International Institute for Applied Systems Analysis
Schlossplatz 1 • A-2361 Laxenburg • Austria
Telephone: (+43 2236) 807 342 • Fax: (+43 2236) 71313
E-mail: publications@iiasa.ac.at • Internet: www.iiasa.ac.at

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Full Carbon Accounting and the Kyoto Protocol: A Systems-Analytical View

Matthias Jonas (jonas@iiasa.ac.at)
Sten Nilsson (nilsson@iiasa.ac.at)
Anatoly Shvidenko (shvidenk@iiasa.ac.at)
Vladimir Stolbovoi (stolbov@iiasa.ac.at)
Michael Gluck (gluck@iiasa.ac.at)
Michael Obersteiner (oberstei@iiasa.ac.at) and (oberstei@ihs.ac.at)
Alf Öskog (oeskog@iiasa.ac.at) and (alf.oskog@ssc.se)

Approved by

Gordon J. MacDonald
Director, IIASA

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Contents

Abstract

IIASA's Sustainable Boreal Forest Resources (FOR) Project, together with the Environmentally Compatible Energy Strategies (ECS) Project, is carrying out a full carbon account (FCA) for Russia. This report discusses the application of FCA in addressing some major scientific issues and challenges underlying the Revised 1996 Guidelines of the Intergovernmental Panel on Climate Change (IPCC) and the Kyoto Protocol.

FOR is moving towards a full-carbon-accounting approach, taking baselines, baseline scenarios and uncertainty into account. We have a number of advantages in carrying out this work by having access to a unique database on Russia. The Russian forest vegetation contains about 20 percent of the world's carbon stored in forest vegetation for which we have generated detailed databases on the forest sector, terrestrial biota, and land use

FOR will also derive full carbon accounts for other countries (Austria, Ukraine, etc.), that will permit the project to generalize findings and to identify knowledge gaps of relevance to make the Kyoto Protocol operational. This work will significantly contribute to the work of the IPCC and International Geosphere-Biosphere Programme, and will naturally link with the remote sensing and biodiversity activities at IIASA.

The study analyzes a number of crucial issues that are relevant to, but are not appropriately taken into account by the Kyoto Protocol. These issues relate to: (1) whether the greenhouse gas guidelines of the Intergovernmental Panel on Climate Change can serve as the main carbon accounting and legal compliance system for the Kyoto Protocol; (2) full carbon accounting; (3) establishing 1990 baselines and post-1990 baseline scenarios; and (4) accounting for uncertainty.

We investigate the role of a systems analysis-based full carbon accounting approach to address these issues.

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About the Authors

Matthias Jonas is a research scholar in the Forest Resources Project at IIASA where he is engaged, together with Sten Nilsson who is Project Leader, Anatoly Shvidenko, Vladimir Stolbovoi, Michael Gluck, Michael Obersteiner and Alf Öskog in a study on determining the Carbon Budget for Russia – Implications for the Kyoto Protocol. Michael Obersteiner is also a research scholar at the Institute for Advanced Studies, Vienna. Alf Öskog is also affiliated with SSC Satellitbild, Kiruna, Sweden, a subsidiary of the Swedish Space Corporation (SSC).

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1. Introduction

The scientific community faces two major carbon-related research challenges: (1) to "close" the carbon cycle on the global scale, and (2) (in order to accomplish the first challenge) to account for carbon on a sub-global or regional scale. We suggest that adequate carbon accounting at the sub-global or regional scale has two requirements:

- full carbon accounting (FCA) is used, and
- this accounting is consistent with the global account.

The uptake or release of CO_2 from the world's oceans and terrestrial ecosystems is central for understanding the relationship between emissions of CO_2 and its atmospheric levels. Of the 7.1 Pg of carbon released into the air each year by human activities, 1.8 Pg of carbon cannot be accounted by land or sea sinks. Modifications to the carbon cycle caused by changes in climate and in atmospheric CO_2 concentrations are believed to render terrestrial ecosystems, particularly in the Northern Hemisphere, as substantial carbon sinks, although direct evidence for this is still missing (Ciais *et al*., 1995; Keeling *et al*., 1996; Cao and Woodward, 1998; Schimel, 1998; Schmidt, 1998).

The Kyoto Protocol to the UN Framework Convention on Climate Change contains legally binding commitments to limit or reduce the emissions of six greenhouse gases or groups of gases (CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6). According to the Protocol, Annex I Parties[1] must reduce their emissions by at least five percent below 1990 levels within the commitment period 2008–2012. Article 3.3 of the Protocol states that biological sources and sinks should be used for meeting commitments during the stipulated period, but limits these sources and sinks to afforestation, reforestation and deforestation since 1990. Further, Article 3.4 provides the possibility of using additional land-use change and forestry activities to meet reduction commitments. Articles 3.3 and 3.4 (as well as other articles), however, give rise to serious scientific concerns. For instance, they have created confusion as to how anthropogenically induced net changes in forest carbon stocks[2] should be treated; furthermore the role of soils in land-use change and forestry introduces an additional complexity. Hence, a key challenge, and required improvement to the Protocol, is to come to grips with the uncertainties relating to "land-use change and forestry" in the carbon cycle (SBSTA, 1998b; Schlamadinger and Marland, 1998; UNFCCC, 1998; WBGU, 1998; MacDonald, 1999).

Our research focuses on the scientific tasks of adequate carbon accounting on a sub-global scale and how to improve the Kyoto Protocol in this respect. This approach uses a full carbon account (spatially complete with respect to the world's terrestrial ecosystems) to avoid misaccounting or introduction of perverse incentives that may result from a partial account. It should be pointed out, however, that our primary focus is on terrestrial ecosystems.

The objectives of this study are to:

- provide a scientific platform for the work on sub-global carbon balances IIASA is carrying out in the form of case studies (Austria, Russia, and Ukraine); and to
- provide a scientific platform supporting the improvement of the Kyoto Protocol.

In the study we analyze a number of crucial issues that are relevant to, but are not appropriately taken into account by the Protocol. The issues relate to:

- whether the revised 1996 greenhouse gas guidelines of the Intergovernmental Panel on Climate Change (IPCC, 1997a, b, c) (referred to as IPCC Guidelines hereafter) can serve as the main carbon accounting system for the Kyoto Protocol and thus serve as a legal basis of compliance;

- a number of scientific and methodological issues, which can be divided into three groups:

  1. issues related to FCA;
  2. issues related to establishing 1990 baselines and post-1990 baseline scenarios; and
  3. issues related to accounting for uncertainty.

We investigate the role of a systems analysis-based FCA approach in dealing with these issues.

2. The UN Framework Convention on Climate Change: The Rio and Kyoto Benchmarks

Section 2 contains a brief overview on the UN Framework Convention on Climate Change, the Kyoto Protocol, as well as post-Kyoto events and activities that deserve mention in the context of this study.

2.1 The UN Framework Convention on Climate Change

In response to a likely threat of a human-induced change in the Earth's climate and its adverse effects[3], the United Nations General Assembly established the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change (INC) in December 1990, with the mandate to negotiate a convention containing "appropriate commitments" in time for signature at the UN Conference on Environment and Development (UNCED) in June 1992. The INC met six times between February 1991 and May 1992, and adopted the UN Framework Convention on Climate Change (FCCC) on 9 May 1992. As of 7 October 1998, the Convention received 176 instruments of ratification. It came into force on 21 March 1994 (UNFCCC, 1992, 1999b; Bodansky, 1994).

The Convention does not commit States to specific limitations on greenhouse gas emissions. It recognizes, however, climate change as a serious threat and establishes a basis for future action. First, it defines, as a common long-term objective, the stabilization of atmospheric concentrations of greenhouse gases *at a level that would prevent dangerous anthropogenic interference with the climate system*. Second, it sets forth principles relating to inter and intra-generational equity, the needs of developing countries, precaution, cost-effectiveness, sustainable development, and the international economy, to guide future work. More importantly, the Convention establishes a process designed to improve our information base and reduce uncertainties, to encourage national planning, and to produce more substantive international standards should scientific evidence continue to mount that human activities are changing the Earth's climate (UNFCCC, 1992; Bodansky, 1994).

To many, the Convention was a disappointment. Despite early hopes that it would seek to stabilize or even reduce emissions of greenhouse gases by developed countries – to start with – the Convention contains only the vaguest of commitments regarding stabilization and no commitment at all on reductions.[4] The Convention fails to include innovative proposals to establish a financial and technology clearinghouse or an insurance fund, or to use market mechanisms such as tradable emissions rights. Furthermore, it not only contains significant qualifications on the obligations of developing countries, but gives special consideration to fossil fuel producing States (Bodansky, 1994).

Nevertheless, it must be stated that – given the complexity of the negotiations, which involved more than 140 States with very different interests and ideologies, and of the causes, effects, and policy implications of global warming – reaching agreement at all in such a limited period of time was a considerable achievement. In fact, the final text is significantly more substantive than previous framework conventions for long range transboundary air pollution and protection of the stratospheric ozone layer (Bodansky, 1994; O'Riordan and Jäger, 1996).

2.2 The Kyoto Protocol

At its third meeting in Kyoto in 1997, the Conference of the Parties (COP)[5] adopted the Kyoto Protocol (also referred to as Protocol hereafter) to the UN Framework Convention on Climate Change. As of 15 March 1999, 84 countries have signed the Protocol, which must subsequently undergo ratification. It will enter into force 90 days after at least 55 Parties to the FCCC have ratified it, provided those countries incorporate Annex I Parties[1] that account for at least 55% of the total CO_2 emissions for 1990 (IISD, 1998; UNFCCC, 1998, 1999b).

The Protocol contains, for the first time, legally binding commitments[6] to limit or reduce the emissions of six greenhouse gases or groups of gases (CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6), but falls short of prescribing non-compliance measures. The targets agreed to under the Protocol for Annex I Parties by the (first) commitment period 2008 to 2012 add up to a decrease in greenhouse gas emissions of ~5% below 1990 levels in terms of CO_2 equivalents. Non-Annex I Parties need not take on specific commitments for emission reductions. The Protocol provides that biological sources and sinks shall also be used to meet 2008-2012 commitments, but limits these sources and sinks as yet to afforestation, reforestation and deforestation since 1990. It further provides for the possibility of taking into account additional human-induced activities that cause changes in greenhouse gas emissions and are related to the categories agricultural soils, and land-use change and forestry. Last but not least, the Protocol also endorses emissions trading, joint implementation between Annex I Parties, and a clean development mechanism (CDM) that allows Annex I and non-Annex I Parties to act together to reduce emissions (Bolin, 1998; Schlamadinger and Marland, 1998; UNFCCC, 1998; WBGU, 1998). Table 2.1 compiles and groups the 28 articles of the Protocol, including its annexes, according to their contents. (The Protocol does not provide its articles with headings.)[7]

To many, the objectives of the Protocol are modest in terms of what may be needed to satisfy Article 2 of the Convention, that is, to stabilize greenhouse gas concentrations in the atmosphere *at a level that would prevent dangerous anthropogenic interference with the climate system*. In fact, the Kyoto agreement, since it essentially leaves out binding reductions from the growing less developed countries and stabilizes rather than reduces continuously the industrial countries' emissions, implies a long-term future in which CO_2 concentrations will double or triple (Schneider, 1998).[8] Nevertheless, the Protocol is generally considered as an important first step.

Moreover, additional efforts are necessary to eliminate the inadequacies of the Protocol, particularly in regard to land-use, land-use change and forestry (LUF), and to turn the Protocol into an operational framework (cf. Section 2.3). But this is not an easy task. So far, very few publications are available that take a scientifically more holistic view of the carbon issue, carry out quantitative analyses, and raise important questions about the ability to implement the Protocol. These publications draw attention to basic scientific and methodological issues that underlie the Kyoto Protocol (cf. Section 4.2).

Table 2.1. Compilation and grouping of the articles of the Kyoto Protocol.
Source: Makundi *et al.* (1998), modified.

Article(s)	Contents
1	Defines terms used.
2, 3, 5, 7	Describe substantive obligations of Annex I Parties.
8	Describes the expert review of the information submitted by Annex I Parties under Article 7 of the Protocol and procedural instructions for its consideration by the COP serving as the meeting of the Parties to the Protocol.
10	Elaborates UNFCCC commitments for all Parties to the Protocol.
11	Restates UNFCCC Articles 4.3 and 11. It also provides guidance on financing by developed country Parties and other developed Parties in Annex II to the Convention to assist developing country Parties in implementing Article 10 above.
9, 13, 14, 15, 16	Describe institutional roles of the UNFCCC COP, Secretariat, and subsidiary bodies and processes with respect to the Protocol.
4, 6, 12, 17	Authorize the use of various joint mechanisms between Parties (including trading) to meet part of their GHG reduction commitments.
13, 16, 18	Mandate the development of compliance procedures and mechanisms.
14, 19	Provide the dispute settlement.
20 - 28	Describe procedural and protocol requirements (amendments, annexes, voting, Depositary, entry into force, reservations, withdrawal, official language, signatories, etc.).
Annex A	Lists the greenhouse gases and sector/source categories covered by the Protocol.
Annex B	Lists the emission limitations or reduction commitments by Annex I Party.

