Chapter 11
Dealing with Uncertainty in GHG Inventories: How to Go About It?

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Abstract The assessment of greenhouse gases emitted to and removed from the atmosphere is high on both political and scientific agendas. Under the United Nations Framework Convention on Climate Change, Parties to the Convention publish annual or periodic national inventories of greenhouse gas emissions and removals. Policymakers use these inventories to develop strategies and policies for emission reductions and to track the progress of these policies. However, greenhouse gas inventories (whether at the global, national, corporate, or other level) contain uncertainty for a variety of reasons, and these uncertainties have important scientific and policy implications. For scientific, political, and economic reasons it is important to deal with the uncertainty of emissions estimates proactively. Proper treatment of uncertainty affects everything from our understanding of the physical system to the economics of mitigation strategies and the politics of mitigation agreements. A comprehensive and consistent understanding of, and a framework for dealing with, the uncertainty of emissions estimates should have a large impact on the functioning and effectiveness of the Kyoto Protocol and its successor. This chapter attempts to

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pull together relevant fragments of knowledge, allowing us to get a better picture of how to go about dealing with the uncertainty in greenhouse gas inventories.

11.1 Introduction

The assessment of greenhouse gases (GHGs) emitted to and removed from the atmosphere is high on both political and scientific agendas. Under the United Nations Framework Convention on Climate Change (UNFCCC), Parties to the Convention (so-called Annex I countries) have published annual or periodic national inventories of GHG emissions and removals since the mid 1990s. Policymakers use these inventories to develop strategies and policies for emission reductions and to track the progress of these policies. Where formal commitments to limit emissions exist, regulatory agencies and corporations rely on inventories to establish compliance records. Scientists, businesses, the public, and other interest groups use inventories to better understand the sources and trends in emissions. Table 11.1 provides general background information on the six GHGs, or groups of gases, considered under the Kyoto Protocol and their global emissions as reported by the Intergovernmental Panel on Climate Change (IPCC) in its assessment reports for the late 1990s and beyond.

GHG inventories contain uncertainty for a variety of reasons – for example, the lack of availability of sufficient and appropriate data and the techniques to process them. Uncertainty has important scientific and policy implications. However, until recently, relatively little attention has been devoted to how uncertainty in emissions estimates is dealt with and how it might be reduced. Now this situation is changing, with uncertainty analysis increasingly being recognized as an important tool for improving national, sectoral, and corporate inventories of GHG emissions and removals [5] (see also [6] and [7]).

At present, Parties to the UNFCCC are encouraged, but not obliged, to include with their periodic reports of in-country GHG emissions and removals, estimates of the uncertainty associated with these emissions and removals; consistent with the Intergovernmental Panel on Climate Change's (IPCC) good practice guidance reports [8,9]. Inventory uncertainty is monitored, but not regulated, under the Kyoto Protocol [5].

We argue that it makes a big difference in the framing of policies whether or not uncertainty is considered: reactively, because there is a need to do so; or proactively, because difficulties are anticipated. We follow [7, p. 2–3] (see also [5]) who clearly state that uncertainty estimates are not intended to dispute the validity of national GHG inventory figures. Although the uncertainty of emissions estimates underscores the lack of accuracy that characterizes many source and sink categories, its consideration can help to establish a more robust foundation on which to base policy.

According to the IPCC good practice guidance reports (notably, [8, p. 6.5]), uncertainty analysis is intended to help "improve the accuracy of inventories in the future and guide decisions on methodological choice." Uncertainty analyses function as indicators of opportunities for improvement in data measurement, data

Table 11.1 The six GHGs, or groups of gases, considered under the Kyoto Protocol to the UNFCCC [1, Annex A] and their global emissions as reported by the IPCC in its Third and Fourth Assessment Reports for the late 1990s and beyond. The GWP (last column) describes the global warming potential for a given GHG. It allows expressing the emissions of a non-CO_2 GHG in terms of CO_2-equivalent, which is the amount of CO_2 that causes the same global warming when measured over a specified timescale (generally, 100 years). The relative uncertainty ranges within which Annex I countries generally report the emissions of these GHGs are specified in Table 11.3

