Jean P. Ometto
Rostyslav Bun
Matthias Jonas
Zbigniew Nahorski
Editors

Uncertainties in Greenhouse Gas Inventories

Expanding Our Perspective

Springer

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Preface

This book has been written to enhance understanding of the uncertainty encountered in estimating greenhouse gas (GHG) emissions and in dealing with the challenges resulting from those estimates. Such challenges include, but are not limited to i) monitoring emissions; ii) adhering to emission commitments; iii) securing the proper functioning of emission trading markets; and iv) meeting low-carbon or low-GHG futures in the long term.

The title of the book, *Uncertainties in Greenhouse Gas Inventories: Expanding Our Perspective*, indicates that researching uncertainty is not a quick exercise but involves a fairly painstaking long-term commitment. Moreover, proper treatment of uncertainty is costly in terms of both time and effort because it forces us to make the step from "simple" to "complex" in order to grasp a wider and more holistic systems view and, only after that, to discuss any simplifications that may be warranted.

This book is a reprint of the 2014 Special Issue 124(3) of *Climatic Change*. Like its predecessors, it is intended for readers who prefer hardcover books to the paperback format of special journal issues. It brings together 16 key papers presented at, or produced subsequent to, the 2010 (3rd) International Workshop on Uncertainty in Greenhouse Gas Inventories. The Workshop was jointly organized by the Lviv Polytechnic National University (http://www.lp.edu.ua/en), Ukraine; the Systems Research Institute of the Polish Academy of Sciences (http://www.ibspan.waw.pl/glowna/en); and the International Institute for Applied Systems Analysis (http://www.iiasa.ac.at/), Austria.

This book follows on from *Accounting for Climate Change: Uncertainty in Greenhouse Gas Inventories – Verification, Compliance, and Trading* (Lieberman et al. 2007); and *Greenhouse Gas Inventories: Dealing with Uncertainty* (White et al. 2011), two books that reflect the outcome of the 2004 (1st) and 2007 (2nd) Workshops on Uncertainty in Greenhouse Gas Inventories held in Poland and Austria, respectively.

The issues of concern at the 3rd Uncertainty Workshop continue to be rooted in the level of confidence with which national emission inventories can be performed. They also go beyond this, bringing new approaches, as explained below. The topics addressed by the 16 key papers in this book follow a structure based on the Workshop sessions:

- *Introduction* (written in retrospect): see paper by Ometto et al. 2014a
- *General & Policy*: see papers by Jonas et al. 2014; Rafaj et al. 2013; Lesiv et al. 2014; and Hryniewicz et al. 2014
- *Energy*: see paper by Uvarova et al. 2014;
- *Land Use, Land-Use Change, and Forestry*: see paper by Ometto et al. 2014b
- *Spatial Inventories*: see papers by Boychuk and Bun 2014; Horabik and Nahorski 2014; and Verstraete 2014;
- *Non-*CO_2 */ Waste*: see papers by Joerss 2013;
- *Economy and Climate Change*: see papers by Xu et al. 2014; Ermolieva et al. 2013; Nahorski et al. 2014; Dolgopolova et al. 2014; and Nijnik and Pajot 2014.

Unsurprisingly, the most important take-home message from the 3rd Uncertainty Workshop is that the existing rationale for improving and conducting uncertainty analyses (see Box 1) is still considered to hold true. The alternative, the past policy approach of ignoring inventory uncertainty altogether (inventory uncertainty was monitored, but not regulated, under the Kyoto Protocol) at the country, sector, corporate, or other level, is problematical. Emission reductions are activity- and gas-dependent and can be wide-ranging. Biases (discrepancies between true and reported emissions) are not uniform across space and time and can discredit flux-difference schemes which tacitly assume that biases cancel out. Human impact on nature is not necessarily constant and/or negligible and can jeopardize a partial GHG accounting approach that is not a logical subset of, and safeguarded by, a full GHG accounting approach. Thus, the legitimate concern was, and still is, that policy agreements are trying to tie down a system that, while considered certain, is not truly controlled. Being aware of the uncertainties involved will help to strengthen future political decision making, for example, the UNFCCC negotiations toward a new universal climate agreement in 2015.

This leads to the important question as to the advances made at the 3rd Uncertainty Workshop. Box 2 provides a summary of the status quo of uncertainty research as it unfolded after the 2007 (2nd) Uncertainty Workshop. Six interdependent key insights materialized at the time which, according to experts, would require further attention. These insights center around (abridged)

1. Verification: reconciling bottom-up and top-down GHG emission analyses;
2. Avoiding systemic surprises: distinguishing between subsystems with fundamentally different emission-dynamic and uncertainty characteristics before superimposing them;
3. Making uncertainty analysis a key component of national GHG inventory analysis to support the development of informed policy in the framing of international environmental agreements: providing advanced guidance, beyond the methodologies offered by the IPCC, to ensureuncertainty is dealt with appropriately in an internationally consistent way across countries, subsystems, sources and sinks, GHGs, and sectors;
4. Minimizing the impact of uncertainty to support the design of advanced policy agreements: providing approaches that allow subsystems to be treated individually and differently rather than collectively (in terms of CO_2-equivalence) and equally (not distinguishing between emissions and removals).