2.3 Post-Kyoto Events and Activities

Three post Kyoto's COP-3 events or activities deserve brief mention:

- the Protocol-related activities of the IPCC;
- COP-4; and
- the activities of the IGBP in carbon research.

At its Eighth Session in Bonn in June 1998, the Subsidiary Body for Scientific and Technological Advice (SBSTA)[9] of the COP requested the IPCC to prepare a special report on land-use, land-use change and forestry (LUF) (SBSTA, 1998a). The purpose of this request is to enable the COP to take decisions on recommendations on LUF issues to the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol (COP/MOP) at its first Session.

The report will address the methodological, scientific and technical implications of the LUF-relevant articles of the Protocol, particularly Article 3; consider the anthropogenic implications of full carbon stock accounting; set the overall scientific context for consideration of LUF activities; and address scientific and technical questions raised in SBSTA (1998b) and other FCCC-related documents (SBSTA, 1998c, d, e; SBI, 1997). In addition, the SBSTA requested the IPCC to examine, to the extent possible, the scientific and technical implications of carbon sequestration strategies related to LUF activities for water, soils, biodiversity, and other environmental and socioeconomic effects, to be included in the special report as appropriate (SBSTA, 1998a).

At its Fourteenth Session in Vienna in October 1998, the IPCC responded positively to the SBSTA request and approved the outline of the report due in mid-2000.

The Fourth Session of the COP (COP-4) to the UNFCCC was held in Buenos Aires, Argentina, in 1998. It concluded with the adoption of the Buenos Aires Plan of Action, under which the Parties declared their determination to strengthen the implementation of the Convention and prepare for the future coming into force of the Kyoto Protocol. The Plan contains the Parties' resolution to demonstrate substantial progress on: the financial mechanism; the development and transfer of technology; the implementation of Articles 4.8 and 4.9 of the Convention, as well as Articles 2.3 and 3.14 of the Protocol[10]; activities implemented jointly (AIJ); the mechanisms of the Kyoto Protocol; and the preparations for COP/MOP-1. The Action Plan's deadline for the completion of work is the year 2000 (ENB, 1998; UNFCCC, 1999a).

In March 1999, the International Geosphere-Biosphere Programme (IGBP), in collaboration with the World Climate Research Programme (WCRP) and the International Human Dimensions Programme (IHDP), launched the IGBP Global Carbon Project. This on-going initiative is in response to the Kyoto Protocol, the involvement of the IPCC in assisting governments to make operational the LUF-relevant articles of the Protocol, and a number of national research initiatives that focus the attention of both the policy and scientific communities on the global carbon cycle. The objectives of the IGBP are to initially provide a scientific overview of the global carbon cycle for inclusion in the IPCC special report on LUF and to create and coordinate an international framework for collaborative research on the carbon cycle (Steffen, 1999).

3. The Scientific Background to Full Carbon Accounting (FCA)

Interest in the carbon system has increased because of the observed increase in levels of atmospheric CO_2 (from ~280 ppmv in 1800 to its present value of 365 ppmv) and because the signing of the UN Framework Convention on Climate Change has forced nations to assess their contributions to sources and sinks of CO_2, and to evaluate the processes that control CO_2 accumulation in the atmosphere (IPCC, 1995; Indermühle, 1999). In Section 3 of this report the concept of full carbon accounting (FCA) is defined, in consideration of consistency, and assessed from different perspectives, including uncertainty. The overall purpose of this assessment is to provide a basis for Section 4, where we analyze the Kyoto Protocol in consideration of the FCA concept.

3.1 Overview of the Carbon System

Atmospheric CO_2 provides a link between geological, biological, physical, and anthropogenic processes. Carbon is exchanged between the atmosphere, the oceans, the terrestrial biosphere, and the lithosphere. These exchanges involve multiple carbon reservoirs[2] with different turnover times and carbon flows[2] among them. The exchange processes can be best illustrated with the help of two interconnected cycles, the geological and the biological cycle. The geological cycle encompasses the slowest components of the system, with turnover times in the order of millennia and beyond, while the biological cycle encompasses the faster components, which have turnover times in the order of decades to millennia. The natural carbon system is defined by the dynamics of these two cycles, under the influence of external forcing mechanisms and in the absence of anthropgenic CO_2 inputs into the atmosphere. Measurements from air bubbles trapped in polar ice indicate that the atmospheric CO_2 concentration during the entire Holocene, that is, during the last 8,000 years, was ~280 ppmv, implying that the natural carbon system was in or near equilibrium during this period. However, on longer time scales, e.g., during the last glacial period prior to the Holocene, the atmospheric CO_2 concentration was found to be lower by ~80 ppmv, i.e., at ~200 ppmv. These natural fluctuations are characterized by slow, long-term transitions and are not yet understood (IPCC, 1995; Heimann *et al.*, 1999; Indermühle, 1999).

Human activities have disturbed the natural, geological-biological balance, in essence through the use of fossil carbon and disruption of terrestrial ecosystems. (Figure 3.1 shows the faster components of the carbon system. It is this subsystem, also termed *global carbon cycle*, which currently receives the particular attention of many scientists and policy makers owing to the Convention.) The resulting accumulation of CO_2 in the atmosphere has caused a number of carbon system processes to become unbalanced. Fossil fuel burning and cement manufacture, together with forest harvest and other changes in land use, all transfer carbon (mainly as CO_2) to the atmosphere. This anthropogenic carbon input then cycles between the atmosphere and the biospheric components of the systems, i.e., the oceans and the terrestrial biosphere. Because carbon cycling in the terrestrial and ocean biosphere occurs slowly, on time scales of decades to millennia, the effect of additional fossil and biomass carbon injected into the atmsophere is a long-lasting disturbance of the carbon system (IPCC, 1995; Heimann *et al.*, 1999).

A current research task for the global carbon cycle is its consistent closure. This includes understanding the direct response of the carbon system as well as the (positive and negative) feedbacks or indirect responses between the climate and the carbon system, as the result of the anthropogenic increase in CO_2 in the atmosphere. It can be stated that our knowledge on the indirect responses is least advanced (Heimann *et al*., 1999).

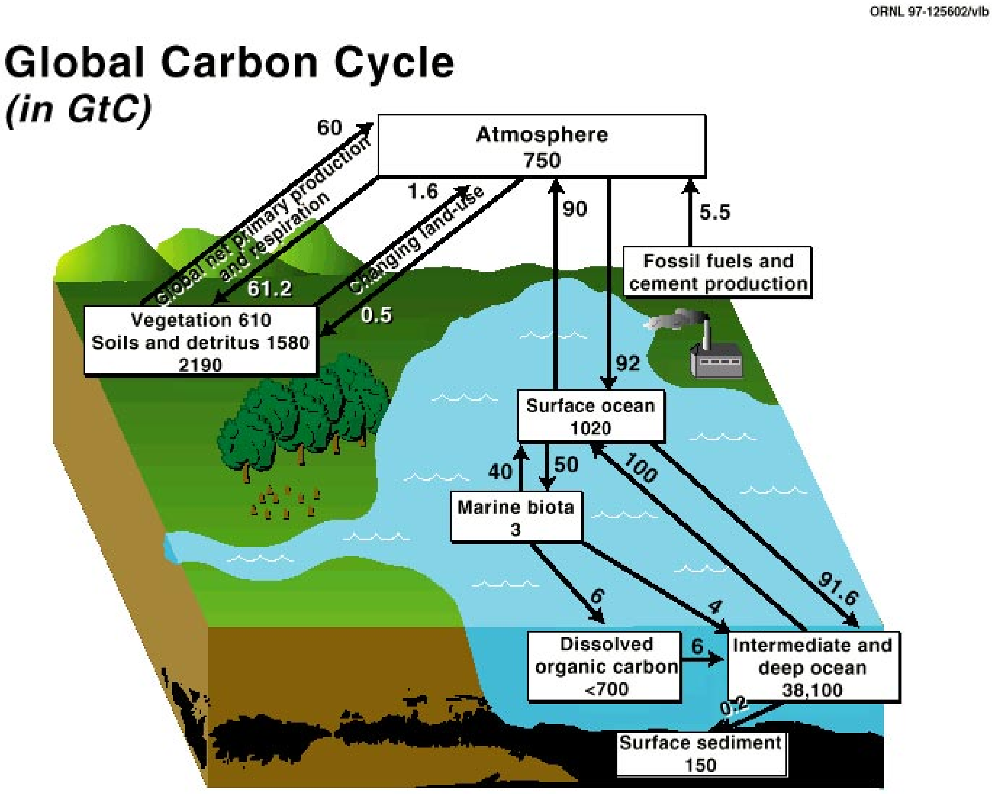

Figure 3.1. The global carbon cycle, showing the reservoirs (in Gt C) and fluxes[2] (in Gt C yr^{-1}) relevant to the anthropogenic perturbations as annual averages over the period 1980 to 1989. The component cycles are simplified and subject to considerable uncertainty. In addition, the figure presents average values. The riverine flux, particularly the anthropogenic portion, is currently poorly quantified and so is not shown here. While the surface sediment storage is approximately 150 Gt C, the amount of sediment in the bioturbated and potentially active layer is of the order 400 Gt C. Accumulating evidence shows that many of the key fluxes can vary significantly from year to year. In contrast to the static view conveyed by the figure, the carbon system is clearly dynamic and coupled to the climate system on seasonal, interannual and decadal time-scales.
Sources: IPCC, 1995, 1996a; downloaded from: http://cdiac.esd.ornl.gov/pns/faq.html.

3.2 Definition of FCA

FCA follows – in a consistent fashion – the full carbon-system concept. In this study, FCA is a full carbon budget that encompasses and integrates all (carbon-related) components of all terrestrial ecosystems and is applied continuously in time (past, present and future). We assume that the components can be described by adopting the concept of pools[2] and fluxes to capture their functioning. The reservoirs may be natural or human-impacted and internally or externally linked by the exchange of carbon (as well as other matter and energy) [c.f. also Steffen *et al*. (1998) and Nilsson *et al*. (1999)].[11]

3.3 Physical Basis

In this Section we briefly review the physical basis behind carbon accounting. This is necessary in order to understand the consequences for practitioners who attempt to determine carbon budgets (cf. Section 3.5). It also permits us to analyze the question whether or not the IPCC Guidelines can serve as the main accounting and legal compliance system for the Kyoto Protocol.

For the purpose of our discussion, it is sufficient to adopt a simplified concept, in which boxes represent the carbon stocks or reservoirs (cf. Figure 3.1). We can visualize, due to the sufficiently low-resolved spatial and temporal scales, the carbon cycle on the basis of continuum mechanics and make use of the continuity equation, which arises from the basic law of conservation of mass (and states that matter can be neither created nor destroyed). In the integral form and in the absence of carbon sources and sinks, this equation is given by

$$\iiint_{(V)} \left\{ \mathrm{div}(\rho\vec{v}) + \frac{\partial\rho}{\partial t} \right\} dV = 0\,; \tag{1}$$

where V represents a carbon reservoir, ρ the local (and sufficiently continuous) carbon density, $\rho\vec{v}$ the respective carbon flux density, and $\mathrm{div}(\rho\vec{v})$ its divergence. The equation states that the net carbon flux out of a reservoir must be balanced with the temporal change in the reservoir's carbon content. Since Equation (1) is valid for any sub-reservoir of V (under the restriction that the continuum-mechanical approach in space and time is preserved), the identity

$$\mathrm{div}(\rho\vec{v}) + \frac{\partial\rho}{\partial t} = 0 \tag{2}$$

follows (e.g., Fichtenholz, 1982). It is this latter equation, which is usually referred to by the term *continuity equation* that can be modified in order to account also for carbon sources and sinks. There are no application restrictions, should exchanges among reservoirs take place (as, e.g., in the case of change in land cover). It is noted that the carbon reservoirs need not be box-like, but may be arbitrary.

We will focus our discussion on the two independent ways of measuring or estimating net carbon fluxes (herein called the net flux approach) that are made available by the continuity equation. The two ways to determine the net flux into/out of a carbon reservoir are:

- the direct[12] or flux-based method, that is, the flows of carbon into and out of a carbon reservoir are estimated directly and separately; and
- the indirect[12] or stock-based method, that is, the change in a reservoir's carbon content is estimated during a specified time interval.

Under ideal conditions of exact (zero-uncertainty) and scale-adapted measurements, these two approaches are redundant to each other.

Under real conditions, however, we face a number of serious problems, one of which becomes apparent if a synopsis of scientific approaches available for assessing terrestrial carbon stocks and fluxes (cf. Table 3.1 and Figure 3.2) is made. Full carbon accounts that comply with our definition of FCA (in particular the requirement of consistency), can most easily be realized experimentally and verified independently (in a physical sense) for closed systems at specific locations, e.g., small-scale experimental plots in the field. At greater scales in both space and time, a number of flux and stock-based methods exist, however, which must be combined in order to achieve and verify full carbon accounts. In fact, this task is a scientific challenge in itself, not easy to accomplish, and not yet solved and made available in the form of a standard procedure that can be taken from the shelf and readily applied. Therefore, carbon accounting, particularly at spatial scales greater than those of specific locations, cannot yet be considered reliable and is difficult to verify independently. A systems analysis-based FCA approach can help to fill this gap.