Kyoto gas	Global emissions [2, Table 4.1], [4, Tables 7.1, 7.6, 7.7]		GWP[a] [3, Table TS.2]
	Anthropogenic late 1990s[b]	Natural late 1990s[b]	
	2000–2005:	*2000–2005:*	
Carbon dioxide (CO_2)	7.2 ± 0.3 Pg C 26.4 Pg CO_2-eq.	-3.1 ± 0.8 Pg C[c] 11.4 Pg CO_2-eq.	1
	1996–2001:	*1996–2001:*	
Methane (CH_4)	428 Tg[d] 9.0 Pg CO_2-eq.	168 Tg[e] 3.5 Pg CO_2-eq.	21 (25)
	1990s:	*1990s:*	
Nitrous oxide (N_2O)	6.7 Tg N[f] 6.5 Pg CO_2-eq.	11.0 Tg N[g] 10.7 Pg CO_2-eq.	310 (298)
Hydroflurocarbons (HFCs)	See below	None	See below
Perfluorocarbons (PFCs)	See below	Negligible	See below
Sulfur hexafluoride (SF_6)	∼6 Gg 0.14 Pg CO_2-eq.	Negligible	23,900 (22,800)
Important HFCs and PFCs:			
HFC-23 (CHF_3)	∼7 Gg 0.08 Pg CO_2-eq.	None	11,700 (14,800)
HFC-134a(CH_2FCF_3)	∼25 Gg 0.03 Pg CO_2-eq.	None	1,300 (1,430)
HFC-152a (CH_3CHF_2)	∼4 Gg 0.56 Tg CO_2-eq.	None	140 (124)
PFC-14 (CF_4)	∼15 Gg 0.10 Pg CO_2-eq.	Negligible	6,500 (7,390)
PFC-116 (C_2F_6)	∼2 Gg 0.02 Pg CO_2-eq.	None	9,200 (12,200)

[a] The net global warming potential (GWP) refers to a time horizon of 100 years. The GWPs stem from the IPCC Second Assessment Report (Climate Change 1995) as these are used for reporting under the UNFCCC. The most recent GWP updates for the IPCC Fourth Assessment Report (Climate Change 2007) are reported in addition (in parentheses)
[b] If not indicated otherwise
[c] Uptake: net atmosphere-to-land flux; and atmosphere-to-ocean flux
[d] Emissions: coal mining; gas, oil and industry; ruminants; rice agriculture; and biomass burning
[e] Emissions: wetlands and termites
[f] Emissions: fossil fuel combustion and industrial processes; agriculture; biomass and biofuel burning; human excreta; rivers, estuaries and coastal zones; and atmospheric deposition
[g] Emissions: soils under natural vegetation; oceans; and atmospheric chemistry

collection, and calculation methodology. Only by identifying elements of high uncertainty can methodological changes be introduced to address them. Currently, most countries that perform uncertainty analyses do so for the express purpose of improving their future estimates; and the rationale is generally the same at the corporate and other levels. Estimating uncertainty helps to prioritize resources and to take precautions against undesirable consequences. Depending on the intended purpose of an inventory, however, this may not be the extent of the utility of uncertainty analysis. Another rationale for performing uncertainty analysis is to provide a policy tool, a means to adjust inventories or analyze and compare emission changes in order to determine compliance or the value of a transaction. While some experts find the quality of uncertainty data associated with national inventories insufficient to use for these purposes, others offer justification for conducting uncertainty analyses to inform and enforce policy decisions. Some experts suggest revising the system of accounting on which current reduction schemes are based, while others seek to incorporate uncertainty measurements into emission and emission change analysis procedures. The latter could offer policy makers enhanced knowledge and additional insight on which to base GHG emission reduction measures.

We follow the proactive track in dealing with uncertainty. In Sect. 11.2 we look into the question of why uncertainty matters in general. Sections 11.3 and 11.4 elaborate on Sect. 11.2. In Sect. 11.3 we provide an overview of the state-of-the-art of analyzing emission changes in consideration of uncertainty. We envision this analysis taking place in accordance with, not independent of, a dual-constrained (bottom-up/top-down) verification framework in Sect. 11.4. We summarize our findings in Sect. 11.5.

11.2 Does Uncertainty Matter?

Reference [5] (see also [7]) offers a number of reasons why the consideration of uncertainty in GHG inventories is important:

- Understanding the basic science of GHG sources and sinks requires an understanding of the uncertainty in their estimates.
- Schemes to reduce human-induced global climate change rely on confidence that inventories of GHG emissions allow the accurate and transparent assessment of emissions and emission changes.
- Uncertainty is higher for some aspects of a GHG inventory than for others. For example, past experience shows that, in general, methods used to estimate nitrous oxide (N_2O) emissions are more uncertain than those for methane (CH_4) and much more uncertain than those for carbon dioxide (CO_2). Whether in multi-gas, cross-sectoral, international comparisons, trading systems, or in compliance mechanisms, approaches to uncertainty analysis need to be robust and standardized across sectors and gases, as well as among countries.