5. Full GHG accounting: ensuring that any differentiated approach to accounting forms a logical subset of a full GHG accounting approach;
6. Compliance versus reporting (bifurcation of agreements) but in a complementary manner: providing options that allow for smarter treatment of subsystems, for example, individually and differently, while at the same time following full GHG accounting.

BOX 1 Rationale for improving and conducting uncertainty analyses. Source: White et al. (2011: 3–18)

- Calculations of greenhouse gas (GHG) emissions contain uncertainty for a variety of reasons such as the lack of availability of sufficient and appropriate data and the techniques for processing them.
- Understanding the basic science of GHG gas sources and sinks requires an understanding of the uncertainty in their estimates.
- Schemes to reduce human-induced global climate impact rely on confidence that inventories of GHG emissions allow the accurate assessment of emissions and emission changes. To ensure such confidence, it is vital that the uncertainty present in emissions estimates is transparent. Clearer communication of the forces underlying inventory uncertainty may be needed so that the implications are better understood.
- Uncertainty estimates are not necessarily intended to dispute the validity of national GHG inventories, but they can help improve them.
- 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 methane (CH_4) and much more uncertain than carbon dioxide (CO_2). If uncertainty analysis is to play a role in cross-sectoral or international comparison or in trading systems or compliance mechanisms, then 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 greater 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 commitments, but it might be separated from negotiation of reduction targets. Future climate agreements will be made more robust, explicitly accounting for the uncertainties associated with emission estimates.

We give here a brief overview of how the 15 core papers of this book contribute to the key insights mentioned in Box 2—or of the likely consequences should insights not be heeded. Ometto et al. 2014a provide an in-depth look at the papers in their *Introduction*.

Together, all the papers confirm or advance key insights 1–4.

Jonas et al. and Rafaj et al. advance key insights 2 and 3, respectively. Jonas et al. broaden our thinking on emissions accounting systems by stepping out of the “here and now” of national emission inventories. They provide a framework that i) allows a country to be consistently embedded in a global emissions and long-term warming context; ii) enables a country's performance—past as well as projected achievements—in complying with a future warming target to be monitored, while at the same time iii) considering uncertainty in historic and projected emissions and quantifying the associated risks of missing target and/or pledged emissions. It is the combination of uncertainty and risk that postulates the need for even stricter emission reductions so as to limit the increase in global mean surface temperature until 2050 and beyond, as currently broadly discussed in the wake of the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2013: SPM). The paper by Rafaj et al., which identifies the principal determinants of the changes in SO_2, NO_x, and CO_2 emissions in Europe from 1960 to 2010, is interesting from two perspectives: i) it also includes ozone precursors; and ii) it does not, ostensibly, focus on uncertainty. However, the authors' methodology is important, as it allows a better understanding of uncertainty in projecting emission changes through isolation and quantification of the main factors that are most influential in reducing emissions.

The three papers by Lesiv et al., Hryniewicz et al., and Uvarova et al. also center on key insight 3, but more from a methodological perspective. Lesiv et al. and Hryniewicz et al. advance our knowledge by studying two important, though rather neglected, issues. Lesiv et al. seek to shed light on changes in the uncertainty of emission estimates due to learning (change in knowledge) and/or structural change in emissions. Hryniewicz et al. provide an answer to a vexing problemthat arises in comparing two parties (e.g., countries), A and B, whose uncertainties encompass the same emissions target—party A manages to just comply with the target but reveals a much greater uncertainty than that of party B, which slightly misses the target. Which party should we consider more credible in terms of meeting this emission target? Finally, Uvarova et al. illustrate the impact of learning, thus confirming Lesiv et al. The authors show how accuracy improves and relative uncertainty decreases through the use of more appropriate (higher-tier) accounting methods where these are available.

The paper by Ometto et al. 2014b centers on key insight 1. They are the only authors in the book to confirm the importance of full GHG accounting. With the focus on bottom-up accounting, the authors show how notable differences among existing biomass maps for the Brazilian Amazon, which combine remote sensing and field data analyses, lead to a wide spread in the estimated carbon emissions from deforestation. The general understanding among all Workshop participants was that it will take carbon-monitoring satellites such as NASA's OCO-2 (Orbiting Carbon Observatory), successfully relaunched in the meantime (Nature: http://blogs.nature.com/news/2014/07/nasa-launches-carbon-monitoring-satellite.html), to take the global carbon cycle and the issue of verification to new levels.

BOX 2 Lessons learned from uncertainty treatment: Conclusions drawn after the 2007 (2nd) International Workshop on Uncertainty in Greenhouse Gas Inventories. Source: White et al. (2011: 339–343)

1. The currently used bottom-up approach to accounting for greenhouse gas (GHG) emissions is incomplete in itself, as it cannot deal with the issue of accuracy. Bottom-up accounting for emissions is important in the sense that it shows which activities and actors are responsible for emissions. However, the ultimate accounting must be directed top-down, and reductions in emissions must be reflected in reductions in atmospheric GHG concentrations.

There are two immediate consequences of this: i) bottom-up accounting will be subject to continued revision in the future and must remain flexible; ii) this perception of emissions accounting runs counter to the ways in which emission trading schemes have been set up to date. To produce the desired results, these trading schemes need to be anchored, not least legally, within a reliable reference system, and this is not the case with current bottom-up accounting. Emission permits by country, which countries can sell at a given point in time but the number of which change because of continuous revisions in the estimates, fall outside conventional economic thinking. As a consequence, anything that raises doubt about the integrity of emission reductions is excluded because such doubt could potentially damage the market.