We expand our discussion upon the IPCC Guidelines in Section 4.1, where we address whether the IPCC Guidelines can serve as the main carbon accounting and legal compliance system for the Kyoto Protocol. In Tables A-1 and A-2 of the Appendix we list, similar to Table 3.1, which net flux method, the flux-based or the stock-based method, is recommended for application in Chapter/Module 4 (Agriculture) and Chapter/Module 5 (Land-Use Change and Forestry) of the Guidelines.

Table 3.1. Scientific approaches available for assessing carbon stocks and fluxes. Confer Figure 3.2 for the spatial and temporal scales of the listed approaches.

Method	Flux-Based	Stock-Based	Strengths	Weaknesses
Establishing full carbon accounts of closed systems at specific locations (e.g., small-scale experimental plots in the field)				
Carbon stock surveys and destructive sampling of terrestrial carbon stocks		✔	Consistent full carbon accounts can be established that encompass all terrestrial carbon stocks and fluxes.	Destructive sampling. Lack of reliable estimates of gradients for up-scaling.
Direct measurement of carbon fluxes (solid, liquid, gaseous)	✔			
Estimating carbon in vegetation, soils and surface waters by inventories and surveys, and assessing human-altered landscapes				
Forest inventories Forest inventories are carried out by ground measurements and remote sensing (generally aerial photography), covering indicators relevant to forest management.		✔	Repeated forest inventories permit the assessment of temporal changes in forest biomass. Can be used to calibrate satellite-based remote sensing (see below).	The primary focus of forest inventories is (still) on wood and its economic use. Incomplete and inconsistent with respect to indicators necessary to assess all carbon stocks (e.g., forest inventories and soil surveys are usually not carried out in a synchronous and complementary fashion and often have long irregular intervals in-between). Involving minor destructive sampling.
Soil inventories Soil inventories include the inventory of soil characteristics, including organic and mineral carbon.		✔	Repeated soil inventories permit the assessment of pedogenetic changes of soil carbon, depending on land-use.	Changes in soil carbon are difficult to measure because of the lateral and vertical heterogeneity of soils. Changes are usually small at the time scale of, e.g., 5 years. Incomplete with respect to depth, constituents (e.g., soil solutions) as well as important landscape components (e.g., forest lands, peatlands). Destructive sampling.
Peat surveys Peat surveys include the inventory of peat stocks and their botanical and chemical composition.		✔	Permit monitoring of territories with active organic accumulation.	Incomplete in terms of processes (e.g., outflow of soluble organic matter is usually not determined) and territories (e.g., only industrially valuable deposits are inventoried). Destructive sampling.
Hydrological surveys Hydrological surveys permit the determination of water flow parameters and hydrological regimes of standing waters (lakes, reservoirs, etc.).	✔ (These methods are complementary to each other, but do not substitute each other.)	✔	Permit assessment of organic transport linking terrestrial and oceanic reserves, and biological and geological cycles. Non-destructive.	The water chemical composition is insufficiently covered. Limited number of measurement points.

Table 3.1. . . . (continued).

Measurement Method	Flux-Based	Stock-Based	Strengths	Weaknesses
Estimating carbon in vegetation, soils and surface waters by inventories and surveys, and assessing human-altered landscapes (continued)				
Land-use/cover monitoring and official (state) statistical surveys Provides information on land-use/cover and other statistics (e.g., areas, agricultural yields and harvested wood, forest fires and insect outbreaks, environmental pollution, biomass products, etc.).	✔ or ---	--- ✔	Information on land-use/cover and other statistics is usually provided regularly and by the same (governmental) agencies. Non-destructive.	Information on land-use/cover and other statistics is usually not provided by one, but different (governmental) agencies. Therefore, their databases may not be consistent to each other. Usually, not all territories, sectors and/or carbon-related indicators that are required for the support of carbon assessments are measured. Often, the data are updated irregularly and their accuracy is difficult to quantify or not known. Monitoring and statistical survey systems may differ from country to country, which hampers international comparisons.
Assessing the CO_2 flux between land and air, at stand level employing towers and regionally employing airborne methods				
Eddy covariance method The eddy covariance method permits the measurement of trace gas flux densities, particularly CO_2, between the terrestrial vegetation and the atmosphere, in essence the net flux of carbon into or out of the ecosystem, including soils, at a tower site (net ecosystem exchange, NEE).	✔		Direct in-situ flux measurement, continuous in time, with minimal disturbance to the system (non-destructive). Sensitive to seasonal and inter-annual variations in NEE. Provides terrestrial bench marks for regional and global carbon balance estimates. Measurements can be used for the independent determination and verification of stock-based carbon balances and for the validation of models that simulate carbon stocks and fluxes of forests (and other terrestrial vegetation) in a dynamical fashion.	So far, the number of tower sites in operation is very limited, because they have not yet left their initial experimental state. Tower flux results overestimate the long-term sink strength of forests because harvesting is not carried out or avoided at the experimental site during the time of operation. There are no scientifically solid methods available that permit to scale-adapt NEE (and its variability) spatially beyond the experimental site.
Convective boundary layer (CBL) method The CBL method is an airborne method, which permits to estimate the surface fluxes of trace gases, particularly CO_2, as well as pollutants and isotopes over regions in the order of 50-100 km^2 and during time intervals in the order of days.	✔		Exploits the natural integrating properties of the well-mixed atmospheric boundary layer with minimal disturbance (non-destructive).	Advection of air masses, if not correctly reflected in the calculations, can lead to large errors in the CBL flux estimates. The CBL method, being a technique that itself integrates across heterogeneous surfaces, can only be validated with the help of smaller-scale surface flux measurements.

Table 3.1. . . . (continued).

Measurement Method	Flux-Based	Stock-Based	Strengths	Weaknesses
Sampling CO_2 levels in the air				
Flask sampling over time The global flask network measures the concentration gradients of CO_2 and other long-lived trace gases and isotope ratios among different points of the globe and provides information on the surface fluxes.	✔		The network is suited to investigate the continental and global-scale aspects of the net exchange of carbon with practically zero-disturbance (non-destructive). The network presents a powerful tool to understand the full carbon budget at the global scale when it is combined with inversion models. They consider the distribution of surface sources and sinks that produces the best agreement with the atmospheric CO_2 record, in consideration of atmospheric transport. (Inversion can be considered as an independent and complementary verification of bottom-up calculations of the CO_2 fluxes.)	The global flask network is less suited to monitor local, national and regional emissions. More measurements at different heights are needed over continents to reduce the current uncertainties on the terrestrial carbon sources and sinks. Inversions depend on prior knowledge of the CO_2 sources and sinks (strengths, geographical distribution, etc.) and the patterns of atmospheric transport.
Using satellite-based remote sensing to estimate photosynthesis, and thus CO2 consumption by plants, across ecosystems				
Remote sensing Land cover, vegetation (e.g., Leaf Area Index/Normalized Difference Vegetation Index) and land use type and changes can be directly interpreted from optical or radar-based remotely sensed data (with some ground-based measurements to assist interpretation). Net primary production (NPP) can then be calculated using the remotely sensed inputs leaf area index and land cover in combination with soil and meteorological data.		✔	Global coverage by most products. This allows comprehensive coverage (e.g., AVHRR, SPOT VGT). Rapid and repeatable measurements (1 to 16 day return cycle). Data is spatially and temporal consistent. Some sensors (e.g., Landsat) have data catalogue for the past 20 years. Inexpensive cost relative to ground-based measurements. Multiple scales of data available (e.g., 6 m IRS1, 10 m SPOT, 1 km AVHRR). Non-destructive sampling.	Indirect estimates requiring models to derive NPP and below ground (soil and root) respiration. There is still much uncertainty in crossing spatial scales, that is, in scaling up from the small scale (or site of the project considered for implementation) to regional or national scales. Land cover changes (e.g., deforestation) may occur at scales undetectable by high-resolution (i.e., AVHRR) sensors that can result in significant errors in estimating total land cover change (e.g., total deforestation). Attempts to estimate biomass from remote sensors have generally shown mixed results.

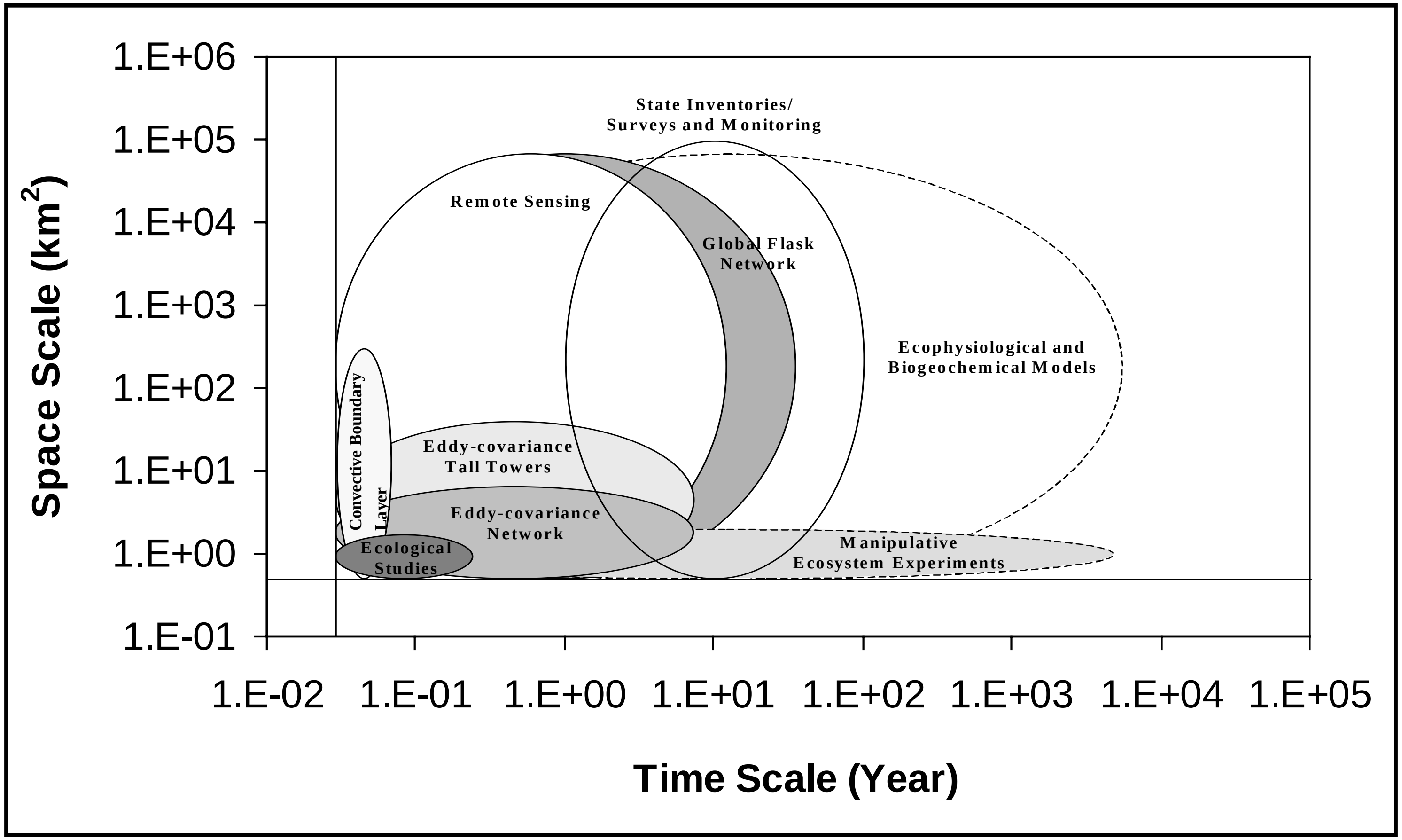

Figure 3.2. Range of temporal and spatial scales at which ecological processes occur, with their suited monitoring technique. See Table 3.1 for more information.
Source: Nabuurs *et al.*, 1999; modified).

3.4 Inherent Problems

3.4.1 Completeness

FCA (which implies consistency according to our definition) is inextricably linked to completeness. Completeness, in turn, should be defined in consideration of other, scientific and non-scientific system requirements, such as complexity and uniformity (with reference to practical standards, etc.). We treat this question in-depth in Nilsson *et al*. (1999), in connection with and based on our experiences in establishing the full carbon accounts of two case study countries: Russia and Austria[13] [see also Shvidenko *et al*. (1999), Jonas (1997), and Jonas *et al*. (1998)]. The items that we consider necessary for completeness are:

- carbon reservoirs and fluxes,
- processes,
- space and time (including spatial and temporal scale-adaptation of local measurements),
- types of carbon-related territorial units (ecosystems),
- types of land-use/land management systems,
- types of greenhouse gases, and
- methods (in terms of net flux approach, i.e., flux-based or stock-based).