Uncertainty analysis helps to understand uncertainties: better science helps to reduce them. Better science needs support, encouragement and investment. Full carbon accounting (FCA) – or full accounting of emissions and removals, including all

GHGs – in national GHG inventories is important for advancing the science. FCA is a prerequisite for reducing uncertainties in our understanding of the global climate system. From a policy viewpoint, FCA could be encouraged by including it in reporting emissions, but it might be separated from targets for reducing emissions. Future climate agreements will become more robust if there is explicit accounting for the uncertainties associated with emission estimates. Hence, understanding uncertainty matters in many ways.

11.3 State of the Art of Analyzing Uncertain Emission Changes

In this section we elaborate on Sect. 11.2 by looking into the state-of-the-art of analyzing changes in emissions and removals of GHGs in consideration of uncertainty. From a physical (measurability) point of view, the uncertainty surrounding emission changes becomes more important in relative terms the smaller are the changes in the emissions, that is, the smaller the dynamics that they exhibit. Two options exist to avoid situations of great uncertainty vs. small change: (1) allowing more time so that greater emission changes can materialize; and (2) increasing measurability, e.g., by focusing on GHG emissions that can be grasped with "sufficient" certainty so that their changes are still "significant" in spite of the uncertainty. (Alternatively, emissions that do not possess these characteristics should be treated differently, e.g., separately from single-point emission targets (see above), or only in connection with targets that are defined as emission intervals or corridors.) Given that renegotiating the commitment times under the Kyoto Protocol cannot happen, Option 1 is not considered further. Option 2 requires the application of techniques that allow analyzing emission changes quantitatively (i.e., on an intra-technique basis) and qualitatively (i.e., on an inter-technique basis). Any of these techniques can be applied to GHG emissions individually, that is, they allow a detailed and thorough comparison of agreed or realized changes in emissions.

While pursuing the analysis of uncertain emission changes (also termed emission signals), we typically refer to the country scale, the principal reporting unit for reporting GHG emissions and removals under the Kyoto Protocol, but we could also refer to any other spatio-thematic scale. Our main motivation for studying the uncertainty of country-scale emissions estimates is the still unresolved issue of compliance (see also [10]). For most countries the emission changes agreed on under the Kyoto Protocol are of the same order of magnitude as, or smaller than, the uncertainty that underlies their combined CO_2 equivalent emissions estimates (compare the right column of Table 11.2 with the second column of Table 11.3).[1] Techniques are not in place to analyze uncertain emission signals from various points

[1] The issue of great uncertainty vs. small change also arises for small, intermediate, reduction targets. For instance, the EU discusses annual reduction steps in the context of an overall (EU-wide) GHG emission reduction of 20% by 2020 compared to 2005 [11, p. 7]. These steps follow a linear reduction path and are small (<2% per year; not compounded).

Table 11.2 Countries included in Annex B to the Kyoto Protocol (KP) and their emission limitation and reduction commitments (commitment period for all countries: 2008–2012; for the ISO Country Code for country abbreviations see below). The individual commitments have to be seen in context, i.e., vis-à-vis the uncertainty that underlies the reporting of emissions at the country scale (see Table 11.3). *Sources:* [14, Article 3.8, Annex B], [1, Decision 11/CP.4], [15], [16], [17, National Inventory Submissions], [18, Sect. 2.b]

Country group	Annex B country	Base year(s) for CO_2, CH_4, N_2O (for HFCs, PFCs, SF_6)	KP commitment %
1a	See below[a]	1990 (1995)	
	See below[b]	1990 (1990)	
1b	RO	1989 (1989)	92
1c	BG	1988 (1995)	
1d	SI	1986 (1995)	
2	US[c]	1990 (1990)	93
3a	JP	1990 (1995)	
	CA	1990 (1990)	94
3b	PL	1988 (1995)	
3c	HU	1985–1987 (1995)	
4	HR	1990 (1995)	95
5a	RU	1990 (1995)	100
5b	NZ, UA	1990 (1990)	
6	NO	1990 (1990)	101
7	AU	1990 (1990)	108
8	IS	1990 (1990)	110