2. Earth's ecology acts as a complex and nonlinear system that is in a constant state of change. This system can be best understood over a long-term perspective; one should not expect to utilize nature to reduce anthropogenic GHG emissions in the same way that we use technological opportunities. By anticipating some accounting pitfalls, we can state that, to avoid surprises, we need to exercise caution in superposing subsystems with different emission-dynamic and uncertainty characteristics.
3. Uncertainty analysis should be used to develop clear understanding and informed policy in the framing of international environmental agreements. To ensure that uncertainty analysis becomes a key component of national GHG inventory analysis in support of international environmental policy, advanced guidance is needed so that uncertainty can be dealt with appropriately in an internationally consistent way across countries, subsystems, sources and sinks, GHGs, and sectors. This guidance goes beyond the methodologies offered by the Intergovernmental Panel on Climate Change (IPCC) to conduct and execute uncertainty analyses.
4. Uncertainty is higher for some GHGs and some sectors of an inventory than for others. Nature-related emissions and removals (e.g., in the land use, land-use change, and forestry (LULUCF) and the landfill sector) have greater uncertainty than technospheric emissions (e.g., in the fossil-fuel sector); and current estimates of nitrous oxide (N_2O) emissions are more uncertain than those of methane (CH_4) and carbon dioxide (CO_2). This raises the option that in designing future policy agreements, some components of a GHG inventory could be treated differently from others. The approach of treating subsystems individually and differently would allow emissions and uncertainty to be looked at simultaneously and would thus allow for differentiated emission reduction policies. This approach could have an advantage over treating all GHG emissions and removals collectively (in terms of CO_2-equivalence) and equally (not distinguishing between emissions and removals), which usually leads to increased uncertainty, with potentially important scientific and policy implications (e.g., in cases where countries claim fulfillment of their commitments to reduce or limit emissions). To recall, under the Kyoto Protocol the agreed emission changes for most countries were of the same order of magnitude as the uncertainty that underlay their combined emission estimates.
5. Any differentiated approach to accounting must form a logical subset of a full GHG accounting approach. Full accounting is the only way to reach a proper understanding of the global climate system and is a prerequisite for reducing the uncertainties in that understanding. Providing reliable and comprehensive estimates of uncertainty cannot necessarily be achieved by applying the approach favored under the UN Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol, which provided only for partial accounting of GHG fluxes to and from the atmosphere. It is virtually impossible to estimate the reliability of any system output if only part of the system is considered.

6. The option of treating subsystems individually and differently, while at the same time following full GHG accounting, forces us to deal with subsystems more skillfully than we have in the past. The maxim to follow would be to treat the technosphere, our built environment, and the biosphere individually but also holistically. Dealing with the technosphere and biosphere individually and differently, but not independently, although leading to agreement bifurcation, has clear advantages for emission inventories. First, it does not jeopardize verification—atmospheric measurements can discriminate between fossil fuel, terrestrial biosphere, and ocean carbon by means of their carbon isotope fingerprints in combination with measurement of atmospheric O_2; but they cannot identify individual fluxes within any of these categories. Second, differentiated accounting offers the option of i) placing emissions from the technosphere, where uncertainty is believed to be lowest, under stringent compliance with clear rules for dealing with uncertainty; while ii) putting biospheric emissions and removals, with their greater uncertainties, under consistent reporting by means of a global monitoring framework.

The three papers by Boychuk and Bun, Horabik and Nahorski and Verstraete are all unique in their own way. However, they should be seen collectively as advancing key insight 3 from the perspective of accounting for emissions of GHGs and air pollutants consistently across spatial (from local/regional to national) scales as well as from the methodological standpoint—a perspective that has not been given adequate importance in the context of insight 3.

The paper by Joerss advances key insight 4. By applying Monte Carlo simulation, it expands the issue of statistical dependence in input data for the overall uncertainty of a country's (here: Germany's) emission inventory from GHGs to particulate matter (PM_{10} and $PM_{2.5}$) and ozone precursors (SO_2, NO_x, NH_3, and NMVOV). This research paves the way for a better, that is, differentiated, understanding of uncertainty in emissions by gas or pollutant and sector.

Finally, the last five papers by Xu et al., Ermolieva et al., Nahorski et al., Dolgopolova et al., and Nijnik and Pajot can also be looked at *en bloc*. They advance our knowledge of emissions trading under uncertainty—and thus of key insight 1 (emissions trading is considered under verification; cf. Box 2)—in various specific ways pertaining to

- the impact of uncertainty on the price of certified emission reductions by examining a gas and sector specific example (Xu et al.);
- the impact of robustness on achieving emission reductions in a multi-country setting by considering decentralized bilateral trade and constraining the probability-based risk that emissions in combination with their uncertainty exceed a priori agreed emissions targets (Ermolieva et al.);
- the impact of uncertainty on trading rules in a multi-country setting by simulating bilateral trade and simple, reverse sealed auction mimicking the Kyoto Protocol with modified, uncertainty dependent rules and with learning versus non-learning agents (Nahorski et al.);
- the impact of economic, institutional and technological uncertainties on trading carbon emissions both at national and business levels by conducting simulations with the help of two systems dynamics models (Dolgopolova et al.);
- and, last but not least, the impact of varying discounting rates for carbon uptake specifically and economic cost-benefit analyses and the policy-making process in general (Nijnik and Pajot).