3.4.2 Uncertainties

In this section we identify and classify the different types of uncertainties that are involved in accounting terrestrial carbon, as referred to in the Kyoto Protocol. Our classification builds on attempts that were published prior to and after the emergence of the Kyoto Protocol (e.g., Shvidenko *et al*., 1996; Vine and Sathaye, 1997; Jonas *et al*., 1998; SBSTA, 1998b; Nabuurs *et al*., 1999; Vine *et al*. 1999). These attempts, however, are restricted to the use of greenhouse gas guidelines or to particular components of the terrestrial ecosystems or they are not sufficiently profound in view of the far-reaching consequences resulting from the different obligations under the Kyoto Protocol.

Table 3.2 provides a more general classification of uncertainties. The uncertainties II–V on the right side of the table refer to the scientific reliability involved in establishing carbon accounts traditionally. In this case, the classification of uncertainties results from the compliance with greenhouse gas guidelines and the Kyoto Protocol. In order to achieve an understanding on how adequate this classification is, we confront it with the consistent approach (I–V, left side) of a scientist, who 1) investigates the full carbon system; 2) is not bound by any guidelines; and 3) applies a full systems approach as well as a detailed, module-by-module approach, in consideration of inter-module consistency as a boundary condition. Of course, this scientific, more general approach (or combination of approaches) results in a more adequate analysis of uncertainties. It is this advantage, which we want to demonstrate by this comparison.

Two important conclusions emerge from this confrontation:

- The user of greenhouse gas guidelines cannot usually address uncertainties, which refer to the approach-inherent, insufficient reflection of reality, i.e., our inadequate understanding of the basic biospheric processes leading to emissions and removals. This is because only a comparison of the greenhouse gas accounting approach (which is typically derived from the application of only one net flux approach and carried out in a module-by-module fashion, without consideration of inter-module consistency as a boundary condition) with a full systems approach can help to assess and determine this uncertainty. However, the provision of instructions on how to carry out a full systems approach in a consistent fashion is not a principal objective of the guidelines. The closure of the carbon cycle on the global scale (e.g., IPCC, 1995; Heimann *et al.*, 1999) may serve as the most widely known example to illustrate this point (the validity of which, of course, is scale-independent).

- Compliance with the Kyoto Protocol necessitates addressing uncertainties, which are specific to the Protocol, not at all easy to determine, and may even have far-reaching, unforeseeable consequences. These uncertainties refer to:
  - the issue of establishing post-1990 baseline scenarios; and
  - the issue of small numbers (as potentially arising in complying with the concept of additionality[14] and the concept of accounting net emissions, etc.).

  The baseline scenarios issue is discussed in Section 4.2. The issue of small numbers is addressed by Jonas *et al*. (1998). Based on the full carbon account of Austria and an incomplete list of uncertainties determined individually, the researchers concluded that the present incomplete knowledge about biospheric processes and data may make it impossible to carry out calculations of net emissions. They stated that this conclusion also holds if only human-induced land-use change and forestry activities are considered, as Article 3.3 of the Kyoto Protocol requires. Based on our Austria work, we are still inconclusive whether or not this Protocol-specific inadequacy can be overcome by using a systems analysis-based FCA approach (cf. also Section 4.2).

We apply our classification of uncertainties in Section 4.2 (Table 4.2c) below, where we confront the Kyoto Protocol with a list of uncertainties, which we identified from screening the scientific literature referring to greenhouse gas guidelines, including those of the IPCC, in general and to the Kyoto event in particular.

Vine and Sathaye (1997) and SBSTA (1998b), for example, note that there are also other uncertainties, which refer to the institutional soundness of organizations conducting carbon-accounting activities. (Institutions affect uncertainties through project development, construction and operational procedures. Institutional uncertainty is affected, among other things, by financing, management, legislation, and rules and regulations that govern the conduct of projects.) However, these uncertainties are not considered here, since they are purely technical and refer to an administrative level that is above the practical level of accounting the carbon of the terrestrial ecosystems.

Table 3.2. Classification of uncertainties in accounting the carbon of terrestrial ecosystems, resulting from the compliance with greenhouse gas (GHG) guidelines and the Kyoto Protocol (right). The classification is confronted with a scientific approach (left), which 1) investigates the full carbon system; 2) is not bound by any guidelines; 3) implies a full systems approach as well as a detailed, module-by-module approach, in consideration of inter-module consistency as a boundary condition; and 4) results in a more adequate analysis of uncertainties demonstrated by this comparison. The roman numerals are for enumeration.

THE CARBON SYSTEM: CLASSIFICATION OF UNCERTAINTIES			
The Consistent Approach of a Scientist		**The Approach of a GHG Guidelines User (in Compliance with the Kyoto Protocol)**	
The Carbon System Under Current Conditions (as Influenced by the Past)			
I	First-order global assessment of knowledge gaps of the full carbon system (full systems approach)	**I**	––– [The full systems approach is not explicitly foreseen!]
II	Assessment of defined subsystems and their linkages (detailed systems approach, in terms of both space and time)	**II**	Addressing uncertainties, which refer to:
II.1	–––	II.1	. . . inappropriate procedural preparations allowing differing interpretations, etc., i.e., to – the inappropriate use of language (definitions of terms, assumptions, interpretations, etc.) – the inappropriate agreement on practical standards (collection and classification schemes for data entering national inventories; data formats and units; measurement methods; calculation procedures; application of parameters and emission factors; application of models; etc.)
II.2	Selection of the methodological approach	II.2	––– [The GHG guidelines provide users with instructions, including alternative instructions, on how to proceed under the given approach.]
II.3	Experimental design and realization (in accordance with the methodological approach)	II.3	. . . data status (as the result of the experimental phase), including the data status of the base year (1990), i.e., to – unavailable or incomplete data (in terms of both space and time) – the unknown or insufficient accuracy of available and accessible data – biased data
II.4	Results	II.4	. . . data processing (adapting scales in space and time, conversion into carbon units, making data carbon-consistent, etc.)

Table 3.2. . . . (continued).

III	Full carbon-system analysis (including analysis of uncertainties)	**III**	Addressing uncertainties, which refer to:
III.1	Comparison of I and II	III.1	. . . the approach-inherent, insufficient reflection of reality, i.e., our inadequate understanding of the basic biospheric processes leading to emissions and removals [usually unknown or simply in the form of a best-guess, because the full systems approach under I has not been considered]
The Full Carbon System Under Projected Conditions		**A Partial Carbon System Under the Kyoto Protocol**	
IV	System-analytical projection of the full carbon system into the future	**IV**	Addressing uncertainties, which refer to:
IV.1	Performance of sensitivity and uncertainty tests (including analysis)	IV.1	. . . issues that are specific to the Kyoto Protocol, i.e., to – the issue of establishing post-1990 baseline scenarios – the issue of small numbers (as potentially arising in complying with the concept of additionality and the concept of accounting net emissions, etc.)
Description of the Full Carbon System		**Reporting of Emissions and Removals Under the GHG Guidelines and the Kyoto Protocol**	
V	Adequate description of the full carbon system (past – present – future)	**V**	Addressing uncertainties, which refer to:
V.1	Review	V.1	. . . errors in reporting
V.2	Verification	V.2	. . . verification

3.4.3 Definitions and Classifications

Definitions and classifications developed at national scales should be made consistent with applicable local classification systems and with those employed in global carbon accounting.

3.4.4 Spatial Up-Scaling

Scaling up local measurements (e.g., point sources) to national scales should take advantage of recognized up-scaling techniques (see Nilsson *et al.* 1999).

3.4.5 Data Integration Issues

FCA integrates multiple sources of spatial (map) and non-spatial data. All information regarding source, acquisition scale, collection purpose and other relevant documentation should be documented as metadata. This will assist in uncertainty calculation and future updating of databases.

3.4.6 Stochastic Elements

Traditional (deterministic) models and approaches cannot accurately predict stochastic phenomena (e.g., fire).

3.5 Realization of FCA

In establishing the full carbon accounts of the case study countries Russia and Austria, we based our work on a set of principles and guidelines. The most important of them are

- maximal use of available information,
- consistency (as a boundary condition),
- transparency, and
- verifiability

and are treated in-depth in Nilsson *et al*. (1999).

4. The Protocol’s Unresolved and Scientific–Methodological Issues

Section 4 is devoted to the Kyoto Protocol and is a logical sequel of the previous section. We analyze the Protocol’s unresolved and scientific-methodological issues, in consideration of the FCA concept and in adherence to a systems-analysis based approach.

4.1 The Unresolved Issue: The Protocol’s Legal Basis of Compliance

In its Articles 3.4 and 5.2, the Kyoto Protocol refers to the methodological work of the IPCC, whose scientists have developed guidelines (IPCC, 1997a, b, c) to establish a common base for determining changes in carbon sources and sinks (cf. also Section 2.3). In this Section we discuss the lack of clear consensus of opinion in the scientific community on the question of whether or not the IPCC Guidelines can serve as the main accounting system for measuring both changes in the full carbon budget and verifiable changes in carbon stocks as required by the Kyoto Protocol (also referred to as Kyoto carbon stocks) (Steffen *et al*., 1998) − and thus serve as a legal basis of compliance for the Kyoto Protocol (Bolin, 1998). Table 4.1 summarizes the present situation. While dealing with this particular question, however, we acknowledge that the IPCC Guidelines can and should also be reviewed more generally, e.g., in regard to the major topics which they address, as was done with other existing greenhouse gas guidelines and protocols by Vine and Sathaye (1997).

Table 4.1. The unresolved issue of whether or not the IPCC Guidelines can serve as the main accounting and legal compliance system for the Kyoto Protocol.

Unresolved Issue	Brief Explanation	Dispute/Arguments	Ref’s
Scientific concept *This unresolved issue has not yet been perceived as one and discussed widely.*	The Kyoto Protocol refers to the methodological work of the IPCC, whose scientists have developed Guidelines (IPCC, 1997a, b, c) to establish a common base for determination of changes in carbon sources and sinks (cf. also Section 2.3).	There is a lack of clear consensus of opinion in the scientific community on the particular question whether or not the IPCC Guidelines can serve as the main accounting system for measuring both changes in the full carbon budget and verifiable changes in Kyoto carbon stocks, and thus serve as a legal basis of compliance for the Kyoto Protocol. The central argument is that the IPCC Guidelines are inadequate in accounting for all of the relevant biological processes and the involved uncertainties. (Proposals on how to modify the IPCC Guidelines, e.g., in regard to calculating global CO_2 emissions from land-use change and forestry by employing biosphere models and satellite data, are being presented only lately. However, accuracy requirements at the resolution scale of individual countries and beyond cannot yet be met.)	(1) - (5)

References: (1) Alexandrov and Yamagata (1998); (2) Bolin (1998); (3) Jonas (1998); (4) Steffen *et al*. (1998); (5) WBGU (1998).

Our starting point for discussing this issue is the provision of an overview on which net flux approach, the direct[12] (flux-based) or the indirect[12] (stock-based) net flux method, is applied in Chapter/Module 4 (Agriculture) and Chapter/Module 5 (Land-Use Change & Forestry) of the IPCC Guidelines. For reasons of convenience, the overview is summarized in Tables A-1 (Chapter/Module 4) and A-2 (Chapter/Module 5) of the Appendix. We consider only carbon-related greenhouse gases.

Two points warrant attention. First, the IPCC Guidelines require estimating net fluxes either directly or indirectly, but never to apply both methods. In some cases, the IPCC Guidelines require the application of (default or expert) emission factors, in essence the realization of the direct net flux method in an approximate way. In most cases, however, the emission-factor approach is not or cannot be applied (because, e.g., difficulties have prevented scientists so far from determining emission factors experimentally and to scale-adapt them to the space and/or time scales required). In these cases, the IPCC Guidelines require the estimation of temporal changes in reservoirs, ΔR, followed by the application of ΔR-to-atmosphere transfer ratios – in essence the realization of the indirect net flux method in an approximate way.

It must be recognized that the direct and the indirect net flux method, as proposed by the IPCC Guidelines or other guidelines (see, e.g., Vine and Sathaye, 1997; Alexandrov and Yamagata, 1998; TFEI, 1998; Vine *et al*., 1999), are bound to be approximate and fraught with inconsistencies. This is not because these guidelines are inadequate. Rather it is a matter of principle. Measurements are scarce and, where they exist, not necessarily complete enough to permit the application of complementary net flux methods (cf. Section 3.4.1). The IPCC Guidelines do not or cannot consider – for whatever reasons – the option of cross-checking flux estimations independently (e.g., by applying the knowledge of emission factors in order to cross-check indirect net flux estimations). Only by doing so, can scientists be sure whether or not their flux estimations are compatible with the principle of mass conservation. Also, having another option at their disposal to estimate net fluxes, where possible, would put scientists into a more favorable position to narrow the uncertainties in their flux estimations. Therefore, in their present form, the IPCC Guidelines cannot be considered adequate in handling the uncertainties underlying the carbon-accounting problem and thus the Kyoto Protocol (cf. also Section 4.2). As already mentioned in Section 3.3, a systems-analysis based FCA approach can help to fill this gap.