[a]Country Group 1a: BE, CZ, DE, DK, EC (= EU-15; the EU-27 does not have a common Kyoto target), EE, ES, FI, GR, IE, LT, LU, LV, MC, NL, PT, SE, UK. Member States of the EU-27 but without individual Kyoto targets: CY, ML. Listed in the Convention's Annex I but not included in the Protocol's Annex B: BY and TR (BY and TR were not Parties to the Convention when the Protocol was adopted). BY requested becoming an Annex B country by amendment to the Kyoto Protocol at CMP 2 in 2006. (CMP = Conference of the Parties serving as the Meeting of the Parties to the Kyoto Protocol.) BY's base years and emission reduction commitments are 1990 (1995) and 92%, respectively

[b]Country Group 1a: AT, CH, FR, IT, LI, SK

[c]Country Group 2: The US has indicated its intention not to ratify the Kyoto Protocol. The US reports all its emissions with reference to 1990. However, information on 1990 in its national inventory submissions does not reflect or prejudge any decision that may be taken in relation to the use of 1995 as base year for HFCs, PFCs and SF_6 in accordance with Article 3.8 of the Kyoto Protocol

Abbreviations: AT Austria, *AU* Australia, *BE* Belgium, *BG* Bulgaria, *BY* Belarus, *CA* Canada, *CH* Switzerland, *CY* Cyprus, *CZ* Czech Republic, *DE* Germany, *DK* Denmark, *EC* European Community, *EE* Estonia, *ES* Spain, *FI* Finland, *FR* France, *GR* Greece, *HR* Croatia, *HU* Hungary, *IE* Ireland, *IS* Iceland, *IT* Italy, *JP* Japan, *LI* Liechtenstein, *LT* Lithuania, *LU* Luxembourg, *LV* Latvia, *MT* Malta, *MC* Monaco, *NL* Netherlands, *NO* Norway, *NZ* New Zealand, *PL* Poland, *PT* Portugal, *RO* Romania, *RU* Russian Federation, *SE* Sweden, *SI* Slovenia, *SK* Slovak Republic, *TR* Turkey, *UA* Ukraine, *UK* United Kingdom, *US* United States

Table 11.3 Emissions and/or removals of GHGs, or combinations of GHGs, classified according to their relative uncertainty ranges (reference: country scale). The bars of the arrows indicate the dominant uncertainty range for these emissions and removals, while the tops of the arrows point at the neighboring uncertainty ranges, which cannot be excluded but appear less frequently. LULUCF stands for the direct human-induced land-use, land-use change, and forestry activities stipulated by Articles 3.3 and 3.4 under the Kyoto Protocol [14]. The arrows are based on the total uncertainties that are reported for the Member States of the EU-25 [19] and the expertise available at IIASA's Forestry Program (cf. http://www.iiasa.ac.at/Research/FOR/unc_bottomup.html) and elsewhere (e.g., [20, Sects. 2.3.7, 2.4.1], [9, Sect. 5.2]). *Source:* [21, Table 1], modified

Class	Relative uncertainty (%) for 95% confidence interval	Classification of emissions and/or removals
1	0–5	⇓ CO_2 from fossil fuel (plus cement)
2	5–10	⇕ All Kyoto GHGs
3	10–20	⇕ Plus LULUCF
4	20–40	⇓
5	>40	⇓ CO_2 net terrestrial (>80%)

of view, ranging from signal quality (defined adjustments, statistical significance, detectability, etc.) to the way uncertainty is addressed (trend uncertainty or total uncertainty). Any such technique, if implemented, could "make or break" compliance, especially in cases where countries claim fulfillment of their reduction commitments. As already mentioned above, inventory uncertainty is monitored, but not regulated, under the Protocol. It remains to be seen whether the current status of ignoring uncertainty and abstaining from specifying clear rules on how to go about it will survive in the long term (see Compliance under the Kyoto Protocol in [12]) .