However, none of these approaches advance key insight 1 from a more fundamental perspective, the reason being that they are still subject to a bottom-up emissions accounting bias and are not yet anchored in a two-sided (bottom-up versus top-down) or verified emissions accounting framework. This means that the approaches cannot handle inaccuracy (at least, not beyond a certain magnitude), only imprecision. Thus, it remains to be seen how economists face up to the challenge of shaping emissions trading under conditions of a changing reference system—until bottom-up/top-down accounting is in place and conducted.

To conclude, it is noted that the challenges of addressing key insights 5 and 6 still exist; they were not tackled at the Workshop. However, on a general note, the approaches to addressing uncertainty discussed by all authors attempt to improve national inventories, not only for their own sake but also from a wider, systems analytical perspective that seeks to strengthen their usefulness under a compliance and/or global monitoring and reporting framework. They thus show the challenges and benefits of including inventory uncertainty in policy analysis, and where advances are being made. The issues that are raised by the authors and featured in their papers, and the role that uncertainty analysis plays in many of their arguments, highlight the importance of such efforts. The general understanding among all Workshop participants was unanimous: uncertainty analysis is needed for developing clear understanding and informed policy. Uncertainty matters, and it is key to many issues related to inventorying and reducing emissions. Dealing proactively with uncertainty allows useful knowledge to be generated that the international community should have to hand before negotiating international successor agreements to the Kyoto Protocol.

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INTRODUCTION

Uncertainties in greenhouse gases inventories – expanding our perspective

Jean P. Ometto · Rostyslav Bun · Matthias Jonas · Zbigniew Nahorski · Mykola I. Gusti

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Strategies for mitigating global climate change require accurate estimates of the emissions of greenhouse gases (GHGs). A strong consensus in the global scientific community states that efforts to control climate change require stabilization of the atmospheric concentration of GHGs (as per a recent compilation; (IPCC 2013)). Estimates of the amounts of carbon dioxide and other GHGs emitted to the atmosphere, as well as the amounts absorbed by terrestrial and aquatic systems, are crucial for planning, analyzing, validating and at global scale verifying mitigation efforts and for analyzing scenarios of future emissions. The magnitude and distribution of current emissions and the path of future emissions are both of considerable importance. It is critical that we have estimates of emissions and that we acknowledge and deal with the uncertainty in our best estimates. The range of issues that derive from uncertainty in emissions estimates was the subject of the 3rd International Uncertainty Workshop held in Lviv, Ukraine, 2010, and is the subject of this special issue.

Resolving national or regional contributions to changes in atmospheric GHG concentrations involves international agreements and national inventories of emissions. Countries, cities, companies, and individuals are now commonly calculating their GHG emissions, and markets

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exist that allow trading emissions permits of carbon. Companies report corporate-level emissions or even the carbon footprint of products. But GHG emissions are seldom measured directly. For instance, it may be considered important that total, and trend, uncertainty in national emissions estimates is smaller than the reductions to which countries agree to under an international compliance regime, as well that emissions mitigation strategies, and trade, be based on accurate knowledge of the magnitudes and sources of emissions.

The 2010 United Nations Framework Convention on Climate Change (UNFCCC-COP 16; Cancun, Mexico) produced an agreement with the desire to limit global average surface temperature to 2 °C above the pre-industrial level. To achieve this objective, the total amount of greenhouse gas emissions emitted to the atmosphere in 2020 has to be targeted at around 44 Pg CO_2-eq, from the current estimated value of 48 Pg CO_2-eq [assuming a linear target path]. However the current emissions trajectories follow the most carbon intensive path of the recently published scenarios of the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC 2013) (based on Representative Concentration Pathways; www.globalcarbonproject.org/). Experience with the Kyoto Protocol shows that quantitative estimation of uncertainty increases the value of the inventory provided by reporting authorities. Yet, only a few Annex I Parties report full uncertainty analysis, although default methods and underlying data are available for all countries.

UNFCCC reporting should be improved as Parties report comprehensive uncertainty analysis of the GHG inventory estimates and provide validation reports (for data and models used). The Intergovernmental Panel on Climate Change (IPCC) has proposed standardized methodologies for adequate accounting of national, natural and human-induced GHG sources and sinks. The methods, applied to national scales, have guided the production of emissions assessments at the country level for several years. Comparable methodologies have been developed within countries and trade groups. The constant evolution of the IPCC scientific review, associated with increasing international concerns over anticipated changes in the future climate, has raised a number of issues about compliance and verification, and about proposed and agreed strategies meant to reduce the impact on the global climate associated with human activities.

Because of the accumulation of GHGs in the atmosphere, concern focuses on not just current rates of emissions but on the trend in emissions and in cumulative emissions totals. Cumulative GHG emission budgets (i.e., for 2000–2050) have been shown to be a robust indicator for global temperatures at, and beyond, 2050 (Meinshausen et al., 2009), and are thus well suited to link long-term global warming targets with near and mid-term emissions. Cumulative global emissions targets can be translated into near term national emissions objectives, but uncertainty in both natural and anthropogenic fluxes of GHGs must be incorporated in monitoring and projecting emissions trends.