Second, the IPCC Guidelines do not make an attempt – neither in applying the direct nor the indirect net flux approach – to be spatially complete in considering carbon fluxes into/out of the terrestrial ecosystems (as the Kyoto Protocol does). The IPCC Guidelines focus only on regions, where human-induced changes have taken and/or are taking place (cf. Figure 4.1). However, separating directly impacted lands from indirectly affected lands may result in carbon accounts that are not only meaningless, but may even lead to false conclusions from an accounting point of view (in particular, if adverse effects cannot be recognized immediately). A typical example is harvesting in sensible ecosystems, which are affected by this measure. Similarly, ensuring sustainable forest management is more sensible in terms of carbon accounting than planting monocultures, which may be susceptible to pest outbreaks, etc., that could threaten the health of larger forest areas. Therefore, in their present form, the IPCC Guidelines cannot be considered sufficiently complete – neither in terms of space nor in terms of carbon reservoirs and fluxes, processes, and types of carbon-related territorial units – to serve as the main accounting system for a partial accounting system as described in the Kyoto Protocol. FCA should be considered in overcoming this inadequacy.

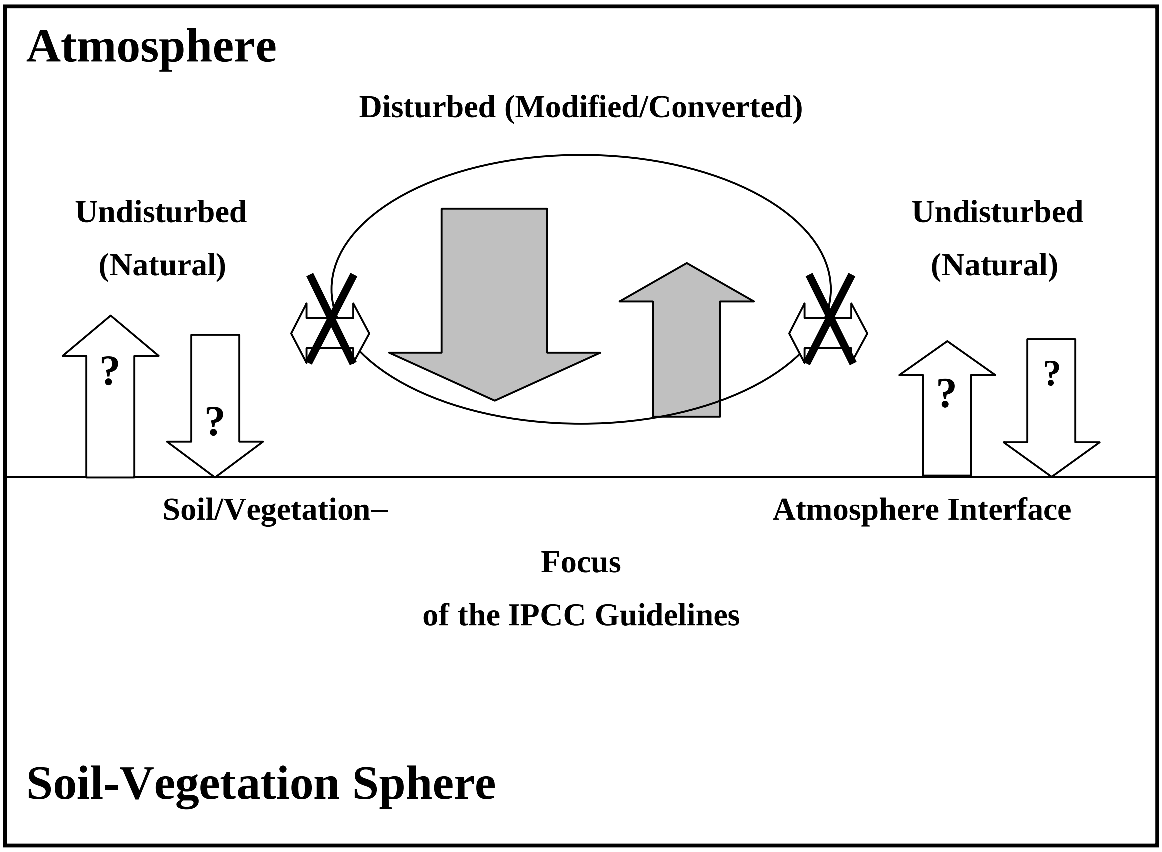

Figure 4.1. The spatial incompleteness of the IPCC Guidelines in estimating carbon fluxes across the soil/vegetation-atmosphere interface. Not standing up to scrutiny: Separation of directly (human-) impacted lands from indirectly affected lands.

4.2 The Protocol's Scientific and Methodological Issues Related to Its Underlying Scientific Challenges

Section 4.2 looks into the Protocol's scientific and methodological issues, which we identified from screening the scientific literature referring to greenhouse gas guidelines, including those of the IPCC, in general and to the Kyoto event in particular. These are issues, which address scientific and/or methodological questions or problems of relevance to the Kyoto Protocol and are not purely technical. Technical issues only merit further clarification and are not considered in the following.

For instance, the German Advisory Council on Global Change states on page 2 of its 1998 Special Report (WBGU, 1998):

> *Article 6, which regulates the joint implementation of measures among industrialized countries, could make it possible to offset emissions against sinks in other industrialized countries that would be prohibited domestically by Article 3 para. 3.*

So far, this statement represents a purely technical issue and would not be eligible for consideration. However, the statement continues by becoming clearly scientific (although not in quantitative terms) in that it refers to what we call the scientific challenge termed 'accounting for uncertainty' below:

> *This would significantly exacerbate the risks and imponderables associated with the accounting of biological sources and sinks. The same risks and imponderables could also result from emissions trading (Article 17).*

On the basis of our literature review, we come to the conclusion that the scientific and methodological issues can be grouped into three classes, each of which represents a principal scientific challenge in itself. The three classes are composed of

1. scientific and methodological issues related to FCA (cf. Table 4.2a).
2. scientific and methodological issues related to establishing 1990 baselines and post-1990 baseline scenarios (cf. Table 4.2b). And
3. scientific and methodological issues related to accounting for uncertainty (cf. Table 4.2c).

The literature review made clear that until now most scientific publications copy a "lawyer's-type-of-approach" in that they meticulously investigate the shortcomings, exclusions, pitfalls, etc., of the present version of the Protocol. This is a beneficial process, which will help to eventually supplement the text of the Protocol to appear more solid and adequate from a legal point of view. However, only very few scientific publications make an attempt to take a scientifically more holistic view of the carbon issue, carry out quantitative analyses, and raise important questions whose answers are most crucial in that they will determine the ultimate success and failure of the Protocol from a scientific point of view. These publications draw attention to basic scientific questions and challenges that underlie the Kyoto Protocol.

Below we take a look into the three-class set of scientific and methodological issues mentioned above. We do *not* aim at giving suggestions on how to supplement the text of the Protocol. [The IPCC Special Report on LUF (cf. Section 2.3) will provide support in doing this.] The crucial question arising is whether or not our grouping of the scientific and methodological issues is sufficient, or whether or not scientific challenges may exist in addition to those identified above. The answer to this question is relevant because it will help us to understand which scientific challenges underlie the Kyoto Protocol and determine the science of carbon accounting. However, in consideration of our knowledge gaps of the carbon system and our linear way of thinking, we must admit that our present answer may be incomplete. Our ability to anticipate issues of higher order is limited. [Typical examples are project spillover[15], market transformation[16] and free riders[17]. Confer Table 4.2a (Issue 1b), Vine and Sathaye (1997) and Vine *et al.* (1999).] Therefore, it remains still to be seen whether or not our list of scientific challenges, which is based on our insight into first and second-order issues, is complete. A systems analysis-based FCA approach can help in answering this question.

Scientific and Methodological Issues Related to FCA

The publications that we reviewed refer to

a) unclear or omitted terminology, particularly in regard to *reforestation*, *regeneration*, *afforestation*, *deforestation*, *degradation*, *land use* and *land cover*;
b) spatial leakage;
c) temporal leakage;
d) land-use activities that run counter to the objectives of the FCCC;
e) misleading forest-related carbon accounts;

f) omission of land conversion activities other than deforestation and afforestation;
g) omission of other human-induced activities, such as forest and soil management, conservation and protection, from the list of activities eligible for carbon credits; and
h) inappropriate classification of emissions.

These scientific and methodological issues are not independent of each other.[18] They are all covered by the scientific challenge of FCA (which must be applied globally to avoid spatial inter-country leakage), with the exception of those that go beyond carbon emission concerns. This may be illustrated by the following two examples. The first example refers to the terms *reforestation*, *afforestation* and *deforestation* (cf. Table 4.2a, Issue 1a), which need not be defined under FCA (cf. Section 3.2). In this sense, FCA is independent of how land-use and land cover change are actually defined. How to define these terms, therefore, is a problem, which is specific to the Kyoto Protocol, but does not exist in the scientific context of FCA.

The second example refers to *land-use activities that run counter to the objectives of the FCCC* (cf. Table 4.2a, Issue 1d). Without proper incentives, the possibility exists under the Protocol that monoculture crops will replace, e.g., old growth and biodiverse heterogeneous forest ecosystems (e.g., Sedjo *et al*., 1998). Monoculture crops are known to sequester carbon rapidly and thus offer great short-term carbon storage gains, while the old growth forest ecosystem close to or at climax levels are believed to act primarily as a fixed carbon reservoir rather than a net sequesterer. Therefore, it is important that incentives are put in place, which reflect the entire set of objectives to be met by a forest ecosystem, over and above carbon emission concerns. However, a thorough investigation to what extent the Protocol creates incentives, which may run counter to the objectives of the other Rio conventions (Biodiversity Convention, Desertification Convention), and to what extent other negotiation processes (e.g., the International Forum on Forests) have been considered, has not yet been done. In fact, it must be realized that this problem is part of a more general problem. The coordination of global environmental protection is inadequate. The objectives and catalogues of measures set up by the individual conventions and other international agreements need to be harmonized more rigorously (WBGU, 1998).

Finally, it is worth noting that only a full carbon accounting approach that is spatially complete bears the potential of contributing significantly to another important carbon-related research task of the scientific community, that is, the closure of the carbon cycle on a global scale. In contrast, a partial accounting approach, which does not form a logical and consistent subset of the full carbon accounting approach, may run the risk of establishing a meaningless carbon account or even becoming counterproductive if it incorporates misaccounting or introduces perverse incentives (cf. also Steffen *et al*., 1998).

Scientific and Methodological Issues Related to Establishing 1990 Baselines and Post-1990 Baseline Scenarios

The Kyoto Protocol explicitly mentions the term *base year* in its Articles 3.5, 3.7, 3.8 and Annex B and refers to the concept of *additionality*[14] in its Articles 6.1(b) (joint implementation) and 12.5(c) (clean development mechanism). In this context, the publications that we reviewed refer to

a) 1990 baselines;
b) post-1990 baseline scenarios; and
c) additionality.

We do not consider these scientific and methodological issues in the form of separate entries in Table 4.2b, but include them under (what we call) the scientific challenge of establishing 1990 baselines and post-1990 baseline scenarios. As explained below, in particular the scientific challenge of establishing post-1990 baseline scenarios cannot – as a matter of principle – be avoided under FCA.

Let us consider joint implementation and CDM projects initially. Emission reductions from each project activity must be additional to any that would otherwise occur, that is, in the absence of the certified project activity. Determining additionality requires a post-1990 baseline scenario, above and beyond a starting value (baseline) for 1990, for the calculation of the carbon sequestered, i.e., a description of what would have happened to the carbon stock had the project not been implemented. Therefore, additionality and post-1990 baselines are inextricably linked. Determining additionality is inherently problematic because it requires resolving the counter-factual question: What would have happened in the absence of the specific project? (Confer, e.g., Vine *et al*., 1999.)

However, the problem of additionality arises, in principle, also in the context of within-country emission reduction projects (in compliance with Articles 3.3 and 3.4) under the Protocol, i.e., outside the aforementioned joint mechanisms between Parties. A post-1990 baseline that is continuous in time is needed to help substantiate that the carbon claimed is real and additional and the result of some Kyoto-compliant (e.g., forestry-based) activity, over and above what would have occurred in the absence of the emission reduction project (confer, e.g., Sedjo, 1998; Sedjo *et al*., 1998). For the purposes of illustration, one can imagine that – as an extreme case – an Annex I Party makes use of its entire vegetational area in a Kyoto-compliant fashion. Applying FCA cannot exempt an Annex I Party from establishing a post-1990 baseline scenario. It helps, however, an Annex I Party to assess all its terrestrial ecosystems, irrespective of whether or not subjected to Kyoto-compliant measures. As explained above (cf. also Table 4.2a), this is important because of a number of Kyoto-adverse effects, such as, e.g., spatial leakage where adverse carbon effects may be induced outside the activity areas.[19]

Therefore, we conclude that in particular the scientific challenge of establishing post-1990 baseline scenarios is a condition, which is needed to satisfy the Protocol's criteria of additionality [although not explicitly mentioned other than in its Articles 6.1(b) and 12.5(c)] and cannot, in principle, be avoided under FCA. It remains to be investigated, however, under which conditions the benefit of establishing a total (national) post-1990 baseline scenario may be considered negligible, if a full carbon accounting system is used that is spatially (and temporally) complete.