The analysis of emission signals in consideration of uncertainty can take three forms involving a multitude of techniques: (1) preparatory, (2) midway, and (3) retrospective signal analysis. Preparatory signal analysis allows generating useful knowledge that one would ideally wish to have at hand before negotiating international environmental agreements such as the Kyoto Protocol or its successors. For instance, it is important to know beforehand how great the uncertainties could be, depending on the desired level of confidence in the emission signal. What is the signal one wishes to detect and what is the risk one is willing to tolerate in meeting an agreed emission limitation or reduction commitment? To this end, it is generally assumed that (1) the emissions path between the base year and commitment year/period is a straight line (this is only a boundary condition, not a restriction); and (2) our knowledge of uncertainty in the commitment year/period will be as good as today's, in relative (qualitative) terms. Preparatory signal analysis allows factoring in the change in uncertainty, which can be due to learning and/or can result from structural changes in the emitters. However, researchers only begin to grasp these two determinants and to discriminate between them [22]. Handling the change in uncertainty is within reach but more data and research are needed. Being able to estimate the change in uncertainty is important in setting appropriate emission reduction targets, but one must not forget that preparatory signal analysis has not yet been applied in its simplest form to Kyoto commitments.

The state-of-the-art of preparatory signal analysis is well summarized by [23] (see also [21,24–26]), who compare six of the most widely discussed techniques.[2] In addition, preparatory signal analysis also allows monitoring the success of a country in reducing its emissions along a prescribed emissions target path between its base year and commitment year/period. This positive feature opens up a range of policy-relevant applications.[3]

Midway and retrospective signal analysis are less advanced than preparatory signal analysis. So far, midway signal analysis still focuses on emissions rather than on emissions changes. Midway signal analysis is an attempt to assess information on an emissions path at some point in time between base year and commitment. It considers a signal's path realized so far vis-à-vis a possible path toward the agreed emission limitation or reduction commitment. In this process, the dynamical moments (velocity, acceleration, etc.) of the historical and envisioned paths are compared, and this indicates (first-order control) whether or not it is likely to achieve the emission commitment. Midway signal analysis generally incorporates information from emissions prior to the base year to determine the signal's dynamical moments more accurately. The techniques explored so far to grasp the dynamics of, mostly, fossil-fuel CO_2 emissions encompass: polynomial regressions [29]; integral transforms [30]; and smoothing splines, parametric modeling and geometric Brownian motion modeling [31]. A related technique based on the analysis of short-term vs. long-term attainability and controllability has been followed by [32] and [33].

Retrospective signal analysis of emission changes becomes important when countries seek to assess their actual achievements in the commitment year/period. We distinguish between two fundamentally different approaches: static and dynamic. The static approach is identical to the one taken under preparatory signal analysis except that the agreed emission limitation or reduction commitment is replaced by the actual emission achievement. The emission signal is evaluated in terms of uncertainty, detectability or statistical significance, risk, etc. In contrast, the dynamic approach additionally considers how the emission signal has actually evolved between the base year and the commitment year/period, taking its dynamics into account. Here, expertise gained under midway analysis can serve as a platform as it also aims at evaluating full emission paths.

In their commensurability exercise, with its focus on six preparatory signal analysis techniques, Jonas and colleagues [23] concluded that a single best technique does not, and most likely will not, exist.[4] This is because the available techniques

[2] It is noted that attempts exist to put one of these six techniques to analyze uncertain emission changes, the verification time concept, on a stochastic basis (see Ermolieva et al., herein; and also [27] and [28]). It is correct to say that this technique still undergoes scientific scrutiny and awaits adjustment in order to operate in a preparatory mode.

[3] See http://www.iiasa.ac.at/Research/FOR/unc_overview.html for an overview on IIASA's monitoring reports and the countries that are monitored.

[4] For the authors' study and numerical results see http://www.iiasa.ac.at/Research/FOR/unc_prep.html. Referring readers to this website facilitates easy replication for follow-up studies or, as in this case, avoiding duplication.

suffer from inconsistencies in dealing with uncertainty that are not scientific but that are related to the way the Kyoto Protocol was designed. One technique, e.g., allows a country with a smaller emission reduction commitment to gain an advantage over a country with a greater emission reduction commitment;[5] while another technique forces countries a priori to realize detectable signals before they are permitted to make economic use of their excess emission reductions.[6] Jonas and colleagues [23] stress that these "inconsistencies" are the consequence of the Kyoto policy process running ahead of science, leaving us with the awkward problem of choosing between bad or undesirable alternatives in applying preparatory signal analysis. We can simply ignore uncertainty knowing that, e.g., emission markets will then lack scientific credibility or we can give preference to one preparatory technique over another knowing that none is ideal in satisfying the Protocol's political cornerstones. As two of the most important shortfalls on the side of policymaking the authors [23] identify (1) the overall neglect of uncertainty confronting experts with the finding that for most countries the agreed emission changes are of the same order of magnitude as the uncertainty that underlies their combined CO_2 equivalent emissions (compare the right column of Table 11.2 with the second column of Table 11.3); and (2) the existence of nonuniform emission limitation or reduction commitments that were determined "off the cuff" (i.e., derived via horse-trading) and did not result from rigorous scientific considerations.[7] From a purely quantitative point of view, the first shortfall is of greater relevance than the second one.