The international workshop in Lviv, Ukraine, was the third in a series exploring the magnitude and implications of uncertainty in GHG emissions estimates. Papers presented at the workshop and peer reviewed for this Climatic Change Special Issue explore the uncertainty in emissions estimates but also focus on detecting and evaluating changes in emissions; independent monitoring and verification of emissions estimates; and determining how to obtain critical information, and how to proceed without information that cannot be obtained. The papers are presented under general themes such as: Spatial Inventories; Land Use, Land Use Change and Forestry; Energy; Non-CO_2 and Waste emissions; Economy and Climate Change; and General & Policy.

In *General & Policy*, *Jonas* et al. ask how uncertainty over time will affect short-term GHG emission commitments and long-term efforts to meet global temperature targets for 2050 and beyond. The study addresses a fundamental problem: how to combine uncertainty about current and historic emissions (diagnostic uncertainty) with uncertainty about projected future emissions (prognostic uncertainty). Although the authors' mode of bridging uncertainty across temporal scales still relies on discrete points in time and is not yet continuous, their study takes a valuable first step toward that objective. The proposed emissions-temperature-uncertainty framework assumes that cumulative emissions can be constrained over time by binding international agreements, as well as that emissions can be estimated only imprecisely, and whether or not they will achieve an agreed temperature target is also uncertain. The framework allows policymakers to understand diagnostic and prognostic uncertainty so that they can make more informed (precautionary) decisions for reducing emissions given an agreed future temperature target. The paper by *Rafaj* et al. examines key factors that have driven the observed evolution of SO_2, NO_x, and CO_2 emissions in Europe from 1960 to 2010, contributing to the understanding of the relationship between emissions and economic growth. It has often been suggested that emissions first increase with growing income and social welfare and subsequently decrease once a certain level of wealth has been attained. However, the authors' analysis demonstrates that observed turning points occur for different countries and pollutants at different income levels, and no turning point has yet been identified for CO_2. Although there are factors determined by economic parameters (e.g. energy intensity, fuel mix, technological advances), the results provide little evidence that the emission control measures are directly linked to economic growth, but their adoption is rather driven by enforcement of deliberate mitigation policies. The methodology presented by the authors provides a quantitative basis for investigating uncertainties related to the determinants of emission projections. Their exemplary decomposition analysis allows for identifying those parameters that are most relevant in assessing the uncertainty of GHG emission inventories. Under the same theme, *Lesiv* et al. deal with the change in the uncertainty of emission estimates which, in general, results from both learning (improvement of knowledge) and the structural change in emissions (change in emitters). Understanding the change in uncertainty due to the two processes and being able to distinguish between them becomes particularly important under a compliance regime when countries claim fulfillment of their commitments to reduce or limit emissions, or for trading emission quotas under such a regime. In the first part of their study, focusing on the individual Member States of the former EU-15, the historical change in the total uncertainty of CO_2 emissions from stationary sources is analyzed. In the second part of their study, the authors present examples of changes in total uncertainty considering scenarios of structural changes in the emitters consistent with the EU's "20–20–20" targets. This exercise shows that the increased knowledge of inventory processes has determined the change in total uncertainty in the past and should also be considered as the driving factor in the prospective future. In the final contribution within *General & Policy*, Hryniewicz et al. return to the problem of checking compliance of uncertain GHG inventories with agreed emission targets. That is, why a direct comparison of emissions with targets is not scientifically robust. The starting point of this study is the IPPC Good Practice Guidelines statement that reporting of inventories should be consistent, comparable and transparent. Thus, there exists the need to explain why inventoried emissions satisfy a target or are closer to it in one case than in another. This idea led the authors to look at a compliance procedure via comparison of uncertain alternatives. Traditionally, probabilistic methods have been used, in which emissions are treated as a random variable. Comparison rules based on moments, such as mean values and variances, are not suitable for the comparison of emissions. More appropriate methods use percentiles and critical values, like a so-called undershooting technique which was discussed earlier, e.g. by Nahorski et al. (Nahorski et al. 2007) and Nahorski and Horabik (Nahorski and Horabik 2010). However, emissions are inventoried usually only once per year, and they are typically not random, so it is difficult to treat them as probabilistic variables. This is why possibility theory, which has grown out of the fuzzy sets, is more suitable to the problem. A possibility distribution is not based on frequencies of observations, but may be constructed, e.g., by experts. Despite the differences in the probability/possibility paradigms, the methods behind both approaches show similarities and the checking rules are often alike. Taking uncertainty into account, additional parameters are proposed to be included in a checking rule: how stringent do we understand compliance; or to which extent is the target met. Such a rule allows for classifying inventories: how credible are these in satisfying the target? This information can be used in elaborating advanced decision rules, which would allow for taking a more or less conservative position.

The evolution in reducing uncertainty in emissions estimates reflects: (1) improvements in knowledge within the scientific community (e.g., more precisely known emission factors and improvements in energy data); and (2) structural changes in the emissions (e.g., an increasing fraction of emissions from the sectors where data can be estimated with smaller uncertainty, such as energy). Within the *Energy* category of the contribution to this Special Issue volume, *Uvarova* et al. focus on a prime emitter – emissions from oil operations in the Russian Federation. The authors provide a good example to illustrate the impact of learning. They investigate improvement in accuracy of emission estimates under a shift of accounting methods: from the production-based IPCC (IPCC 2000) Tier 1 to the mass-balance-based IPCC (IPCC 2006) Tier 2. The authors' comparison shows that the estimates in accordance with the higher-tier method result in a greater accuracy and lower relative uncertainty (26 % under Tier 2 versus 54 % under Tier 1). The authors suggest that this uncertainty can be reduced further, e.g., by improving the accuracy of the parameters, including the use of more geographically explicit emission factors, employed in the emissions calculations.