Scientific and Methodological Issues Related to Accounting for Uncertainty

The uncertainty issue may have played a role in developing the Kyoto Protocol, but this is insufficiently reflected in the text of the Protocol. Uncertainties are mentioned only twice, namely in Article 3.4 in the context of additional human-induced activities that might be considered, and in Article 10(d) in the context of developing data archives to reduce uncertainties related to the climate system, respectively.

In order to classify the limited number of uncertainty-related methodological and scientific issues that are reported in the literature so far, we ordered them in accordance with Table 3.2, classifications II-V, excluding classifications II.1, II.2 and V.1. We excluded the latter because they are purely technical or inapplicable. The modified classification scheme permitted us to preserve a high degree of generality, given today's knowledge deficit. Thus, the modified scheme classifies uncertainties, which refer to

a) data status (II.3);
b) data processing (II.4);
c) the approach-inherent reflection of reality (III.1);
d) issues that are specific to the Kyoto Protocol (IV.1); and
e) verification (V.2).

Our literature review showed that there are few solid numbers available that quantify uncertainties. Whether the uncertainties in estimating carbon fluxes associated with land-use change and forestry are so large as to threaten the compliance process is difficult to answer (Bolin, 1998; Steffen *et al*., 1998). We see, however, two reasons to be less optimistic than Steffen and collaborators, who state that, in their view, these uncertainties can be reduced to acceptable levels with the application of appropriate inventory techniques. First, this remains to be proven. The techniques, if available, are scientific ones, not yet in place, costly, and cumbersome. Second, the individual and combined effect of these uncertainties has not yet been considered with sufficient rigor in light of the issues that are specific to the Kyoto Protocol, e.g., the issue of small numbers (cf. Table 3.2 and d above). Based on the full carbon account of Austria, Jonas *et al*. (1998) concluded that the incomplete knowledge about biospheric processes and data may make it impossible to carry out calculations of net emissions. The maximum change in Austria's net flow of carbon into the atmosphere between 1990 and 2050[20] is considerably smaller than a (limited) number of uncertainties determined individually, which are inherent in Austria's 1990 LUC (land-use/cover) data, in particular forest-related data. The authors stated that their conclusion may also apply if only human-induced land-use change and forestry activities are considered, as Article 3.3 of the Kyoto Protocol requires. It remains to be seen, however, whether or not this finding can be generalized in regard to other countries. The example demonstrates, how a systems-analysis based FCA approach can assist in getting a more complete overview on the crucial uncertainties underlying in particular the Kyoto Protocol (cf. Section 3).

Table 4.2a. The Kyoto Protocol: Scientific and methodological issues related to FCA. The scientific and methodological issues are not independent of each other and their list may be not complete.

No.	Scientific Challenge	Issue	Brief Explanation	Dispute/Arguments	References
1	**Full carbon accounting** *Under the condition that full carbon accounting is applied globally, this scientific challenge covers all scientific and methodological issues below except for those, which go beyond carbon emission concerns. (Like other international conventions and agreements, the Kyoto Protocol does not aim at their harmonization. It reveals incentives that can impact negatively upon climate protection, conservation of biodiversity and soil protection.)*		FCA follows the carbon-system concept. It is based on a full carbon budget that encompasses and integrates all components of all terrestrial ecosystems and is applied continuously in time, where it is assumed that the overall system as well as its components can be described by adopting the concept of pools and fluxes.	Understanding the nature of terrestrial carbon sinks – their distribution, control, longevity, and reliability – requires a full-system carbon budget applied over large space and time scales (ecosystem approach). A full carbon budget, over sufficient time scales to reflect changes in long-term carbon storage, that is, in NBP (net biome production), is the appropriate basis for any accounting system for terrestrial carbon. Partial accounting systems, such as that described in the Kyoto Protocol, should be logical subsets of the whole-system approach.	(1), (4), (33)
a		Unclear or omitted terminology, particularly in regard to: *reforestation*, *regeneration*, *afforestation*, *deforestation*, *degradation*, *land use* and *land cover*	The terms *reforestation*, *afforestation* and *deforestation* are ambiguously defined and, in the context of the Kyoto Protocol, the term *land use* is possibly ill-defined. More clearly defined and appropriate terms in regard to carbon storage, like *land cover*, *degradation* and *regeneration*, are not used.	To avoid obscurities, the authors require that the key terms used in the Kyoto Protocol are standardized and re-inspected in regard to the extent other requirements of the Kyoto Protocol are affected.	(2) - (4), (18), (19), (20), (29), (31)
b		Spatial leakage	This type of leakage may happen, e.g., if deforestation and other carbon-emitting land-use practices are shifted to other locations and carbon sequestration is evaluated at the project level. (It is noted that positive spatial leakage effects termed *project spillover* may also exist, which are related to the more general concept of *market transformation*.)	To avoid within-country spatial leakage, the authors require that carbon sequestration be evaluated within the more comprehensive framework of a national carbon budget, which permits to keep track of additions and deletions in reference to a national baseline (cf. Table 4.2b). To avoid spatial inter-country leakage, carbon accounting must be globally complete.	(5), (6), (18), (21), (22), (24), (25), (27), (31), (32)

Table 4.2a. . . . (continued).

No.	Scientific Challenge	Issue	Brief Explanation	Dispute/Arguments	References
c		Temporal leakage	This type of leakage may happen, e.g., in the case of deforestation prior to the first commitment period, followed by reforestation or land conversion. In the case of reforestation, carbon removal would be accounted for under the commitment period as well as the smaller part of the post-deforestation emissions due to decomposition and soil processes, but not the greater part of the emissions caused by logging or burning in the year of deforestation.	To avoid temporal leakage prior to the first commitment period and beyond, the authors require that carbon sequestration be evaluated continuously in time, on the basis of continuous commitment periods, and that the monitoring period lasts longer than the implementation period of the sequestration activity.	(1), (3), (4), (18), (19), (22) - (25, (27)
d		Land-use activities that run counter to the objectives of the FCCC	Potential for such activities arises because the Kyoto Protocol disregards biodiversity and other objectives to be met by a (forest) ecosystem.	To avoid counterproductive activities, the authors require that the Kyoto Protocol be supplemented with appropriate definitions, interpretations and agreements, and that incentives are put in place which reflect the entire set of objectives to be met by a (forest) ecosystem, over and above carbon emission concerns.	(2) - (6), (18), (21), (23), (27), (31)
e		Misleading forest-related carbon accounts	Potential for misleading carbon accounts arises because the Kyoto Protocol deals with only a limited part of the forest sector and the forest C cycle.	To avoid carbon accounts that may depart from those based on a more complete accounting, the authors require that C sequestration assessments include carbon in the biomass of trees, in soils, harvested woods and wood products, as well as the interactions between and use of these pools.	(3), (4), (23), (26), (31), (35), (36)
f		Omission of land conversion activities other than deforestation and afforestation	Under the Kyoto Protocol, the conversion of, e.g., primary to secondary forests, grasslands to croplands, or wetlands to other uses is not accounted for.	The authors recall that land conversion can lead to losses of stored carbon that are considerable and of similar magnitude as those caused by deforestation. They also point out that the CO_2-only greenhouse-gas-accounting perspective, e.g., in the case of wetland conversion, is insufficient.	(4), (19), (31)

Table 4.2a. . . . (continued).

No.	Scientific Challenge	Issue	Brief Explanation	Dispute/Arguments	References
g		Omission of other human-induced activities, such as forest and soil management, conservation and protection, from the list of activities eligible for carbon credits	These activities may protect carbon stocks that already exist and contribute to carbon sequestration by reducing destruction (e.g., of forests) and degradation (e.g., of soils).	The authors stress that, in its current formulation, the Kyoto Protocol is set up to ignore many changes, including positive ones that humans make to sequester carbon. Forest management, conservation and protection, e.g., may avoid new debits in national emission inventories and may thus generate far more carbon sequestration than credit received.	(3) - (6), (18), (19), (23), (31)
h		Inappropriate classification of emissions (which is also reflected by the difficulties in defining *reforestation*, *afforestation* and *deforestation*; cf. Issue 1a above!)	The Kyoto Protocol classifies emissions by making use of the term *human-induced* (in contrast to the term *natural)*, which is scientifically inappropriate. The Protocol excludes indirect effects (not *human-induced* influences).	The authors state that this and similar attempts to classify emissions (*human-induced* vs. *natural* or *indirect*, etc.) cannot be firmly incorporated into source/sink calculations. Therefore, they require for scientific reasons that the Kyoto Protocol avoid imprecisely defined terms when attempting to classify emissions by sources and removals by sinks.	(2), (7), (8)

Table 4.2b. The Kyoto Protocol: The scientific challenge of establishing 1990 baselines and post-1990 baseline scenarios.

No.	Scientific Challenge	Issue	Brief Explanation	Dispute/Arguments	References
2	**Establishing 1990 baselines and post-1990 baseline scenarios** *In particular, the scientific challenge of establishing post-1990 baseline scenarios cannot – as a matter of principle – be avoided under FCA. The scenarios are needed to satisfy the Protocol's criteria of additionality [although ‘additionality’ is not explicitly mentioned other than in Articles 6.1(b) and 12.5(c) of the Protocol]. It remains to be investigated, however, under which conditions the benefit of establishing a total (national) post-1990 baseline scenario may be considered negligible, if a full carbon accounting system is used that is spatially (and temporally) complete. So far, this scientific challenge has not yet been discussed as broadly and thoroughly as necessary within the scientific community.*		The Kyoto Protocol requires Parties 1) to come up with a baseline assessment for 1990 of their net greenhouse gas emissions from all sources – including land-use change and forestry – and of their carbon stocks; and 2) to comply with the criteria of additionality in applying joint mechanisms (joint implementation, CDM) between them to meet part of their greenhouse gas commitments. As a matter of principle, the problem of additionality arises also in the context of (within-country) Kyoto-compliant emission reduction projects. The amount of carbon claimed must take into consideration what would have occurred in the absence of such a project.	The authors recall that accounting of joint implementation and CDM projects as well as (within-country) Kyoto-compliant emission reduction activities under the Protocol requires, over and above a 1990 baseline, the consideration of *additionality*, which – in turn – requires to establish a post-1990 baseline in the form of a scenario that is continuous in time. Establishing post-1990 baseline scenarios cannot – as a matter of principle – be avoided under FCA. It remains to be investigated, however, under which conditions the benefit of establishing a total (national) post-1990 baseline scenario may be considered negligible, if a full carbon accounting system is used that is spatially (and temporally) complete.	(3) - (6), (8), (9), (21), (24), (25), (27), (32)

Table 4.2c. The Kyoto Protocol: The scientific and methodological issues related to accounting for uncertainty. The issues are ordered in accordance with Table 3.2, classifications II-V (excluding II.1, II.2 and V.1, which are purely technical or inapplicable).

No.	Scientific Challenge	Issue	Brief Explanation	Dispute/Arguments	References
3	**Uncertainty** *This scientific challenge has not yet been widely addressed (not to speak of its quantification) within the scientific literature. The uncertainty issue may have played a role in developing the Kyoto Protocol, but this is insufficiently reflected in the text of the Protocol.*		In particular, uncertainties in estimating carbon fluxes associated with land-use change and forestry are unavoidable and not negligible.	The crucial question is whether the uncertainty in estimating carbon fluxes associated with land-use change and forestry is so large as to threaten the compliance process. There are hardly any solid numbers available. Therefore, "early warnings versus hope and believe" can best describe the present situation (which, however, is reflected so far only within a small part of the scientific literature). Suggestions also exist on how to minimize the problem, e.g., by not permitting additional sinks according to the provisions of Article 3.4, because each credited sink considerably exacerbates the uncertainties in verification and diminishes commitments to reduce emissions from fossil fuels.	(1), (4), (7) - (11)
a		**Uncertainty referring to data status:**			
		1) Uncertainty due to shortcomings of data	In setting the 1990 baseline, a scientifically rigorous inventory for forests is required.	The scientists point out that hardly any country has a scientifically rigorous 1990 forest inventory available. Important indicators are usually inaccurately known, or not known over a sufficiently long time period, or are not or have never been measured. This can strongly impact final carbon calculations, e.g., in that countries may be rewarded for savings that simply result from more accurate field data.	(4), (9), (28), (34)

Table 4.2c. . . . (continued).