[5] See, for instance, the so-called undershooting (Und) concept: Excel file available via *numerical results* to [23] at http://www.iiasa.ac.at/Research/FOR/unc_prep.html: Worksheet *Undershooting 4*:
column C = Kyoto commitments δ_{KP} for country groups 1–8 (see also Table 11.2);
column E = the accepted risk α that a country's true emissions in the commitment year/period are equal to, or greater than, the country's true Kyoto target (risk α can be grasped although true emissions and targets derived from them are unknown by nature); and
columns F–N or U–AC (restricted to rows 14–16) = presumed relative uncertainty ρ of the country's reported emissions.
The Und concept requires undershooting of the countries' Kyoto targets in the commitment year in order to handle and decrease risk α (see columns F–N, rows $\geq$ 17, for the required undershooting). Varying δ_{KP} while keeping the relative uncertainty ρ and the risk α constant (e.g., at $\rho = 15\%$ and $\alpha = 0.3$) exhibits that countries complying with a smaller δ_{KP} are better off than countries that must comply with a greater δ_{KP} (see columns U–AC, rows $\geq$ 17, for the modified emission limitation or reduction target, which is the sum of the agreed target under the Kyoto Protocol plus the required undershooting). Such a situation is not in line with the spirit of the Kyoto Protocol!

[6] See, for instance, the so-called combined undershoot and verification time (Und&VT) concept: Excel file available via *numerical results* to [23] at http://www.iiasa.ac.at/Research/FOR/unc_prep.html: Worksheet *Und&VT 1:* Fig. 1 therein. The Und&VT concept requires a priori detectable emission reductions, not limitations. That is, it requires the Protocol's emission limitation or reduction targets to be corrected for nondetectability through the introduction of an initial or obligatory undershooting so that the countries' emission signals become detectable before the countries are permitted to make economic use of their excess emission reductions. This nullifies, de facto, the politically agreed targets under the Kyoto Protocol!

[7] The situation would be different if the nonuniformity of the emission limitation or reduction commitments would be the outcome of a rigorously based process resulting in a straightforward

However, it appears that the first shortfall will vanish soon as mankind is increasingly under pressure to adopt and realize greater emission reductions in the mid to long-term [36], [37, Decision 1/CP.13]. Notwithstanding, we would still be left with the problem of which analysis technique to give preference to. This discussion has not even started.

11.4 How to Deal with Uncertainty?

In this section we elaborate on Sect. 11.2 from a holistic point of view. Our starting point is FCA (or more generally, full accounting of all emissions and removals of all GHGs). We consider FCA a prerequisite for constraining and reducing uncertainties in our understanding of the global climate system. A dual-constrained (verified) full carbon analysis can compare the sum of Earth-based measurements of flows to and from the atmosphere with atmosphere-based evaluation of exchanges with the Earth. As specified by [5], a verified FCA, including all sources and sinks of both the technosphere and terrestrial biosphere considered continuously over time, would allow the research and inventory communities to:

- Present a real picture of emissions and removals at continental and smaller scales.
- Avoid ambiguities generated by such terms as "managed biosphere," "base-line activities," and "additionality." Elimination of splitting the terrestrial biosphere into directly human-impacted (managed) and not directly human-impacted (natural) parts would be advantageous from a verification point of view as there is no atmospheric measurement that can discriminate between the two [21, Sect. 3].
- Make available reliable and comprehensive estimates of uncertainties that cannot be achieved using the current approach under the UNFCCC and Kyoto Protocol [8, 9]. It is impossible to estimate the reliability of any system output if only part of the system is considered. The tacit assumptions underlying the Protocol are that man's impact on nature, the not-accounted remainder under the Protocol, is irrelevant and inventory uncertainty only matters from a relative point of view over space and time, not an absolute one. However, this approach is highly problematic because biases (i.e., discrepancies between true and reported emissions), typically resulting from partial accounting, are not uniform across space and time. In addition, man's impact on nature need not be constant or negligible.[8]

rule that applies equally to all countries as would be the case, for instance, under the so-called contraction and convergence approach (e.g., [34, Sect. 2.3.2], [35]).