Furthermore, in the session dedicated to emissions associated with Land Use, Land Use Change and Forestry, *Ometto* et al., explore uncertainties associated with emissions related to land use change in the tropics, focusing on deforestation. As reported by Le Quéré et al. (Le Quéré et al. 2013), net emissions from deforestation are decreasing, although this issue is far from resolved. The carbon stock in the terrestrial biosphere is enormous and the pressure for land use and agricultural expansion is constant, especially in tropical systems (Dalla-Nora et al. 2014). The methods currently adopted to estimate the spatial variation of above- and below-ground biomass in tropical forests are usually based on remote sensing analyses coupled with field datasets. Field measurements in tropical forests are, typically, relatively scarce and often limited in their spatial distribution. Thus, lack of data is one major step to be overcome concerning reducing uncertainty in estimating GHG emissions from land use change, in particular in tropical regions. In this paper, the authors do a comparative analysis of recently published biomass maps of the Amazon region, including the official data used by the Brazilian government for its report to the UNFCCC Secretariat. Among the outcomes of their analysis, the evolvement to higher resolved, spatially distributed forest biomass data is key to reduce uncertainty in emissions estimates in tropical regions. Establishing national systems of GHG emissions estimation and reporting in Land Use, Land Use Change, and Forestry (LULUCF) is under continuous improvement, with key features given by the availability of datasets and in-country improving capacity of data generation. However, regional harmonization of methods involved in national GHG estimation systems is rather poor. There are also necessary within-country steps toward better coordination of the research effort supporting GHG estimation, reporting and accounting under UNFCCC requirements. As well, the increase of data availability for external evaluation is an important step further toward better estimates of uncertainty.

The spatial distribution and estimates of emissions are further explored in the *Spatial Inventories Section*. Emission inventories with high spatial and temporal resolution can be related to a process-level understanding of emissions sources and yield many advantages in the realm of designing and evaluating emission control strategies; and they would be very helpful for climate models and for monitoring emissions and checking emissions commitments in greater detail where necessary. *Boychuk and Bun*, also referring to the *Energy Section* of this Special Issue, present a Geographical Information System (GIS) approach to the spatial inventory of GHG emissions in the energy sector. It includes the mathematical background for creating the spatial inventories of point-, line-, and area-type emission sources, caused by fossil-fuel use for power and heat production, the residential sector, industrial and agricultural sectors, and transport. The approach is based on the IPCC guidelines, official statistics on fuel consumption, and digital maps of the region under investigation. As an example, the western Ukraine region with an area of 110.6th km^2 was used for experiments. The uncertainty of inventory results is calculated, and the results of sensitivity analysis are investigated. The approach proposes that allocating emissions to the places where they actually occur helps to improve the inventory process and to reduce the overall uncertainty. Such methodology is useful for large countries with uneven distribution of emission sources. Spatial inventories support decision making in reducing emissions at the regional level. Such mathematical tools and algorithms can also be used in climate models, for the analysis and prediction of the emission processes and their structure for a variety of scenarios. In a similar vein, *Horabik and Nahorski* present an original approach to allocating spatially correlated data, such as GHG emission inventories, to finer spatial scales, based on covariate information observable in a fine grid. This approach is useful for data disaggregation, like activity data in some categories of human activity, during GHG spatial inventory. Dependences are modeled with the conditional autoregressive structure introduced into a linear model as a random effect. The maximum likelihood approach to inference is employed, and the optimal predictors are developed to assess missing values in a fine grid. The authors propose a relevant disaggregation model and illustrate the approach using a real dataset of ammonia emission inventory in a region of Poland in 15 km, 10 km, and 5 km grids. For the considered inventory, the fourfold allocation benefits greatly from the incorporation of the spatial component, while for the ninefold allocation, this advantage is limited, but still evident. Also, the proposed method is found to be particularly useful in correcting the prediction bias encountered for upper range emissions in the linear regression models. In this case study, the authors use the original data in a fine grid to assess the quality of resulting predictions, but for the purpose of potential applications, they also developed a relevant measure of prediction error. It is an important step to quantify the prediction error in situations, where original emissions in a fine grid are not known. The method of improving resolution opens the door to uncertainty reduction of spatially explicit GHG emission inventories.

Processing spatial data, such as GHG inventories, poses several problems, as the data are represented as grids. *Verstraete* proposes an approach to optimize the mapping of values in mismatched grids. When data that are represented using different grids need to be combined, the main problem is that the underlying distribution of activity data or any other parameter is not known, and thus a remapping from one grid onto another grid is difficult. Traditional methods work by making simple assumptions regarding the underlying distribution, but as those often do not match reality, it decreases the accuracy of the data. However, often there is knowledge available that can help with better estimating the real distribution. In the article, the author presents a new method, which allows additional data to be used. The method presented uses techniques from artificial intelligence (fuzzy sets, inference systems, etc.) to determine how one grid can be remapped onto another grid. Even with additional data, this is not straightforward, as data may not match exactly or may be incomplete. The article describes the concept of the approach, and discusses the results of experiments on artificial datasets.