No.	Scientific Challenge	Legal Shortcoming	Brief Explanation	Dispute/Arguments	References
		2) Uncertainty due to the combined effect of past land-use/cover (LUC) changes	The task to come up with a baseline assessment for 1990 of their net greenhouse gas emissions from all sources and sinks and of their carbon stocks, requires Parties to take also into account past events over long periods of time.	The authors emphasize that – in particular, if different changes in land use and/or land cover overlay each other – it is almost impossible to judge the resulting effect without making use of direct measurements of changes in carbon stocks. Therefore, given the long time periods and large areas usually involved, the authors expect considerable uncertainties related to assessing the combined effect of past LUC changes on a country's level of carbon stocks in 1990.	(8)
b		**Uncertainty referring to data processing:**			
		1) Uncertainty due to inconsistent land-use/cover (LUC) databases	A prerequisite for any accurate inventory of natural greenhouse gas emissions and removals is the use of a consistent LUC database that provides data coverage for a country's total territory.	The authors' experience leads them to conclude that extracting the most reliable LUC data subsets and piecing them together into a nationally consistent LUC database does help both to reduce data uncertainties and to increase confidence in data reliability considerably.	(8), (12), (13)
		2) Uncertainty involved in transforming local (point) measurements to aggregated characteristics	The more general space-time problem underlying this uncertainty goes back to the question how the scaling-down of the "missing carbon sink" compares with the scaling-up of carbon fluxes from local to regional to global?	The authors draw attention to the fact that a scale mismatch exists: The size of the carbon problem is global, but measurements dealing with the problem are mainly local. Local measurements have to be scale-adapted (spatially from meters to continental scale and temporally from hours to years), taking into account the large geographical and temporal variations. Knowledge on this uncertainty across the full range of space and time scales has not yet been compiled and integrated as thoroughly and rigorously as necessary. This is mainly because hierarchical sets of consistent carbon inventories from local to regional to global do not yet exist.	(14) - (17), (24), (25), (28)-(31)

Table 4.2c. . . . (continued).

No.	Scientific Challenge	Legal Shortcoming	Brief Explanation	Dispute/Arguments	References
c		**Uncertainty referring to the approach-inherent reflection of reality:**			
		Uncertainty inherent in the scientific understanding of the basic processes leading to emissions and removals	This type of uncertainty goes beyond the detailed-systems approach underlying greenhouse gas guidelines. Its assessment requires also carrying out a total-systems approach in parallel.	This uncertainty has been identified in the literature, but the user of greenhouse gas guidelines can usually not address it, because the provision of instructions on how to carry out a total-systems approach is not a principal objective of the guidelines (cf. Section 3.4.2).	(24), (25), (28), (29)
d		**Uncertainty referring to issues that are specific to the Kyoto Protocol:**			
		1) Uncertainty involved in the determination of post-1990 baseline scenarios	Carbon sequestration is closely tied to the determination of post-1990 baseline scenarios, which must precede the application of the additionality concept.	The authors note that a list of measurement uncertainties must also include the uncertainty in "measuring" items that cannot be directly measured, e.g., post-1990 baseline scenarios.	(25), (27)
		2) Uncertainty involved in complying with the concept of additionality	Carbon sequestration is closely tied to the concern that carbon sequestration activities are real and additional. This means that carbon sequestration, for which credits are given, e.g., as a result of some forestry-based activity, are over and above what would have occurred in the absence of an emissions reduction program.	So far, additionality is generally recognized as a "Kyoto condition", while only a few authors perceive it also in terms of uncertainty – as a consequence of the uncertainty involved in the determination of post-1990 baseline scenarios. However, additionality is not yet perceived in the context of uncertainties that are involved in the calculation of small numbers. This may be so because relevant experiences are still scarce.	(3) - (6), (27), (31)
		3) Uncertainty involved in complying with the concept of accounting net emissions	Article 3.3 of the Kyoto Protocol provides that biological sources and sinks shall also be used in meeting 2008/12 emission commitments, but limits these sources and sinks as yet to afforestation, reforestation and deforestation since 1990.	Based on the full carbon account of Austria and an incomplete list of uncertainties determined individually, researchers conclude that at present the incomplete knowledge about biospheric processes and data in particular may make it impossible to carry out calculations of net emissions. They state that this conclusion also holds if only human-induced land-use change and forestry activities are considered, as Article 3.3 of the Kyoto Protocol requires. They, therefore, advocate a differentiated approach – as it is also requested elsewhere in the meantime.	(4), (8), (34)

Table 4.2c. . . . (continued).

No.	Scientific Challenge	Legal Shortcoming	Brief Explanation	Dispute/Arguments	References
e		**Uncertainty referring to verification:**			
		Uncertainty involved with verification	Above and beyond the questions that remain to be answered in regard to interpreting Articles 3, 6, 12, and 17 consistently (in terms of permissible land-use change and forestry activities), the Kyoto Protocol requires that changes in carbon stocks due to forest-based activities must be verifiable. If the scope of carbon sequestration develops to include agriculture and other land uses, verification methods will have to accommodate a rapidly increasing number of land use portfolios that comprise the global carbon stock.	So far, scientists perceive verification either as an institutional challenge (not covered here) or as an uncertainty problem that is linked with the question of data reliability. In the latter case, they draw attention to the major and fundamental uncertainties that are inherent in terrestrial carbon stock and flux estimations. These insights lead the majority of scientists to conclude that the verifiability of the legally binding commitments is greatly reduced.	(4) - (6), (13), (14), (21), (27), (31)

References: (1) Steffen *et al*. (1998); (2) Lund (1999); (3) Schlamadinger and Marland (1998); (4) WBGU (1998); (5) Sedjo (1998); (6) Sedjo *et al*. (1998); (7) Bolin (1998); (8) Jonas *et al*. (1998); (9) Schmidt (1998); (10) Pearce (1998); (11) Jonas (1998); (12) Jonas (1997); (13) Alexandrov and Yamagata (1998); (14) Kaiser (1998); (15) Renner (1998); (16) Brüning (1998); (17) Compiling literature reporting on mismatching scales, or certain aspects thereof, is a task in itself!; (18) Brown (1998); (19) MacDonald (1999); (20) Nabuurs and Verkaik (1998); (21) Goldberg *et al*. (1998); (22) Hasselmann (1998); (23) EU (1998); (24) Vine and Sathaye (1997); (25) Vine *et al*. (1999); (26) Apps *et al*. (1997); (27) Gustavsson *et al*. (1998); (28) Shvidenko *et al*. (1996); (29) SBSTA (1998b); (30) Karjalainen *et al*. (1998); (31) Nabuurs *et al*. (1999); (32) Sohngen *et al*. (1998); (33) Nilsson *et al*. (1999); (34) CCRS (1999); (35) Marland and Schlamadinger (1999); (36) Karjalainen *et al*. (1999).

5. Conclusions

In our study we discuss the scientific background to FCA. We define FCA on the basis of a full carbon-system concept, in consideration of consistency and other scientific and non-scientific system requirements, such as completeness, complexity and uniformity. Our discussion is followed by a FCA-based analysis of the unresolved and scientific-methodological issues of the Kyoto Protocol. It leads us to the following major conclusions:

- *The unresolved issue of the Protocol's legal basis of compliance.* The IPCC Guidelines do not or cannot consider − for whatever reasons − the option of cross-checking flux estimations independently. [The IPCC Guidelines require to estimate net fluxes either directly (i.e., in a flux-based fashion) or indirectly (i.e., in a stock-based fashion), but never to apply both methods.] Only by doing so, can scientists be sure whether or not their flux estimations are compatible with the principle of mass conservation. Having another option at their disposal to estimate net fluxes, where possible, would put scientists into a more favorable position to narrow the uncertainties in their flux estimations. Therefore, in their present form, the IPCC Guidelines cannot be considered adequate in handling the uncertainties underlying the carbon-accounting problem and thus the Kyoto Protocol. A systems-analysis based FCA approach can help to fill this gap.

  The IPCC Guidelines do not make an attempt to be spatially complete in considering carbon fluxes into/out of the terrestrial ecosystems. The IPCC Guidelines focus only on regions where human-induced changes have taken and/or are taking place. However, separating directly impacted lands from indirectly affected lands may result in carbon accounts that are not only meaningless, but may even lead to false conclusions from an accounting point of view (in particular, if adverse effects cannot be recognized immediately). Therefore, in their present form, the IPCC Guidelines cannot be considered sufficiently complete − neither in terms of space nor in terms of carbon reservoirs and fluxes, processes, and types of carbon-related territorial units − to serve as the main accounting system for a partial accounting system as described in the Kyoto Protocol. FCA should be considered in overcoming this inadequacy.

- *The scientific challenge of FCA.* Owing to the fact that the Protocol does not adhere to the scientific challenge of FCA, it reveals a number of serious, not purely technical, scientific and methodological issues, which it would not do otherwise. (Confer Table 4.2a for the list of issues.) Complying with the concept of FCA would cover these issues, with the exception of those that go beyond carbon emission concerns − pointing to the more general problem of inadequate coordination of global environmental protection. The objectives and catalogues of measures set up by the individual conventions and other international agreements need to be harmonized more rigorously. FCA must be applied globally to avoid spatial inter-country leakage.

  A full carbon accounting approach that is spatially complete bears the potential of contributing significantly to the important research task of closing the carbon cycle on a global scale. In contrast, a partial accounting approach, which does not form a logical and consistent subset of the full carbon accounting approach, may run the risk of establishing a meaningless carbon account or even becoming counterproductive if it incorporates misaccounting or introduces perverse incentives.

- *The scientific challenge of establishing 1990 baselines and post-1990 baseline scenarios.* The Protocol requires, over and above a 1990 baseline, the consideration of additionality, which – in turn – requires establishing a post-1990 baseline in the form of a scenario that is continuous in time. In particular, the scientific challenge of establishing post-1990 baseline scenarios cannot – as a matter of principle – be avoided under FCA. The scenarios are needed to satisfy the Protocol's criteria of additionality [although ‘additionality’ is not explicitly mentioned other than in Articles 6.1(b) and 12.5(c) of the Protocol]. It remains to be investigated, however, under which conditions the benefit of establishing a total (national) post-1990 baseline scenario may be considered negligible, if a full carbon accounting system is used that is spatially (and temporally) complete.
- *The scientific challenge of accounting for uncertainty.* This scientific challenge has not yet been widely addressed (not to speak of its quantification) by the scientific community. The uncertainty issue may have played a role in developing the Kyoto Protocol, but this is insufficiently reflected in the text of the Protocol. The crucial question whether the uncertainties in estimating carbon fluxes associated with land-use change and forestry are so large as to threaten the compliance process cannot yet be answered with sufficient rigor. Initial research indicates that the individual and combined effect of these uncertainties are not yet understood and may pose major difficulties in making the Protocol operational (e.g., the issue of establishing post-1990 baseline scenarios and the issue of small numbers). A systems analysis-based FCA approach can assist in getting a more complete overview on the crucial uncertainties underlying the Kyoto Protocol.

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Notes

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[1] "Annex I Party" or "Party included in Annex I" means a Party included in Annex I to the Convention, as may be amended, or a Party which has made a notification under Article 4, Paragraph 2(g), of the Convention (UNFCCC, 1998).

[2] The terms stock, reservoir and pool as well as the terms flow and flux are used interchangeably in this study.

[3] The first international scientific assessment of the possible consequences of the increasing atmospheric concentration of CO_2 was undertaken by a group of scientists at a meeting in Villach, Austria, in 1980, initiated by the newly established WMO/UNEP/ICSU World Climate Programme (WMO, 1981).

At this meeting, it was estimated that for a doubling of the pre-industrial concentration of CO_2 the increase of the global mean surface temperature would be in the range of 1.5 - 4.5°C. A few years later, a more extensive scientific assessment was undertaken, in which the additional effect of a number of other greenhouse gases as well as aerosols in the atmosphere was taken into account (Bolin *et al.*, 1986). This assessment included also the associated impacts on ecosystems.

In 1988, WMO and ICSU established the Intergovernmental Panel on Climate Change (IPCC). Following a coordinated effort, in which several hundred scientists participated, this Panel produced a synthesis of the scientific information available on the climatic change that can be expected due to an enhanced greenhouse effect. It also produced an evaluation of the climate-induced environmental and socioeconomic consequences as well as formulations of response strategies (IPCC, 1990). These evaluations have subsequently been updated (IPCC, 1991, 1992, 1995, 1996a, b, c).

[4] The IPCC frequently estimated the required reductions of the anthropogenic emissions of the major greenhouse gases to stabilize their atmospheric concentrations at present day levels (IPCC, 1990, 1995, 1996a; Houghton, 1991; Döös, 1997; Wigley *et al.*, 1997). These emission reductions have to be substantial. For instance, CO_2 emissions from burning fossil fuels and producing cement have to be reduced globally by more than 60%.