[8] In their recent study [38, Table 1] show that, making use of global carbon budget data between 1959 and 2006, the efficiency of natural carbon sinks to remove atmospheric CO_2 has declined by about 2.5% per decade. Although this decline may look modest, it represents a mean net "source" to the atmosphere of 0.13 PgC y^{-1} during 2000–2006. In comparison, a 5% reduction in the mean global fossil emissions during the same time period yields a net "sink" of 0.38 PgC y^{-1}. Thus, deteriorating natural carbon sinks as a result of climate change or man's direct impact exhibit the potential to offset efforts to reduce fossil fuel emissions. This shows that man's impact on nature

FCA is essential for good science. However, it would be for policymakers to decide how FCA is used. FCA could be used for "crediting" in the sense of the Kyoto Protocol (i.e., for compliance) or only for "accounting" and scientific understanding as required under the UNFCCC. Given that the treatment of the land use, land-use change, and forestry (LULUCF) sector in general poses a number of characteristic challenges (see box), we prefer FCA accounting under which, however, the Kyoto compliance accounting as required under the Protocol would form a logical and consistent subset.

Uncertainty in the LULUCF sector

Expressing uncertainties in the LULUCF sector can be challenging because of:

- The complexities and scales of the systems being modeled.
- The fact that human activity in a given year can impact emissions and removals in these systems over several years, not just the year in which the activity took place.
- These systems being strongly affected by inter-annual, decadal, and long-term variability in climate.

Knowledge of the temporal dynamics of systems – what has happened in the past, and how actions in the present will affect emissions/removals in the future – is important; gaps in this knowledge add to uncertainties about the immediate impacts of human activities.

Approaches to estimating emissions and removals in the LULUCF sector frequently involve the use of detailed data and computer models to simulate the complex functional relationships that exist in natural systems. But a consequence of using more detailed methods is that the estimation of uncertainty also comes more into play. However, despite conceptual and technical challenges, powerful tools for combining different kinds of information from multiple sources are becoming available and are increasingly being used by modelers to reduce uncertainties in the LULUCF sector.

These tools allow modelers to increase their focus on model validation and on reconciling results from alternative approaches. However, one key barrier remains. Reporting under the UNFCCC and Kyoto Protocol provides only a partial account of what is happening in the LULUCF sector. To close the verification loop would require the adoption of FCA.

Despite improvements in approaches to estimating uncertainty in emissions and removals in the LULUCF sector, some challenges remain. The treatment of this sector in future policy regimes requires special consideration.

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is indeed not negligible and stresses the need to look at the entire system, that is, to develop a FCA system where emissions and removals and their trends are monitored in toto.

FCA is expected to facilitate the reconciliation of two broad accounting approaches: top-down and bottom-up accounting. Top-down accounting takes the point of view of the atmosphere. It relies on observations of atmospheric CO_2 concentrations, changes in concentrations, and atmospheric modeling to infer fluxes from land and ocean sources. Bottom-up accounting takes the opposite perspective. It relies on observations of stock changes or fluxes at the Earth's surface and infers the change in the atmosphere. FCA – estimating all land and ocean-based fluxes, whether human-induced or not – is necessary to reconcile the top-down and bottom-up approaches.

While methods of both top-down and bottom-up accounting have improved in recent years, both approaches still have areas of weakness. Investment in research is needed to tackle these limitations, improve the FCA approach, and hence reduce uncertainties (see also [39]).

Last, but not least, it must be kept in mind that verification of emission estimates does not necessarily imply detection of emission signals (e.g., decreased emissions) over time. It is the detection of emission signals that is needed to complement the bottom-up/top-down accounting of GHGs and the prime goal of this research community to close the existing gaps in the accounting.

Thus, from a policy perspective, there are pressing issues regarding how uncertainty can be dealt with through uncertainty analysis techniques and improvements to science. The implications for policymakers working to reduce human impacts on the global climate include [5]:

- Uncertainty analysis helps to understand uncertainties: better science helps to reduce uncertainties. Better science needs support, encouragement, and investment. FCA in national GHG inventories is important for advancing the science. It could be included in reporting but separated from targets for reducing emissions.
- Uncertainty is inherently higher for some aspects of an inventory than for others. For example, the LULUCF sector has higher uncertainties than the fossil fuel sector and estimates of N_2O emissions tend to be more uncertain than those of CH_4 and CO_2. This raises the possibility that in designing future policy agreements some components of a GHG inventory could be treated differently than others.[9]
- Improving inventories requires one approach; improving emissions trading mechanisms another. Inventories will be improved by increasing their scope to include FCA. In contrast, one option for improving emissions trading mechanisms would be to reduce their scope. Currently, emissions trading mechanisms may include estimation methodologies with varying degrees of uncertainty but they do not explicitly consider uncertainty or treat it in a standardized fashion. There are two options for improving this situation. The first option, as mentioned, is to reduce