Joerss, contributing to the *Non-CO_2 / Waste Section*, compares results of air pollutant inventories from several European countries with the results of the PArticle REduction Strategies (PAREST) research project in Germany. The author uses a Monte-Carlo simulation for assessing the uncertainties in emissions of particulate matter (PM10 & PM2.5) and aerosol precursors (SO_2, NO_x, NH_3 and NMVOC). The methodology and analysis for uncertainty assessment in the emissions inventories is successful for particulate matter and aerosol precursors. The uncertainty of the pollutant species analyses is determined and falls in the range of recent uncertainty assessments of European countries. The analysis by *Xu* et al, also part of this section, reveals a link between *Non-CO₂* emissions and economy, where the authors tackle the problem of uncertainty assessment in coal mine methane emissions projects, and estimation of its impact on a negotiated Certified Emission Reduction (CER) price. They use the Rubinstein-Ståhl bargaining model to fill the gaps in the database and to simulate negotiations concerning CER price, assuming that a buyer's willingness to negotiate a CER depends on the uncertainty associated with the emission reduction. The bargaining model is broadened by introducing dependence of some parameters on the probability of a contracted CER amount not to be realized. To quantify this probability, the authors develop a conditional distribution given information on the point estimate of methane emissions for the project under consideration, and on the distribution of available estimates from coalmines having similar characteristics. The proposed methodology is applied to a coalmine methane project implemented in the Huainan coalmine, the Anhui Province in Eastern China. The parameters of uncertainty distribution of the methane content are estimated using data, which are gathered from 25 Chinese coalmines with similar geological conditions. The results indicate that the uncertainty influence on price is significant, particularly when the credibility of a seller increases, and the probability of a failure to fulfill the project decreases.

The aggregated impact of climate change on society, economy and ecosystems, comprises the total impact across regions. Producing results of aggregated impact involves the challenge of discerning how adaptation will occur in society and ecosystems (what is the resilience of natural systems) and what are the paths that future development (economic and social) will follow (IPCC AR5). The section dedicated to the *Economy & Climate Change* brings some of these elements to the discussion. *Ermolieva* et al. develop a novel trading-market model which mimics decentralized bilateral trade of emission permits under uncertainty. In contrast to existing emissions markets, the proposed model allows for addressing long-term socio-economic and environmental consequences of trade, irreversibility, and inherent uncertainty including asymmetric information of agents (countries). The model relies on an anonymous computerized optimization system (computerized market system) that can be viewed as "cloud computing". Trading between both countries and regions is shown to be robust. The trading process converges to the core solution and the trading parties create the stable (core) solution without incentives to leave the trading coalition. Numerical results show that the explicit treatment of uncertainty may significantly change the trading process by turning sellers of emission permits into buyers.

Looking at the carbon market under the Kyoto Protocol, *Nahorski* et al. present a simulation system that mimics trading of GHG emissions among parties, according to the Protocol's rules. It is admitted that the emissions are uncertain and this knowledge affects the trading rules, as presented in earlier studies by Nahorski et al. (Nahorski et al. 2007) and Nahorski and Horabik (Nahorski and Horabik 2010). These rules lead to more uncertain emissions that are less expensive on the market. The simulation does not assume an ideal market: the equilibrium prices are not known during the trade. Bilateral negotiations and sealed bid reverse auctions are considered for pricing the traded emissions. Only transactions profitable for both participants are accepted. A multi-agent approach is used as a tool for simulating the trading process. Non-learning and learning agents are considered. The former use fixed probability distributions for placing orders, while the latter learn to modify the distribution according to the success/lack of success in winning transactions. Negotiation examples present phenomena similar to those spotted in real markets.

Following up on carbon trading, and on the influence of uncertainty on driving the market and defining prices, *Dolgopolova* et al. employ system dynamics models to analyze the impact of different uncertainties on emission trading - both on national and business levels. Economic, institutional and technological uncertainties determine the benefits from trading emissions permits. For any country participating in an international trading market, the uncertainty in the price range becomes crucial. In the case of business investment decisions for implementing resource-saving technologies, the proposed system dynamics model shows that the first-mover investor will obtain significantly fewer advantages than his followers, which leads to a delay in primary investments.

Nijnik & Pajot analyze the social function of forests and the opportunity for mitigation through maintaining and replanting trees, and discuss the economic impact of dealing with uncertainties in using forests to mitigate climatic change. Limiting the analysis of uncertainty to discounting, the authors challenge the traditional cost-benefit analysis. Different settings of discounting are tested for carbon sequestration of the forestry sector in Scotland and Ukraine. The policy consequences of the exercise are also investigated. The choices of discounting protocols are shown to have a major influence on both the economic analysis and the decision-making process, which directly affect the climate change mitigation strategies in these countries. The authors highlight the implications on the policy decisions when uncertainty is considered in mitigating climate change through forestry.