[5] The States ratifying the Convention make up the Conference of the Parties (COP), which was established in the sequel of Article 7 of the Convention and which, as the supreme body of the Convention, is charged with the responsibility for implementing it. Between summer 1992 and fall 1996, the COP met two times. In Berlin in 1995, COP-1 addressed questions about the adequacy of the commitments being made by the different countries and what might be the appropriate action for the period after 2000. (The agreement reached on beginning this process toward appropriate action, which should also include the strengthening of the commitments of Annex I Parties[1] through the adoption of a protocol or another legal instrument, is called the Berlin Mandate.) At the meeting, several subsidiary bodies were established to review scientific, technical, and technological assessments of the problem; to map out how the intents of the Convention could be achieved; to provide means for the Parties to the Convention to discuss and resolve their questions on implementation; and to assess how signatories to

the Convention that have indicated an intent to reduce greenhouse gas emission levels might formalize their commitments and cooperate with others in producing those reductions (Global Climate Change Digest, 1998).

In Geneva in 1996, COP-2 recognized the need for flexible methods for the signatories to achieve their emission reductions. The "Geneva Declaration" endorsed the conclusions of the IPCC and called for legally binding objectives and significant reductions in greenhouse gas emissions. COP-2 also saw a significant shift in position by the US, which for the first time supported a legally binding agreement to fulfill the Berlin Mandate. However, even as Parties prepared to strengthen commitments, COP-2 highlighted the sharpest differences between them. In particular, two proposals complicated the deliberations. The first, from the European Union, suggested a 15% cut in emissions of three greenhouse gases (lumped together) between 1990 and 2010. The other, from the United States, called for "meaningful participation", i.e., commitments to reduce greenhouse gas emissions, by developing countries and the establishment of a linkage between their involvement in the negotiations and their commitment to contribute to the solution. The discussion of the two proposals was inconclusive (ENB, 1997; Global Climate Change Digest, 1998).

[6] Annex B of the Kyoto Protocol lists the quantified emission limitations or reduction commitments by Party.

[7] To assist the readership in understanding the Kyoto Protocol, other documents also attempt to give short annotations that highlight the most important passages in the individual articles of the Protocol (cf., e.g., UNEP, 1999).

[8] The IPCC (1996a) concluded that in order to prevent a doubling or even tripling of atmospheric CO_2 concentrations in the middle to late 21st century, at least half to three quarters of the expected fossil-fuel based CO_2 emissions will need to be replaced by 2050 and beyond [cf. Schneider (1998) and also Endnote 4 above].

[9] Several subsidiary bodies advise the COP (IISD, 1998):

- The Subsidiary Body on Science and Technical Advice (SBSTA) links scientific, technical and technological assessments, the information provided by competent international bodies, and the policy-oriented needs of the COP.
- The Subsidiary Body for Implementation (SBI) was created to develop recommendations to assist the COP in the review and assessment of the implementation of the Convention and in the preparation and implementation of its decisions. The SBSTA and SBI meet once or twice a year in back-to-back sessions.
- The open-ended Ad Hoc Group on the Berlin Mandate (AGBM) was created following COP-1 to consider the adequacy of commitments for the period beyond 2000, including the strengthening of the commitments of Annex I Parties through the adoption of a protocol or another legal instrument. This process culminated in December 1997 with the Kyoto Protocol.
- The Ad Hoc Group on Article 13 (AG13) was set up to consider the establishment of a multilateral consultative process (MCP) available to Parties to resolve questions on implementation. It first met in October 1995. Over the course of four subsequent

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meetings, delegates agreed that the MCP should be advisory rather than supervisory in nature and that AG13 should complete its work by COP-4, in November 1998.

[10] Articles 2.3 and 3.14 of the Protocol refer to Articles 4.8 and 4.9 of the Convention, which reflect the concern for sustainable development of the developing country Parties. COP-4 recognizes that, in the implementation of the commitments in Article 4 of the Convention, the Parties shall give full consideration to what actions are necessary under the Convention, including actions related to funding, insurance and the transfer of technology, to meet the specific needs and concerns of developing country Parties arising from the adverse effects of climate change and/or the impact of the implementation of response measures [UNFCC, 1992, 1998, 1999a (Decision 5/CP.4)].

[11] It is noted that we additionally assume that the pool-flux concept reflects the specific, soil-vegetation structural composition of the terrestrial ecosystems and apply soil-vegetation carbon ensembles that are characteristic for a terrestrial ecosystem (Nilsson *et al*., 1999).

[12] Here the terms *direct* and *indirect* are used from an emission point of view, in consideration of the ultimate objective of the Kyoto Protocol to limit or reduce the emissions of a number of greenhouse gases, in compliance with Article 2 of the Convention, rather than from an applicatory point of view, whether a physical quantity can be measured directly or indirectly.

[13] The full carbon accounts of Russia and Austria refer to different degrees of sophistication. A comparison of the two country accounts, in consideration of ongoing model developments, is beyond the scope of this study and will be presented elsewhere. Suffice to mention here that the two accounts cover CO_2-C and CH_4-C. The addition of other carbon-related greenhouse gases is under completion.

[14] *… a reduction in emission by sources, or an enhancement of removals by sinks, that is additional to any that would otherwise occur …* [UNFCCC, 1998: Article 6.1(b)].

[15] When measuring changes in carbon stock, it is possible that the actual reductions in carbon are greater than measured because of changes in participant behavior not directly related to the carbon sequestration project, as well as to changes in the behavior of other individuals not participating in the project. Project spillover may be regarded as an unintended consequence of a carbon sequestration project or also perceived as a strategic, intended mechanism for reducing greenhouse gas emissions (Vine *et al*., 1999).

[16] Market transformation is defined as the reduction in market barriers due to a market intervention, as evidenced by a set of market effects, that lasts after the intervention has been withdrawn, reduced or changed. Increasing market transformation is expected to be a strategic mechanism (i.e., an intended consequence) for reducing carbon emissions in a particular sector (Vine *et al*., 1999).

[17] It is possible that carbon sequestration projects are undertaken by participants who would have conducted the same activities if there had been no project and, therefore, the carbon sequestered by these "free riders" would not be perceived as additional to what

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would otherwise have occurred. Although free riders may be regarded as an unintended consequence of a carbon sequestration project, free ridership should still be estimated (if possible, during the estimation of the baseline). While free riders can also cause spatial leakage and project spillover, these impacts are typically considered to be insignificant compared to the impacts from other participants (Vine and Sathaye, 1997; Vine *et al.*, 1999).

[18] But the scientific and methodological issues can be grouped in an independent fashion, e.g., by applying the concept of completeness. (Confer Section 3.4.1, where we consider the different kinds of completeness.) However, in the absence of additional advantages, we did not take this re-grouping into account here.

[19] In the case that the Kyoto-compliant activity areas are small relative to a country's total area (as it is the case with many Annex I country Parties), we face the general situation that changes in the carbon account outside the Kyoto-compliant activity areas are more important than the changes in the carbon accounts inside the Kyoto-compliant activity areas. Under these conditions, the benefit of establishing a total (national) post-1990 baseline scenario may be considered negligible under FCA.

[20] The maximum change in Austria's net flow of carbon into the atmosphere between 1990 and 2050 is defined according to $\Delta \mathrm{Cnet}_{\max} = \max\{|\mathrm{Cnet}(1990) - \mathrm{Cnet}(t)|, t = 1990, 2000, \ldots, 2050\}$, where Cnet is the difference between Austria's total flow of carbon into and out of the atmosphere.

Appendix

The Appendix provides an overview of the direct (flux-based) and the indirect (stock-based) net flux method, as they are applied in Chapter/Module 4 (Agriculture) and Chapter/Module 5 (Land-Use Change and Forestry) of the Revised 1996 IPCC Guidelines (IPCC, 1997a, b, c). The overview is given in the form of summary tables, Table A-1 summarizing Chapter/Module 4, and Table A-2 summarizing Chapter/Module 5. Only carbon-related (direct and indirect) greenhouse gases (GHG's) are considered.

Table A-1. Overview on which 1) type of flux (Submodule), 2) carbon-related GHG, 3) net flux approach, and 4) flux template (Worksheet) is applied in Chapter/Module 4 (Agriculture) of the IPCC Guidelines. The abbreviation "Pr" stands for "Present" and indicates the time, for which the flux approach is considered.

Chapter/Module 4: Agriculture					
Submodule	**GHG**	**Approach**			**Worksheet**
(Flux)		**Direct**	**Indirect**	**Remark**	**(Template)**
CH_4 Emissions from Domestic Livestock Enteric Fermentation and Manure Management	CH_4-C	Pr: ✔ (Tier 1; cf. a)	Pr: ✔ (Tier 2; cf. b)	The IPCC Guidelines present two approaches, a simplified approach (Tier 1) and a more complex approach (Tier 2), to estimate CH_4-C emissions from enteric fermentation and manure management. The two approaches differ in how accurate a country's livestock and manure management conditions are reflected.	4-1
CH_4 Emissions from Flooded Rice Fields	CH_4-C	Pr: ✔			4-2
Prescribed Burning of Savannas	CO_2-C			CO_2-C net emissions are assumed zero.	4-3
	CH_4-C		Pr: ✔	The CH_4-C and CO-C emissions are derived from the total biomass exposed to burning.	
	CO-C		Pr: ✔		
Field Burning of Agricultural Residues	CO_2-C			CO_2-C net emissions are assumed zero.	4-4
	CH_4-C		Pr: ✔	The CH_4-C and CO-C emissions are derived from the annually produced crop pool.	
	CO-C		Pr: ✔		

a) The simplified Tier 1 approach relies on default emission factors and is likely to be sufficient for most animal types in most countries.

b) The more complex Tier 2 approach requires country-specific information on livestock characteristics and manure management practices and is recommended when the data used to develop the default approach do not correspond well with a country's livestock and manure management conditions.

Table A-2. Overview on which 1) type of flux (Submodule), 2) carbon-related GHG, 3) net flux approach, and 4) flux template (Worksheet) is applied in Chapter/Module 5 (Land-Use Change and Forestry) of the IPCC Guidelines. The abbreviations "Pa" and "Pr" stand for "Past" and "Present", respectively, and indicate the times, for which the flux approach is considered.

Chapter/Module 5: Land-Use Change and Forestry					
Submodule	**GHG**	**Approach**			**Worksheet**
(Flux)		**Direct**	**Indirect**	**Remark**	**(Template)**
Changes in Forest and Other Woody Biomass Stocks	CH_2-C		Pr: ✔	CH_2-C removals or emissions are derived by considering the total annual biomass increment, reduced by the total annual biomass loss (removed and consumed).	5-1
Forest and Grassland Conversion: Carbon Released by Burning of Biomass	CH_2-C		Pr: ✔	The immediate CH_2-C emissions released by burning of biomass are derived by considering the total biomass before and after conversion.	5-2
Forest and Grassland Conversion: Carbon Released by Decay of Biomass	CH_2-C		Pr: ✔	The delayed CH_2-C emissions released by decay of biomass are derived by considering the total biomass before and after conversion.	5-2
On-site Burning of Forests: Non-CO_2 Gas Emissions	CH_4-C CO-C		Pr: ✔ Pr: ✔	Builds upon → Forest and Grassland Conversion: Carbon Released by Burning of Biomass	5-3
Abandonment of Managed Lands: Carbon Uptake by Aboveground Regrowth	CH_2-C		Pa–Pr: ✔	The CH_2-C uptake is derived by considering the annual regrowth of aboveground biomass on land abandoned prior to the inventory year.	5-4
Change in Soil Carbon for Mineral Soils: For Native Ecosystem Types and for Agriculturally Impacted Lands	CH_2-C		Pa–Pr: ✔ (cf. a)	The net change in soil carbon in mineral soils is calculated on the basis of changes in carbon stocks over a multi-year period.	5-5
Carbon Emissions from Intensively Managed Organic Soils	CH_2-C	Pr: ✔			5-5
Carbon Emissions from Liming of Agricultural Soils	CH_2-C	Pr: ✔			5-5

a) In the case of changes in soil carbon for mineral soils, a 20-year time interval is considered in the calculations.
In the case of changes in soil carbon for agriculturally impacted lands, the application of a set of factors is proposed. They account for changes in soil organic matter associated with the conversion of the native vegetation to agricultural use (irrespective of when this has happened), and for effects of various management practices of lands in agricultural use (over the inventory period of 20 years). Therefore, calculations of past reservoir contents are only very approximate.

The IPCC Guidelines require to estimate net fluxes either directly or indirectly, but never to apply both methods (also not for the calculation of CH_4 emissions from domestic livestock enteric fermentation and manure management). In some cases, the IPCC Guidelines require the application of (default or expert) emission factors, in essence the realization of the direct net flux method in an approximate way. In most cases, however, the emission-factor approach is not or cannot be applied (because, e.g., difficulties have prevented scientists so far from determining emission factors experimentally and to scale-adapt them to the space and/or time scales required). In these cases, the IPCC Guidelines require the estimation of temporal changes in reservoirs, ΔR, followed by the application of ΔR-to-atmosphere transfer ratios, in essence the realization of the indirect net flux method in an approximate way.