[9] This view of treating subsystems individually and differently runs counter to the approach typically taken. The tendency has been to treat subsystems collectively and equally and to dispose over a wide range of options in order to minimize costs or maximize benefits resulting from the joint emissions reduction of GHGs and air pollutants (e.g., [40], [41, (77)], [42]).

the scope of emissions trading mechanisms – by excluding uncertain methodologies or more uncertain GHGs – to make them more manageable (see also [43]). The second option is to retain the scope of emissions trading mechanisms but to adopt a standardized approach to estimating uncertainty. But we could not guarantee that the latter approach would eventually withstand large biases resulting, e.g., from a mismatch in the bottom-up vs. top-down accounting.

In the context of pricing uncertainty, it needs to be mentioned that uncertainty is an inherent part of any emissions accounting and that it will play an important role in both the scientific understanding of emissions and in their political treatment. At present, however, uncertainty does not play a role in trading of emissions credits. Ultimately, uncertainty can be borne by either the buyer or seller of any asset, and it should be agreed in advance of any exchange how this is to be dealt with. Risky or uncertain assets will be traded at a discount to the extent that the risk and uncertainty are to be assumed by the buyer.

Literature on treating scientific uncertainty upfront in financial markets is already emerging (e.g., [26, 44, 45]), but this has not yet been applied widely to GHG emissions credits. For now it appears that buyers of emissions credits generally accept credits without uncertainty and the seller is obligated to ensure that the credits are fulfilled.

With the current system of trading in allowances and credits, neither buyers nor sellers have much incentive to reduce the uncertainty associated with emissions inventory or reduction estimates; to do so might impact the single-point emission (or reduction) estimate, thus directly affecting the value of allowances or credits. For example, a highly uncertain emission reduction estimate that is biased high will tend to be worth more (claiming greater reductions), presupposing the market's willingness-to-pay, than the same reduction figured more accurately and with greater uncertainty. This suggests the possibility that other, more complex, pricing mechanisms than the current cap-and-trade system might exist and would be better able to deal with uncertainty by, for example, monetizing (i.e., rewarding) increased confidence. Such a system might also differentiate between different types of emissions and/or reductions and their uncertainties.

11.5 Conclusions

We see a clear rationale for conducting and improving uncertainty analysis:

- Uncertainty analysis improves the monitoring of GHG emissions. Uncertainty analysis helps to understand uncertainties and encourages better science that will help to reduce uncertainty.
- Better science requires the adoption of FCA. More investment in research is needed to reconcile the bottom-up and top-down accounting approaches that are fundamental to FCA and that dual-constrain uncertainty. FCA may only be used for "accounting" but with the Kyoto compliance accounting as a logical

and consistent subset used for "crediting." We anticipate that within a few years scientists will overcome still existing bottom-up/top-down accounting gaps for the Kyoto GHGs at the scale of continents. Scientists may even be able to down-scale validated, and verified (dual-constrained), emissions estimates to the scale of countries or groups of countries. That is, scientists will be able to verify (correct) politically driven (mis-)accounting reported annually bottom-up under the Kyoto Protocol and its successor.

- Some GHG emissions and removals estimates are more uncertain than others. Options exist to address this issue, and these could be incorporated in the design of future policy regimes. These options also include (1) the option of not splitting the terrestrial biosphere into a directly human-impacted (managed) and a not-directly human-impacted (natural) part to avoid sacrificing bottom-up/top-down verification; and (2) the option of not pooling subsystems, including sources and sinks, with different relative uncertainties but treating them individually and differently.
- We expect the treatment of scientific uncertainty in emission trading markets to gain relevance. Neither buyers nor sellers of GHG emission credits have a strong interest to let this issue go unresolved.
- The issue of compliance also goes unresolved and requires directing attention to the appropriate treatment of emission changes in consideration of uncertainty. Currently, signal analysis is still treated independently of bottom-up/top-down verification, but scientists will eventually be able to make the two consistent and to go hand-in-hand.

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