Changes in relative uncertainty over time and scientific understanding of the main determinants of that change have obvious implications, e.g., for assessing the uncertainty of emissions with regard to compliance with emission reduction commitments and for trading emission quotas under the Kyoto Protocol or REDD+ mechanisms. Advances in methodology and mathematical modelling to constrain uncertainties associated with ecosystems and some carbon pools, are observed. However, investments in methodology-oriented research are particularly important for a full-system uncertainty estimate. In terrestrial systems, historical patterns and long-term datasets are important to draw a more accurate picture of the carbon pools evolution. In this respect we see the following scientific advances evolving from the workshop that should be considered in future studies: (i) combining diagnostic and prognostic uncertainty in a (e.g.) emissions-temperature setting that seeks to constrain global warming and linking uncertainty consistently across temporal scales; (ii) developing methodologies and information technologies that allow estimating GHG emissions and sinks with lower uncertainties, e.g., spatial GHG cadastres, and higher level tier methods; (iii) evaluating the influence of uncertainty on GHG emission markets aiming at robust and efficient emission trading; (iv) studying issues that influence the dynamics of GHG emissions estimates, e.g., learning curves and structural changes in emitters, as well as social, political and economic drivers, etc.; (v) constraining uncertainties in land use change emissions, as having great potential for reduction, and per its influence on ecosystem services and social aspects; and developing marked strategies for making emissions reduction economically attractive.

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Uncertainty in an emissions-constrained world

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Abstract Our study focuses on uncertainty in greenhouse gas (GHG) emissions from anthropogenic sources, including land use and land-use change activities. We aim to understand the relevance of diagnostic (retrospective) and prognostic (prospective) uncertainty in an emissions-temperature setting that seeks to constrain global warming and to link uncertainty consistently across temporal scales. We discuss diagnostic and prognostic uncertainty in a systems setting that allows any country to understand its national and near-term mitigation and adaptation efforts in a globally consistent and long-term context. Cumulative emissions are not only constrained and globally binding but exhibit quantitative uncertainty; and whether or not compliance with an agreed temperature target will be achieved is also uncertain. To facilitate discussions, we focus on two countries, the USA and China. While our study addresses whether or not future increase in global temperature can be kept below 2, 3, or 4 °C targets, its primary aim is to use those targets to demonstrate the relevance of both diagnostic and prognostic uncertainty. We show how to combine diagnostic and prognostic uncertainty to take more educated (precautionary) decisions for reducing emissions toward an agreed temperature target; and how to perceive combined diagnostic and prognostic uncertainty-related risk. Diagnostic uncertainty is the uncertainty contained in inventoried emission estimates and relates to the risk that true GHG emissions are greater than inventoried emission estimates reported in a specified year; prognostic uncertainty refers to cumulative emissions between a start year and a future target year, and relates to the risk that an agreed temperature target is exceeded.

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1 Introduction

This study focuses on the uncertainty in estimates of anthropogenic greenhouse gas (GHG) emissions, including land use and land-use change activities. It aims to provide an overview of how to perceive uncertainty in a systems context seeking to constrain global warming.

It focuses on understanding uncertainty across temporal scales and on reconciling short-term GHG emission commitments with long-term efforts to meet average global temperature targets in 2050 and beyond. The discussion is a legacy of the 2nd International Workshop on Uncertainty in Greenhouse Gas Inventories, which concluded:

> 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" (Jonas et al. 2010a).

It addresses a fundamental problem: how to combine diagnostic (retrospective) and prognostic (prospective) uncertainty. Current (and historic) GHG emission inventories contain uncertainty in relation to our ability to estimate emissions (Lieberman et al. 2007; White et al. 2011). Diagnostic uncertainty results from grasping emissions accurately but imprecisely (our initial assumption). It can be related to the risk that true GHG emissions are greater than inventoried estimates reported at a given time point (Jonas et al. 2010b: Tab. 3). (The opposite case, true emissions being smaller than inventoried estimates, is not relevant from a precautionary perspective.)

Diagnostic uncertainty, our ability to estimate current emissions, stays with us also in the future. Assuming that compliance with an agreed emissions target is met in a target year allows prognostic uncertainty to be eliminated entirely. How this target was reached is irrelevant; only our real diagnostic capabilities of estimating emissions in the target year matter. This is how experts proceeded, e.g., when they evaluated ex ante the impact of uncertainty in the case of compliance with the Kyoto Protocol (KP) in 2008–2012, the Protocol's commitment period (Jonas et al. 2010b).

Emissions accounting in a target year can involve constant, increased or decreased uncertainty compared with the start (reference) year, depending on whether or not our knowledge of emission-generating activities and emission factors becomes more precise. The typical approach to date has been to assume that, in relative terms, our knowledge of uncertainty in the target year will be the same as it was in the start year.

However, uncertainty under a prognostic scenario always increases with time. The further we look into the future, the greater the uncertainty. This important difference suggests that diagnostic and prognostic uncertainty are independent. This differs from how prognostic modelers usually argue. A prevalent approach is to realize a number of scenarios and grasp prognostic uncertainty by means of the spread in these scenarios over time—which increases with increasing uncertainty in the starting conditions built into their models. However, this approach nullifies diagnostic uncertainty once a target (future) is reached.

To stabilize Earth's climate within 2 °C of historic levels, treaty negotiations have pursued mechanisms that reduce GHG emissions globally and lead to sustainable management of the atmosphere at a "safe," steady-state level. In recent years, international climate policy has increasingly focused on limiting temperature rise as opposed to achieving GHG concentration–related objectives (Rogelj et al. 2011). A promising and robust methodology for adhering to a long-term global warming target appears to be to constrain cumulative GHG emissions in the future (WBGU 2009; Allen et al. 2009; Matthews et al. 2009; Meinshausen et al. 2009; Zickfeld