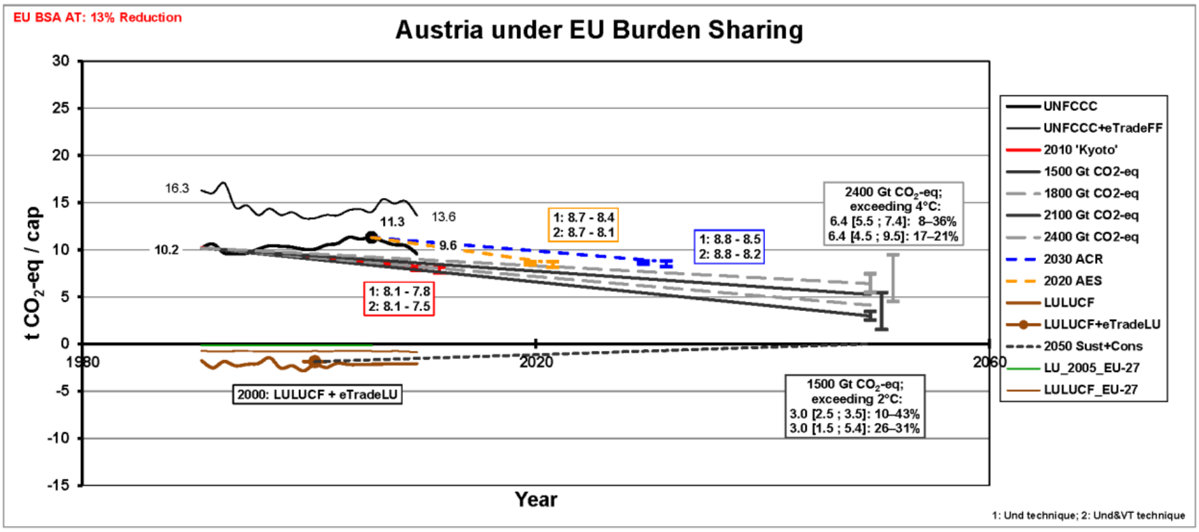
Figure S4 (see also Tab. 2) shows that in order to meet global cumulative emission constraints for 2000–2050 ranging between 1500 and 2400 Pg CO_2-eq each individual within Austria must reduce his or her GHG emissions on average between 71 % and 37 % between 1990 and 2050. In contrast to the US, Austria did ratify the Kyoto Protocol and agreed to an 8 % emission reduction under the KP and to a 13 % emission reduction (reflected in Fig. S4) 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 ºC (rather than 2 ºC) in 2050 and beyond (Tab. 1a).

In addition, Figure S4 shows Austria's targeted and projected emissions as specified for 2020 under Austria's energy strategy (AES) and 2030 in Austria's climate protection report (ACR) 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 Pg 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 ºC 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 (AES), and 2030 (ACR) ranges between 0.3 to 0.6 t CO_2-eq/cap, depending on the emission change-uncertainty analysis techniques applied.

Austria is too small to be resolved by GCP's LU emission data (Section 2.7). 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. S3).

Fig. S4 Austria (1990–2050): See caption to Figure 2a and text.



For comparison and to better understand the relevance of this upward correction, Figure S4 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. 2a). This relation – uncertainty in land use and land-use change emissions being greater than the production-to-consumption correction of these emissions – is opposite to how we can currently handle technospheric emissions, at least for countries with good emission statistics.

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